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TECHNOLOGY, EMPLOYMENT,
AND OUTPUT PER MAN IN

PETROLEUM AND NATURAL-GAS PRODUCTION

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(List continued on inside back cover)

FEDERAL WORKS AGENCY
WORK PROJECTS ADMINISTRATION

F. C. HARRINGTON
Commissioner

CORRINGTON GILL
Assistant Commissioner

NATIONAL RESEARCH PROJECT

on

Reemployment Opportunities and Recent Changes
in Industrial Techniques

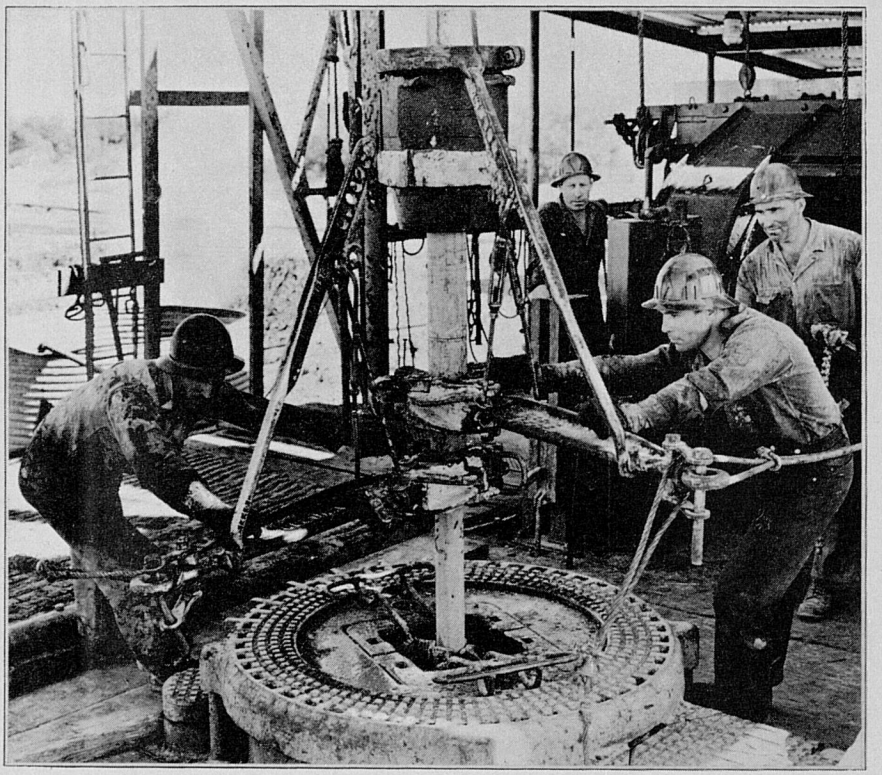
DAVID WEINTRAUB
Director

In cooperation with

UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

JOHN W. FINCH, Director

Mineral Technology and Output Per Man Studies
O. E. Kiessling, Economist in Charge



"COMING OUT OF THE HOLE" – A ROTARY DRILLING CREW
"BREAKING A STAND" OF DRILL PIPE

In rotary drilling it is necessary to remove the drill pipe from the hole and to return it in the performance of certain tasks. This operation – called a "round trip" – consists of unscrewing the drill pipe in sections (usually in "stands" of 3 or 4 joints), racking the stands, and later rejoining the stands as the pipe is returned to the hole. Where the wells are deep and 2 miles or more of pipe must be handled, 12 hours or more may be required to make a round trip. Special equipment, such as the tongs shown gripping the joint to be "broken", are essential aids to manpower in virtually all oil-field operations.

TECHNOLOGY, EMPLOYMENT, AND OUTPUT PER MAN IN PETROLEUM AND NATURAL-GAS PRODUCTION

by

O. E. Kiessling, H. O. Rogers, G. R. Hopkins, N. Yaworski,
R. L. Kiessling, J. Brian Eby, Lew Suverkrop,
J. S. Ross, R. E. Heithecker, W. B. Berwald,
Andrew W. Rowley, M. A. Schellhardt,
Richard Sneddon, Boyd Guthrie,
Herbert Schimmel, and
J. C. Albright

WORK PROJECTS ADMINISTRATION, NATIONAL RESEARCH PROJECT
In cooperation with
DEPARTMENT OF THE INTERIOR, BUREAU OF MINES

Report No. E-10

Philadelphia, Pennsylvania

July 1939

THE WPA NATIONAL RESEARCH PROJECT ON REEMPLOYMENT OPPORTUNITIES AND RECENT CHANGES IN INDUSTRIAL TECHNIQUES

Under the authority granted by the President in the Executive Order which created the Works Progress Administration, Administrator *Harry L. Hopkins* authorized the establishment of a research program for the purpose of collecting and analyzing data bearing on problems of employment, unemployment, and relief. Accordingly, the National Research Program was established in October 1935 under the supervision of *Corrington Gill*, Assistant Administrator of the WPA, who appointed the directors of the individual studies or projects.

The Project on Reemployment Opportunities and Recent Changes in Industrial Techniques was organized in December 1935 to inquire, with the cooperation of industry, labor, and governmental and private agencies, into the extent of recent changes in industrial techniques and to evaluate the effects of these changes on the volume of employment and unemployment. *David Weintraub* and *Irving Kaplan*, members of the research staff of the Division of Research, Statistics, and Finance, were appointed, respectively, Director and Associate Director of the Project. The task set for them was to assemble and organize the existing data which bear on the problem and to augment these data by field surveys and analyses.

To this end, many governmental agencies which are the collectors and repositories of pertinent information were invited to cooperate. The cooperating agencies of the United States Government include the Department of Agriculture, the Bureau of Mines of the Department of the Interior, the Bureau of Labor Statistics of the Department of Labor, the Railroad Retirement Board, the Social Security Board, the Bureau of Internal Revenue of the Department of the Treasury, the Department of Commerce, the Federal Trade Commission, and the Tariff Commission.

The following private agencies joined with the National Research Project in conducting special studies: the Industrial Research Department of the University of Pennsylvania, the National Bureau of Economic Research, Inc., the Employment Stabilization Research Institute of the University of Minnesota, and the Agricultural Economics Departments in the Agricultural Experiment Stations of California, Illinois, Iowa, and New York.

FEDERAL WORKS AGENCY
WORK PROJECTS ADMINISTRATION
1734 NEW YORK AVENUE NW.
WASHINGTON, D. C.

F. C. HARRINGTON
COMMISSIONER OF WORK PROJECTS

July 25, 1939

Colonel F. C. Harrington,
Commissioner of Work Projects

Sir:

The report on *Technology, Employment, and Output per Man in Petroleum and Natural-Gas Production*, submitted herewith, deals with an industry which occupies an important place in our national economy. Oil and gas together now supply more than a third of the country's total energy requirements. Total gross investment in the industry was reported to have been 14.5 billion dollars in 1937. Annual expenditures for supplies needed in oil and gas production were estimated at 876 million dollars for 1935. Three-quarters of a million workers were engaged in the transportation, refining, and marketing segments of the industry in 1935, and an additional 135,000 wage earners were employed at oil and gas wells and natural-gasoline plants in the same year.

Contrary to the outlook for most of the other extractive industries, it is expected that over-all employment opportunities in oil and gas production probably will increase for at least the next decade and a half, although the manpower requirements of the different divisions of the industry will vary. The upward trend of employment at oil and gas wells - characteristic of developments until 1929 - has been resumed and probably will continue for the next 10 or 15 years. The arresting of employment expansion in this segment of the industry during the depression years resulted largely from the drastic curtailment of drilling and its restriction to proved areas rather than from advancing technology. With growing consumption, the drilling operations, which require a large part of the labor force in oil and gas production, have been resumed on a more extensive scale in recent years. This development may be expected to

continue, for it appears likely that demand will continue to increase.

It is also likely that a larger labor force will be required at natural-gasoline extraction plants. A steadily growing demand for the lighter constituents of raw natural gasoline, which for many years were allowed to go to waste, plus the wider use of polymerization at natural-gasoline plants are factors tending toward an upward employment trend.

Corresponding closely to the trend of crude-oil and natural-gas production, employment in refining reached an all-time high in 1937, when 83,183 wage earners were employed in the manufacture of petroleum products. On the basis of present anticipated developments, moreover, labor requirements at refineries probably will continue to increase for possibly the next 15 years.

No extensive changes are anticipated in the employment needs of the transportation and storage segment of the industry in the next decade. The relatively small labor force now required for maintenance and operation possibly will continue to decrease slightly with the installation of more efficient equipment at remaining old plants, but with a large part of pipe-line operations already mechanized, future opportunities for labor saving in this manner are very limited. On the other hand, there is little promise of resumption of an extensive construction program which would greatly increase employment. The need for storage facilities has decreased, for example, because of more effective proration of oil production. Furthermore, the crude-oil and gas pipe-line network is now fairly well completed. Prevailing tanker rates have operated to increase the tanker movement to the East Coast and to eliminate through-pipe-line movements from the Mid-Continent, and the shifting of the center of production southward in recent years has reduced the average length of pipe-line movement incident to consumption at Gulf and East Coast refineries. In view of these developments only a moderate extension of crude-oil lines may be expected for the next decade. Likewise, the prospects favor gradual extension of gas lines in the East, and gas from the recently proved deposits in California eventually may be piped north to Oregon and Washington. Continued gasoline pipe-line construction on a moderate basis will doubtless continue.

A factor that cannot be ignored when future employment possibilities are being considered is the length of

the workweek. How important this may be is illustrated by a brief resume of significant changes in work schedules in the past two decades. After the World War the majority of refineries established an 8-hour day with a 48- to 56-hour workweek. Under the NRA the length of the workweek was reduced to 40 hours. This schedule for refinery workers and a similar one for operating employees of major transportation companies were generally followed at the time of the enactment of the Fair Labor Standards Act of 1938. Since both the refining and the transportation divisions were already largely complying with the maximum-hour provisions of the 1938 act, no large increases in employment took place in the industry when this law became effective, and only a moderate increase can be expected in the future. In drilling operations, however, there has been an increase in employment due to the maximum-hour provisions. Prior to this regulation the employees of a number of producing companies, as well as drilling contractors, worked a 56-hour week. To conform with the 44-hour maximum prescribed for the first year of the law's operation, these companies hired a considerable number of additional men. Further increases in the number of men employed are anticipated in the second year of the law's operation, when the workweek will be shortened to 42 hours, and again after 2 years, when the workweek will be limited to 40 hours. The long-time trend shows a notable reduction in the length of the workday and the workweek, and this reduction has been an important factor in maintaining and expanding employment in the industry.

Respectfully yours,

Corrington Gill

Corrington Gill
Assistant Commissioner

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PREFACE

The petroleum and natural-gas industry has only within the last 50 years come to use and rely on specialized scientific methods of exploration and production. Organized research and scientific training gradually brought about the substitution of engineering principles for the rule of thumb. This resulted in the invention and improvement of new techniques of discovery and production and in other scientific developments which had their impact on all branches of the industry. Continually improving methods of exploration have been uncovering more oil fields in unsuspected places; new methods of drilling and exploitation have made accessible more oil pools and more of the oil in them; new means of transportation have provided oil and gas with a vastly increased market; and improved techniques of refining have further increased that market by making possible the manufacture of an almost infinite variety of products.

The physical results of the application of science can be partly seen in the statistics of the industry's growth and in the tremendous increase in output per man. The petroleum and natural-gas industry of today has an annual gross income that is the highest in the extractive industries, and its total employment outranks all of them except coal production. Less spectacular, perhaps, but more significant from the viewpoint of relationships between changes in industrial techniques and employment opportunities has been the role of the oil industry's technology as it advanced within the framework of the existing economic, legal, and social institutions.

The petroleum and natural-gas industry supplies today more than a third of the country's total energy requirements. The energy furnished by oil and gas is obtainable with only about half the expenditure of labor per B. t. u. that is required for an equivalent amount of energy obtained from coal.[1] Insofar as the former is being substituted for coal, the increase in its importance is one of the factors responsible for the failure of total employment in mineral-fuel production to keep pace with the Nation's rising utilization of energy. More

[1] N. Yaworski, V. Spencer, and Others, *Fuel Efficiency in Cement Manufacture, 1909-1935* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-5, Apr. 1938), p. 14.

specifically, this development has contributed to the current unemployment problems in the coal industry.

Unlike most other industries, however, the long-run outlook for production of petroleum and natural gas and for employment in those industries depends not so much on demand and the trend of productivity as on the rate of depletion of present reserves and the discovery of new oil fields. Discovery is in reality the first and most important step in production. Technical victories in other branches of the industry will be largely in vain if achievements in exploration fail to keep reserves abreast of growing demand. If supplies remain adequate for the next two decades, then a sufficient increase in production may be expected to result in increased employment in the petroleum and natural-gas industry in spite of further increases in output per man. An increasing rate of discovery cannot, however, be projected indefinitely into the future. Eventually, growing natural difficulties in the form of depletion of known reserves and the failure to find new ones promise to become a factor that is bound to mean decreased employment opportunities at primary producing operations as we now know them.

The pronounced depletive characteristic of petroleum and gas resources also affects the character of capital investment in the industry. The investment of a large amount of new capital in manufacture, for example, is usually reflected in a sizable increase in new capital equipment. This is also true of the petroleum and gas industry where investment in a new refining plant or in a new pipe line brings similar results. On the other hand, a large volume of the capital invested annually in petroleum and gas production tends to disappear entirely in the sense that it is not used for productive purposes. The statement that "the way to discover 1 billion barrels of oil is to drill 4,000 dry holes"[2] suggests the large amount of fruitless effort required by the industry in order that output may be maintained. The average direct cost of drilling a dry hole is about $17,000, and the amount of money expended in drilling unproductive holes is roughly 80 million dollars a year. The days have passed when anyone

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[2] J. E. Pogue, *Economics of the Petroleum Industry* (New York: The Chase National Bank, Mar. 1939), p. 12.

with a little capital and much luck could prospect for oil with as much chance for success as the next person. The areas with surface indications of oil - inviting so-called random wildcat drilling - have practically disappeared. Modern prospecting has become a complicated activity that requires large amounts of capital, expensive apparatus, scientific training, and great skill. Not only in prospecting but in drilling, production, refining, and transportation as well, technological advances and the capital requirements which they engendered have been one set of causes for a rapid increase in the size of enterprises. Moreover, some of these new technological developments have made possible a more efficient use of capital equipment. For example, a refinery of 25,000 barrels daily capacity constructed in the period 1920-25, using the old batch process, required as many as 100 stills and represented a capital investment of 15 to 18 million dollars. A similar amount invested in a modern plant, using one or two combination units, would today result in a refining capacity of more than 50,000 barrels.

By reducing the area of competition through an increase in the size of areas underlain with oil that are controlled by single companies, the growth in the size of enterprises has served to reduce much of the waste that has characterized the industry. This is true because excessive wastes are not due to a lack of technical knowledge or engineering skill but are primarily the result of the existing economic and legal arrangements of exploitation. These cannot usually be geared to the geological characteristics of the occurrence of oil and gas and therefore do not make for efficient production and socially desirable exploitation of a natural resource. Under the "rule of capture", competitive drilling has been the general method of development without regard to potential output or efficient production from the underlying reservoir. Such competitive drilling into single pools serves to dissipate the gases that are needed to bring the oil to the surface and otherwise to reduce the quantity of oil that can be extracted. Total output and the amount of employment over the life of the pool are thus held far below the levels that could be attained if efficient known technical procedures were fully utilized.

Despite much progress in the elimination of preventable waste, present practices still fall far short of representing efficient production from a technical viewpoint. The fact is that governmental regulations directly affecting the technology of production have in the past and can in the future go far toward conserving this natural resource. Such regulations, in increasing the effective life of specific oil fields, also serve to stabilize employment. Geographic shifts in employment opportunities have been accompaniments of the rapid depletion of producing areas and the tapping of new pools. The statistical center of output and employment, originally in the Appalachian area, has moved west and south. There has been a pronounced decline in the number of jobs in the older producing areas and a rapid rise in employment in new producing districts, particularly in such States as Texas, Oklahoma, California, and Louisiana. Notable shifts in job opportunities take place even within a single State; drilling and production crews in Texas, for example, are known to have moved from the Gulf Coast to the Panhandle during a single year. Immediately following a rich new find, tens of thousands of workers crowd into what were previously rural counties, only to move on a year or two later, or to remain stranded after production at the oil well has run its course. Certainly, the more petroleum and gas that is made available by conservation and modern technology, the greater will be the likelihood for operations and employment opportunities to last longer in particular oil fields.

In the refining segment of the industry, also, technological developments have been an important factor in the conservation of crude oil. During the last two decades the amount of gasoline obtainable from a barrel of crude has nearly doubled. Were it not for this increased yield, resulting from the application of cracking techniques and other improved methods of distillation, a vastly greater quantity of crude oil would be needed today to supply the needs of our motorized civilization. More recently introduced processes are likely to increase the yield further and to result in additional improvements of the quality of motor fuel.

In view of the competition that prevails among the different sources of energy - a major factor in the economic environment of coal, oil, and gas - the question naturally arises as to

the effects that developments in petroleum and natural-gas production are likely to have on the total volume of man-power that will be required in the future for the Nation's energy output, and particularly as to the likely effects on employment in coal mining. Clearly, no answer can even be attempted without an appraisal of all principal energy-supplying activities collectively. Aside from bringing together much needed information on the technology of petroleum and natural-gas production and developing and analyzing some new statistical materials on employment, this report, being one in a series that also includes studies on bituminous coal and anthracite, is also intended to contribute to an answer concerning the future of employment in fuel production. In fact, parts of this report have already been used for similar purposes by a subcommittee of the National Resources Planning Board.[3]

This study (conducted by the National Research Project in cooperation with the United States Bureau of Mines) is the result of collaboration among many contributers. The authors are indicated at the beginning of each chapter, and others who aided the work are thanked in the Acknowledgments. As a number of the contributions were completed in cooperation with individuals and Government officials who worked at a distance through the necessity of continuing on duty at their regular posts, the responsibility of rearranging such material to meet the limitations of space and contributions of other authors was left to Dr. O. E. Kiessling, Economist in Charge. The completed manuscript was edited and prepared for publication under the supervision of Edmund J. Stone.

DAVID WEINTRAUB

PHILADELPHIA
July 20, 1939

[3] In August 1938 a preliminary draft of the findings of this report on technical progress in oil and gas production was made available for consultation to the staff of Ralph J. Watkins, Director of the Board's study of *Energy Resources and National Policy* (now in press), and some of the illustrations in the Board's report are preliminary versions of the graphs found in the present study.

ACKNOWLEDGMENTS

In the preparation of this report much aid and collaboration were obtained from official and private agencies and from individuals. The completeness of the discussion, in fact, is in no small measure due to the help of many reviewers, themselves notable authorities, who made important suggestions for improvement and addition.

Acknowledgment is made of the important assistance given by officials of the United States Bureau of Mines. Data and valuable suggestions on methodology were supplied by G. R. Hopkins, Assistant Chief Economist, and H. A. Breakey, Economic Analyst of the Petroleum Economics Division. G. R. Hopkins, in addition, served as codirector of the study and aided in the preparation of other chapters of the report besides those of which he was joint author. Technological aspects of the survey were planned and completed in collaboration with R. A. Cattell, Chief Engineer; Harry C. Fowler, Senior Petroleum Engineer; N. A. C. Smith and W. B. Berwald, Supervising Engineer and Senior Petroleum Engineer, respectively, at the Bartlesville, Oklahoma, Station; and C. P. Bowie, Supervising Engineer, San Francisco Station - all of the Petroleum and Natural Gas Division. Chapters prepared in the field offices of the same division were developed and completed with the aid of N. A. C. Smith, W. B. Berwald, Ludwig Schmidt, M. A. Schellhardt, Boyd Guthrie, and R. E. Heithecker. H. C. Fowler, A. G. Kraemer, and H. S. Kennedy rendered special services in reviewing the drafts of all contributions that were concerned primarily with technology. Statements made in the chapters are, of course, those of the authors indicated; the reviewers who have been named share no responsibility for the conclusions drawn.

Grateful acknowledgment is also made to J. S. Ross, Consulting Petroleum Engineer, and Lew Suverkrop, Engineer and Geologist, Bakersfield, California, who served in a consulting capacity during the course of the study. Both contributed much to the broad development of the survey in addition to the contributions credited to each in the main body of the report. Thanks are also extended for help given by Norman D. Fitzgerald, Petroleum Economics Department, Chase National Bank, who assisted in organizing the study at its inception and who continued to supply significant data.

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The following members of the staff of the WPA National Research Project have made special contributions: In addition to collaborating on chapter II, N. Yaworski served as a consulting economist to authors preparing discussions of technology and directed the preparation of most of the new statistical material on employment and output per man presented in the report. George Perazich made helpful suggestions regarding refining technology and progress in industrial research. Besides serving as joint author of chapters III and IX, R. L. Kiessling collaborated with the senior authors in the preparation of chapters II, IV, VII, VIII, X, and XI and supervised the assembly of the statistical appendix. Graphic presentation was under the direction of Cooke Settle, and P. J. Wester carried out special assignments connected with the preparation of the manuscript. Reid S. McBeth and Keith Clevenger completed background studies on natural-gas production and transportation. J. J. Ossermann, N. G. Dumbros, and L. L. Gosselin conducted much of the field work and assisted in preparing the statistical compilations. Daniel Carson made available an analysis of census data that was utilized in the preparation of table A-12, and H. Magdoff and V. Spencer made available an analysis of employment in petroleum refining that was utilized in preparing table A-13.

Through the courtesy of Commissioner I. Lubin of the United States Bureau of Labor Statistics, H. O. Rogers, Economic Analyst, was made available for collaboration with the Economist-in-Charge in coordinating the manuscript. In addition to the contributions made in chapters I to IV, VIII, X, and XI, Mr. Rogers aided in other tasks incident to the preparation of the report. Cordial acknowledgment is also made to A. F. White, Assistant Director, Bureau of Statistics, Interstate Commerce Commission, for help given in the analysis of employment data in pipe-line transportation.

Ralph J. Watkins, Director of the study of the National Resources Planning Board entitled *Energy Resources and National Policy* (now in press), made available for consultation the manuscript of that section of his report entitled "Fuel Reserves" that included reviews by H. D. Miser, G. B. Richardson, C. H. Dane, R. W. Richards, and others.

A complete list of the many persons throughout the industry and elsewhere who aided in the preparation of this report is not available. Special mention must, however, be made of A. I. Levorsen,

Consulting Geologist, Tulsa, Oklahoma; Ralph T. Zook, The Sloan and Zook Company, Bradford, Pennsylvania; K. B. Nowels, Consulting Petroleum Engineer, Abilene, Texas; George S. Bays, Stanolind Oil and Gas Company, Tulsa, Oklahoma; C. P. Parsons, Haliburton Oil Well Cementing Company, Duncan, Oklahoma; L. E. Smith, Independent Petroleum Association of America, Tulsa, Oklahoma; Arch L. Foster, *The National Petroleum News*, Cleveland, Ohio; George Reid, *The Refiner and Natural Gasoline Manufacturer*, Houston, Texas; and R. E. Miller, Hanlon-Buchanan, Incorporated, Tulsa, Oklahoma.

Finally, this survey is more adequate by virtue of special data and information that were courteously supplied by Paul Ryan of the American Gas Association, New York City, and by the Washington and New York City offices of the American Petroleum Institute.

CHAPTER I

INTRODUCTION*

Oil and gas now supply more than a third of the country's energy requirements,[1] and petroleum alone is the source of virtually all industrial lubricants. Aside from coal mining, oil and gas production (including natural gasoline) is the most important segment of the mineral industry. By value these products exceed coal and were about 30 percent of the total value of mineral output during the decade 1926-35. In terms of employment, the primary phases of production of oil, gas, and natural gasoline gave jobs to 17 percent of the wage earners required in mineral extraction in 1935, the most recent year for which figures are available on the number of workers employed in all branches of mining. Indeed, in that year, more workers were employed in oil and gas production than in all branches of metal mining combined.[2]

Moreover, oil and gas production is one of the most important divisions of mining where the demand for manpower grew notably during the post-war decade.[3] At the turn of the century, when the automobile was still regarded as a "rich man's toy" and certain features of modern industrialism began to be discernible, 33,400 wage earners were employed in the production

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*By O. E. Kiessling, Chief Economist, Mineral Production and Economics Division, U. S. Bureau of Mines; H. O. Rogers, Economic Analyst, U. S. Bureau of Labor Statistics; and G. R. Hopkins, Assistant Chief Economist, Petroleum Economics Division, U. S. Bureau of Mines.

[1] M. E. McMillan, R. L. Anderson, and Others, "Bituminous Coal," *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), p. 703.

[2] Data are from table A-1. Apart from the workers employed in the primary production of oil and gas, roughly three-quarters of a million additional workers are engaged in the transportation, refining, and marketing segments of the industry. (See figure 2 and table A-2.)

[3] Increases in employment during the post-war decade were reported for several of the nonmetallic industries and also for copper, mercury, and lead and zinc mining, but the mineral industries listed below showed the following declines in employment between 1919 and 1929:

Industry	Percent	Industry	Percent
Anthracite (Pa.)	3.1	Iron ore	37.7
Barite	8.2	Magnesite	21.7
Basalt	8.5	Manganese	61.1
Bituminous coal	16.0	Mica	49.6
Clay	24.1	Minor metals	9.3
Fluorspar	6.3	Phosphate rock	26.8
Gold and silver, lode	48.5	Sandstone	49.7
Gold, placer	58.1	Sulphur and pyrites	4.4
Gypsum	5.2	Talc and soapstone	42.6

Data are from *Fifteenth Census of the Unites States: 1930*, "Mines and Quarries: 1929" (U. S. Dept. Com., Bur. Census, 1933), pp. 33-5.

of petroleum and natural gas - only a small proportion of the total number of workers engaged in mineral extraction. In 1929, by contrast, the production of petroleum, natural gas, and natural gasoline required a labor force of 179,000 - nearly a fifth of the wage earners engaged in mining. Because of its expanding labor requirements the industry has absorbed a part of the constantly increasing labor supply and thereby reduced somewhat the serious social results of declining employment opportunities in other industries.[4]

OBJECTIVES OF THE STUDY

The depression checked employment expansion in oil and gas production. In 1937 the output of petroleum and gas reached new all-time highs, and employment was 38 percent above the depression low, although still below the level of 1929.[5] Has the growth of employment been permanently arrested? What will be the net probable employment opportunities in the future? It is the purpose of this study to answer these questions as completely as available data permit.

The task, however, is beset with difficulties. As in other industries, discovery and invention are constantly prompting far-reaching changes in the technical processes of production. In the petroleum and natural-gas industry, moreover, the hazards of prognosis are heightened by the uncertainty of recoverable reserves. Despite these handicaps, an examination of the past record and present status of the industry offers valuable clues to future trends of output and manpower requirements, and such a procedure is followed in this analysis.

The long-time trends of production are first developed to indicate whether these trends are likely to continue or change their present course. The trends of employment are next examined for an understanding of significant influences that have affected the size and character of the industry's working force. Since it is possible that production might continue

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[4] Some idea of the compounding effect upon general employment of expansion in the oil and gas industry is suggested by the large amount of machinery and other supplies that are constantly required. For 1935 alone the supply bill of the petroleum industry has been estimated at $876,000,000. See Independent Petroleum Association of America, R. B. Brown, General Counsel, *Statement of The Independent Petroleum Association of America Supporting Necessity of Continuance of Present Excise Taxes on Petroleum Imports and Opposing Their Reduction in Trade Agreement With Venezuela*, Before the Committee on Reciprocity Information (Washington, D. C.: Aug. 6, 1938), p. 32.

[5] *Monthly Labor Review*, Vol. 48, No. 3 (Mar. 1939), p. 738.

to increase but that the increase could be achieved with less manpower owing to advancing technology or to a more bounteous nature, statistical series on output per man are examined as rough measures of the rate of technical progress and of changing physical conditions of operation. Technology is studied further to determine the labor saving that has attended successive technical advances in the past and to ascertain probable effects of impending technical improvements. Finally, such limited conclusions as can be drawn regarding the probable outlook for production, output per man, and employment are presented.

To some extent the undertaking is simplified by the comparative youthfulness of the industry, for its commercial beginning dates back only a little more than three-quarters of a century. Over this period, moreover, the record of technical advances is relatively complete. Some of the other phases of the industry's development, it is true, are obscured by important gaps in the information; but by using such factual data as are available in combination with supplementary qualitative material, it is possible to suggest a number of interesting conclusions, even though certain trends cannot be projected very far into the future with hope of great precision.

SCOPE OF THE INQUIRY

From an economic viewpoint, the petroleum and gas industry extends beyond the primary raw-material production stage. In a real sense the industry comprises not only oil and gas wells but also petroleum refineries, natural-gasoline plants, the network of oil and gas pipe lines, and even the delivery of refined products to consumers. These separate branches converge to form the complicated and interlocking structure that is the oil and gas industry. Together they represented an investment estimated at about 12 billion dollars in 1934;[6] more recent estimates suggest that by 1937 the gross investment had increased to about 14.5 billion dollars.[7] Although the boundaries of the different branches are fairly well defined, the broad view of the industry is taken in the present study.

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[6] National Resources Board, *A Report on National Planning and Public Works in Relation to Natural Resources and Including Land Use and Water Resources, With Findings and Recommendations* (Dec. 1, 1934), p. 405.

[7] J. E. Pogue, *Economics of the Petroleum Industry* (New York: Chase National Bank, Mar. 1939), p. 56.

Major emphasis is given, however, to the primary producing activities, for which additional data could be developed as byproducts of the 1935 census.[8] Other branches - for which data are less comprehensive - are given relatively less attention. Marketing is considered only briefly in presenting a perspective of over-all activity and employment.[9]

In establishing the frontiers of the inquiry it should also be noted that the corporate structure of the industry has little importance in a study of the amount of labor required for the various operations. Although, as in many other branches of mining, the large integrated company is dominant and probably at least two-thirds of the aggregate business is now controlled by some 20 large corporations whose operations extend from the wells to an extensive corps of service stations,[10] petroleum and natural-gas production is essentially an industry of many thousands of individual units (see figure 2), which in 1935 numbered 341,000 oil wells, 54,000 "dry"-gas wells, about 194,000 miles of oil, gasoline, and natural-gas pipe lines, approximately 400 tank steamships,[11] 395

Table 1.- PRODUCTION AND VALUE OF THE MAJOR PRODUCTS OF THE PETROLEUM AND GAS INDUSTRY, 1937[a]

Product	Quantity produced	Value at wells or plant
Crude oil	1,279,160,000 bbl.	$1,513,340,000
Natural gas[b]	2,447,620,000 M cu. ft.	123,457,000
Natural gasoline	2,065,434,000 gal.	97,125,000
Refined products	1,183,440,000 bbl.[c]	2,546,746,000

[a] Adapted from data of the U. S. Bureau of the Census and the U. S. Bureau of Mines.

[b] Marketed production and corresponding value; data are preliminary and subject to revision.

[c] Represents quantity of crude oil run to stills.

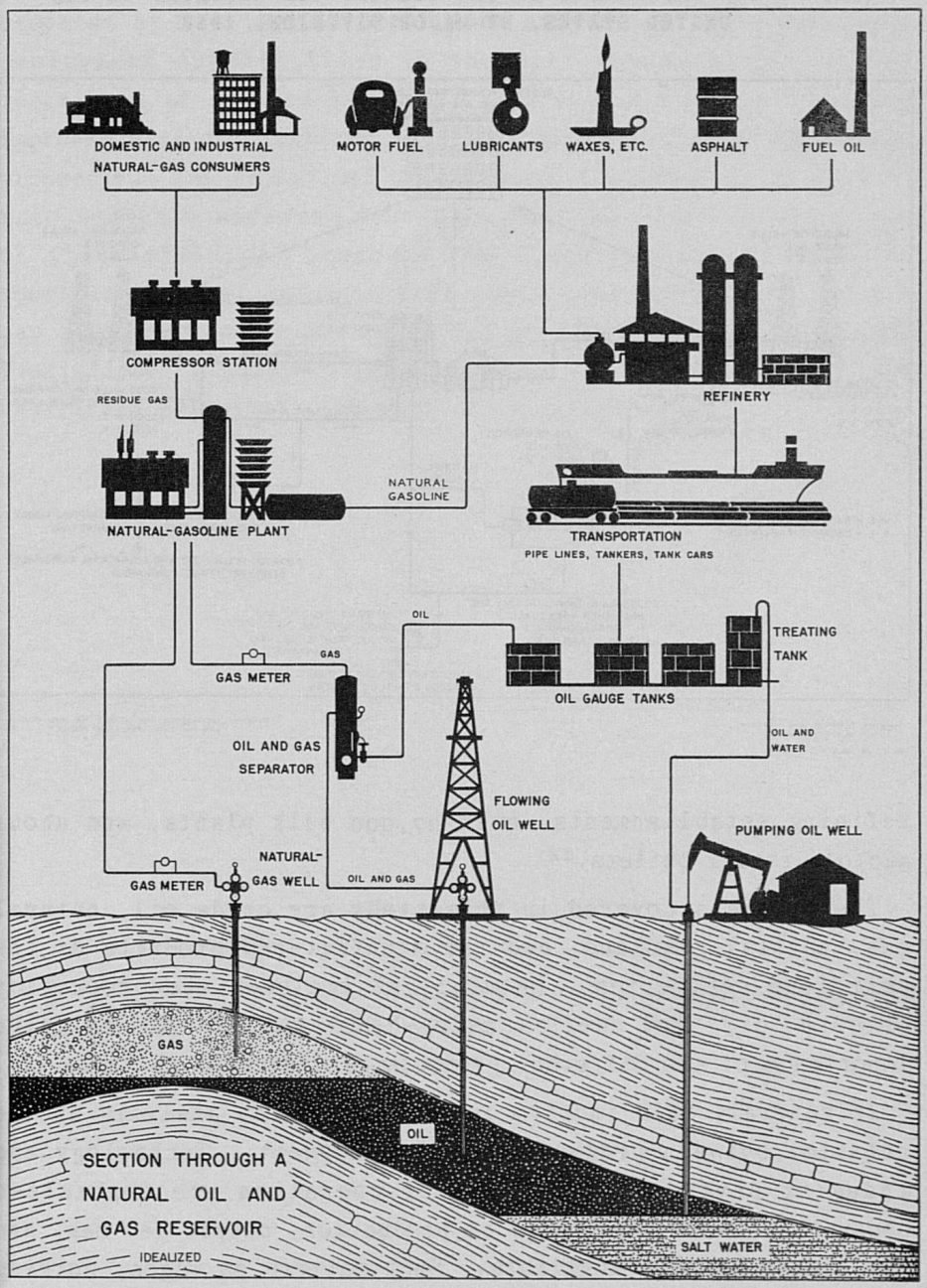
[8] Conducted jointly by the U. S. Bureau of Mines and the U. S. Bureau of the Census.

[9] While the importance of marketing to total employment in the industry is recognized, adequate discussion of this point would require a more solid factual basis than is available at present. Moreover, certain business considerations, such as the nature of competitive practice in retailing petroleum products, appear as important factors affecting employment in marketing. This suggests that the subject can be treated more effectively as a separate study of employment in wholesale and retail trade rather than as part of a report concerned with the effects of changing physical conditions of operation and of changing technology upon employment in production.

[10] G. W. Stocking, "Oil Industry," *Encyclopaedia of the Social Sciences* (New York: The Macmillan Co., 1933), XI, 443-4.

[11] American Petroleum Institute, *Petroleum Facts and Figures* (5th ed.; New York: 1937), p. 143.

Figure 1.- ILLUSTRATION OF PRODUCTION OF PETROLEUM, NATURAL GAS, AND NATURAL GASOLINE, AND PRINCIPAL STEPS IN FLOW OF PRODUCTS TO CONSUMERS

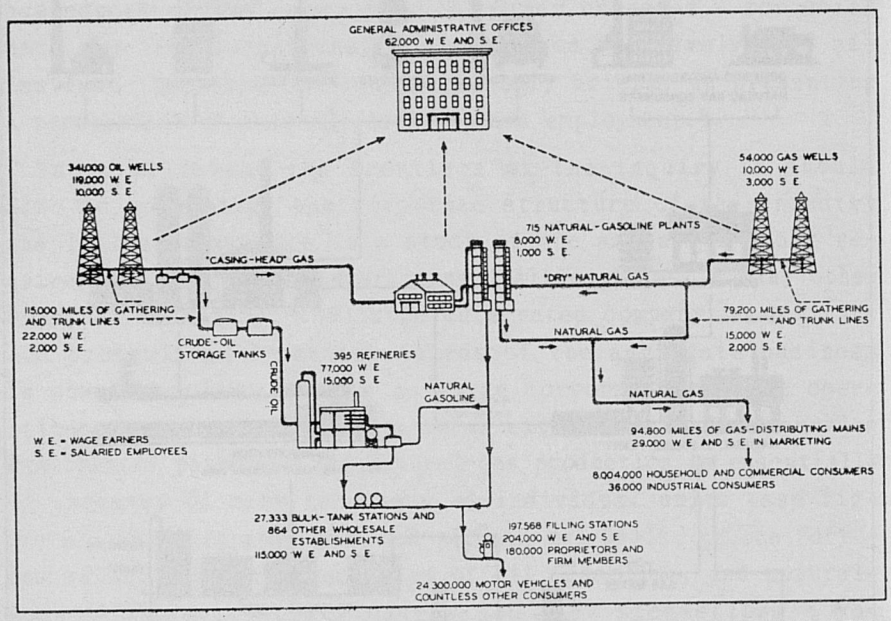


ROSS AND KIESSLING
U. S. BUREAU OF MINES

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
WPA-NATIONAL RESEARCH PROJECT E-108

Although a wide variety of products ultimately reaches different types of consumers from the oil and gas industry, the primary phases of oil, gas, and natural-gasoline production are closely related. For example, more than 40 percent of the total volume of natural gas produced and consumed in the United States comes to the surface of the ground in association with oil (see p. 173). Similarly, natural gasoline is extracted from natural gas obtained both from wells producing oil and gas and from wells that produce gas only. Under modern production engineering, moreover, natural gas may be used extensively to maintain the reservoir pressure of an oil pool as a means to efficient extraction. These and other physical and technical features of the industry suggest the advisability of grouping primary producing activities for the purposes of analysis.

Figure 2.- EMPLOYMENT IN THE OIL AND GAS INDUSTRY IN THE UNITED STATES, BY MAJOR DIVISION, 1935



HOPKINS, DUMBROS, AND YAWORSKI
U.S. BUREAU OF MINES
BASED ON TABLE A-2

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
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refining establishments, over 27,000 bulk plants, and about 340,000 retail outlets.[12]

The products covered in this study are crude oil, natural gas, natural gasoline, and the manufactured products of the petroleum refineries. Natural gas includes the production of both "dry" and "wet" (casing-head) gas.[13] The relative importance of the different products is indicated in table 1.

In general, this inquiry is confined to an analysis of the relation between production and employment. Technology and changing physical conditions of operation are emphasized because of their importance to production, output per man, and the number of jobs available. Such matters as wages, working conditions, and other economic factors are mainly beyond the scope of the survey and are considered only when they affect

[12] The "about 340,000 retail outlets" include the 197,568 filling stations reported in table A-2 that sell petroleum products as a main activity, plus an estimate of 140,000 garages, stores, and other enterprises that retail petroleum products as a supplementary activity. See American Petroleum Institute, Committee on Marketing, W. J. Hartman, chmn., "Marketing," *American Petroleum Industry* (New York: 1935), p. 137.

[13] "Wet" (casing-head) gas is that obtained from wells producing both oil and gas; "dry" gas is that obtained from wells producing gas only.

employment or the technical art of production. The study proceeds by tracing the conditions and events that determined employment opportunities in the past, examines prevailing techniques of oil and gas production with a view to impending improvements, and inquires into the nature of future employment prospects. For analytical convenience, the industry is divided into segments wherever possible, but the close relationship of these different segments and their dependence upon the specific physical and technical conditions under which oil and gas are found and produced should be kept constantly in mind. Predictions of future trends, insofar as they can be made, are restricted principally to short-term outlooks.

CHAPTER II

LONG-TIME TRENDS IN PRODUCTION, EMPLOYMENT, AND OUTPUT PER MAN*

Although the wide use of petroleum and natural gas for the needs of man is essentially an accompaniment of the age of power, the use of these products has not been a recent development. Petroleum played a part in both the spiritual and material life of antiquity;[1] natural-gas seepages fed fires that burned continuously before the shrines of the Baku fire worshippers and the Chinese used natural gas for the evaporation of brine in salt manufacture long before the Christian Era.[2] However, these early uses were scattered and largely accidental, and the extensive domestication of oil and gas to the demands of industry and society was delayed until relatively modern times. It was not until the internal-combustion engine became a practical source of power, moreover, that the industry became important as a source of raw materials and a large employer of labor.

FACTORS INFLUENCING EARLY DEVELOPMENT

Among the forces responsible for stimulating the development of the oil and gas industry, two were of outstanding importance. One was the rapidly increasing demand for lubricants by a changing industrialism that relied more and more on power and machinery. The second was the invention in 1784 of the Argand oil lamp that greatly stimulated the demand for high-grade illuminating oils.[3]

Before the middle of the nineteenth century animal and vegetable fats were the principal source of lubricants and

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*By H. O. Rogers; N. Yaworski, Mineral Economist, WPA National Research Project; G. R. Hopkins; and O. E. Kiessling.

The authors acknowledge their indebtedness to R. L. Kiessling and J. J. Ossermann who, under the supervision of N. Yaworski, conducted extensive statistical researches that produced most of the new statistical material that is summarized in this chapter.

[1] G. W. Stocking, "The American Petroleum Industry," in H. T. Warshow, ed., *Representative Industries in the United States* (New York: Henry Holt and Co., 1928), p. 535.

[2] W. T. Thom, Jr., *Petroleum and Coal: The Keys to the Future* (Princeton, N. J.: Princeton University Press, 1929), pp. 167-8.

[3] G. W. Stocking, "Oil Industry," *Encyclopaedia of the Social Sciences* (New York: The Macmillan Co., 1933), XI, 439.

illuminants. Lard oils and tallow were widely used for lighting purposes, and the whale fisheries supplied most of the lubricating oil. The fisheries could meet the modest needs for lubricants in the premachine era, but they were hard-pressed by the larger demand that accompanied the growing use of mechanical power, and serious shortages both of lubricating and illuminating oils developed in the early stages of the industrial revolution. During most of the second half of the eighteenth century the British Government paid a bounty to vessels engaged in whaling. Although New England was the center of the whaling industry in America, fishing was first done off the Virginia and Carolina coasts; by the early part of the nineteenth century, however, the hunt had extended into West Indian and South American waters. Later, as the factory system spread through western Europe and to America, the search for whales was pushed still farther afield, and the price of oil increased sharply.[4]

Apart from scarcity and high prices, whale oil was unsatisfactory for other reasons. As a lubricant it was acid in reaction and had to be treated with potash before it was suitable for contact with metal. It was also objectionable as an illuminating oil because of its strong, fishy odor.

Thus powerful influences converged to stimulate the search for substitute sources of illuminants and lubricants. Experiments with artificial gas for lighting were made by William Murdock in the closing decade of the eighteenth century; in spite of popular opposition, the use of gas was established in England by 1813 after the London and Westminster Chartered Gas Light & Coke Company was chartered in 1810.[5] The use of artificial gas spread rapidly, and plants were installed in Paris in 1818 and in Baltimore in 1821. In the latter year natural gas was used also for lighting houses in Fredonia, New York.[6] The extensive use of gas - both natural and artificial - was retarded, however, because of high prices[7] and because

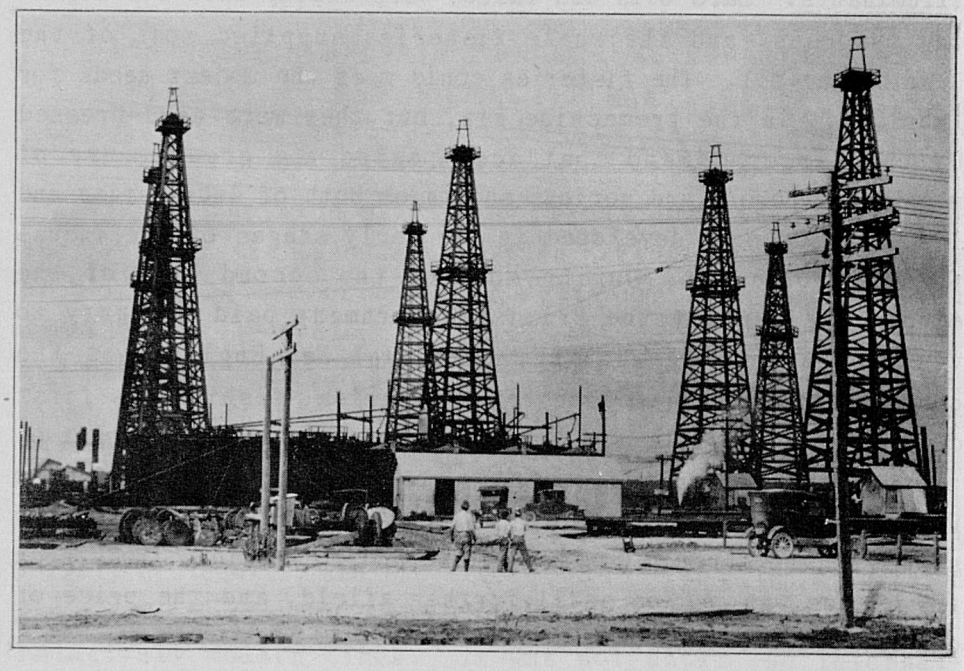
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[4] In 1835 sperm oil sold in England for $60 a barrel and whale oil brought $35. A decade later, a Pittsburgh cotton mill was paying $55 a barrel for sperm oil. The average price of whale oil during 1820-40 was about $25 a barrel.

[5] B. J. Stern, "Resistances to the Adoption of Technological Innovations," *Technological Trends and National Policy* (National Resources Committee, June 1937), p. 52.

[6] J. D. Weeks, "Natural Gas," *Eleventh Census of the United States: 1890*, "Report on Mineral Industries in the United States" (U. S. Dept. Int., Census Office, 1892), p. 507.

[7] Some idea of the cost of gas during the early part of the nineteenth century may be had from the prices charged by the New York Gas Light Company from 1824 to 1848. During 1824-28 this company manufactured oil gas (presumably from whale oil) exclusively and charged $10 per thousand cubic feet. The same firm manufactured resin gas during 1828-48 and sold it for $7 per thousand cubic feet.



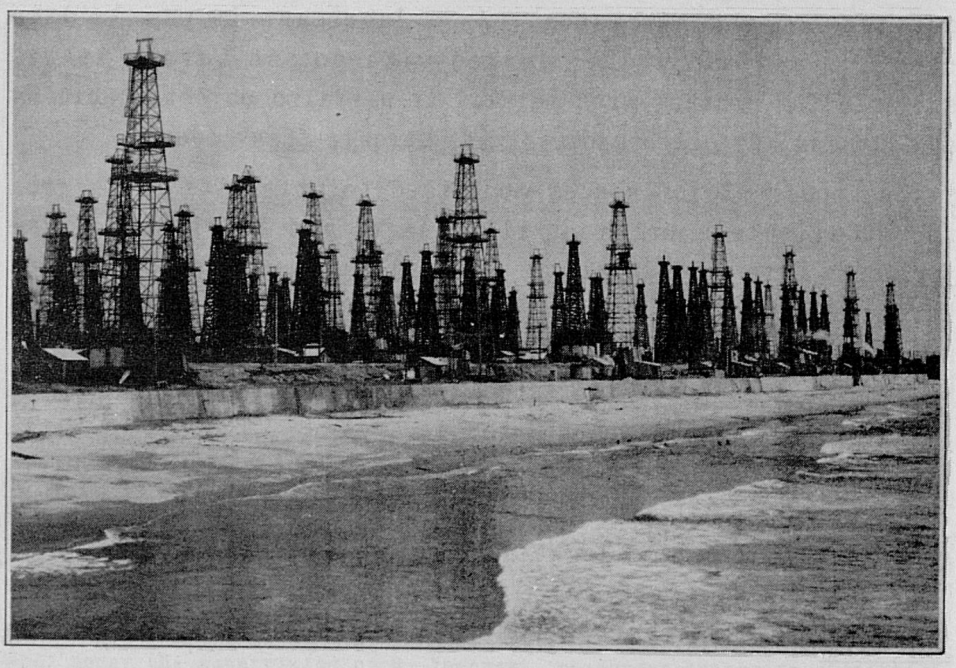
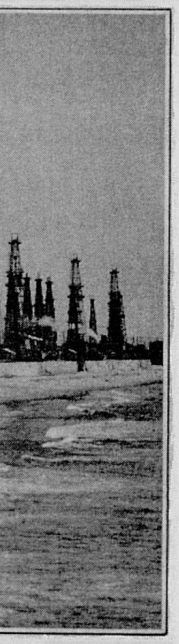


ILLUSTRATION 1.— DERRICKS ARE THE MOST OBVIOUS SIGNS OF ACTIVITY IN OIL AND NATURAL-GAS PRODUCTION

The upper view shows development work and close drilling in the Spindletop field, Texas. The lower view shows intensive development along the ocean front at Huntington Beach, California. Both views were taken in 1927.





ACTIVITY

the Spindletop
long the ocean
in 1927.

inadequate pipes and fittings limited transportation to very short distances.

Another link in the chain of circumstances that led to the establishment of the petroleum and natural-gas industry was the development by James Young in Scotland of a technique for extracting oil from cannel coal and oil shale. The process was patented in 1850 and was quickly adopted in several European countries and in the United States. By 1859 there were 78 distillation plants in this country, the largest having a daily capacity of approximately 6,000 gallons. Even this new source of illuminating oil failed to satisfy the growing demand, although an elementary technology was developed that was to be of notable importance later in petroleum refining.

In view of the urgent industrial and social need of the times, it is surprising that the broad use of petroleum and natural gas was delayed until the last half of the nineteenth century. Both products had been recognized in different parts of the country for many years, and it was known also that petroleum was being utilized to some extent in other parts of the world.[8] Yet many wells that were drilled for salt during the early part of the nineteenth century were considered worthless and promptly abandoned when oil was struck. It is true that enterprising apothecaries had for years recovered and sold small quantities of petroleum for medicinal purposes and that Benjamin Silliman reported in 1855 that petroleum "gave a most perfect flame with the Argand burner",[9] but 1859 is generally conceded as marking the commercial beginning of crude-oil production in the United States. Although natural gas had been utilized in the United States as early as 1821, moreover, it did not become commercially important until the late seventies.[10]

GROWTH OF PRODUCTION

A notable feature of the petroleum and natural-gas industry is the rapidity with which it has risen to a place of great

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[8]As early as 1814 De Witt Clinton reported to the New York Literary and Philosophical Society: "There is a bituminous spring in Alleghany County whence the famous Seneca oil is obtained. . . . At Amaino, in Italy, the petroleum of a spring discovered within a few years is employed to light the cities. . . . It might be of considerable consequence to discover whether the petroleum of our spring might not be used for beneficial purposes." See D. White, "Outstanding Features of Petroleum Development in America," *Bulletin of the American Association of Petroleum Geologists*, Vol. 19, No. 4 (Apr. 1935), pp. 482-3.

[9]P. H. Giddens, *The Birth of the Oil Industry* (1st ed.; New York: The Macmillan Co., 1938), p. 40.

[10]Weeks, *op. cit.*, pp. 507-9.

importance in our national economy. From the commercial beginning of each division of the industry down to the time of the great depression, production showed an almost uninterrupted increase. The rate of growth, moreover, has been rapid, and the period of greatest expansion was the post-war decade, when the growth of production of other minerals was slowing down.[11] During this period output in all branches of the petroleum and natural-gas industry more than doubled (see figure 3). Even the depression served only as a temporary check; in 1937 production, with the exception of natural-gasoline extraction, exceeded all previous records in each of the major divisions of the industry.

As a result of this remarkable growth the petroleum and natural-gas industry, measured in terms of value of products, now ranks as the country's most important mineral industry. In 1937 the value of the crude petroleum, natural gas, and natural gasoline produced totaled $1,733,922,000,[12] more than 60 percent above the combined value of anthracite and bituminous coal and more than a third of the total value of all minerals.[13] Measured in the same way, oil refining ranks among the five leading manufacturing industries of the country.[14]

In the aggregate, about 946,000 wells were drilled in the United States from 1859 through 1937. Of this total, approximately 741,000 were oil and gas wells and 205,000 unproductive holes. Furthermore, 417,470 of the wells completed were listed as producers of oil or gas on December 31, 1937.

Crude Oil

Although popular legend gives "Col." E. L. Drake credit for starting the petroleum industry on its spectacular career, the men who organized the Pennsylvania Rock Oil Co. and the Seneca Oil Co. were more responsible for establishing it on a commercial basis.[15] Drake, nevertheless, should be recognized

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[11] F. G. Tryon, "The Double Task of Mineral Technology," *Technology and the Mineral Industries* (WPA National Research Project in cooperation with the U. S. Department of the Interior, Bureau of Mines, Report No. E-1, Apr. 1937), chart 2 (opposite page 4).

[12] Revised data representing the value of oil and gas at wells and of natural gasoline at extraction plants. This is much smaller than value at points of consumption that is frequently used, especially for natural gas.

[13] M. B. Clark, "Statistical Summary of Mineral Production," *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), pp. 4-5.

[14] *Statistical Abstract of the United States, 1937* (U. S. Dept. Com., Bur. For. and Dom. Com., 1938), pp. 743-64.

[15] Giddens, *op. cit.*, pp. 30-52.

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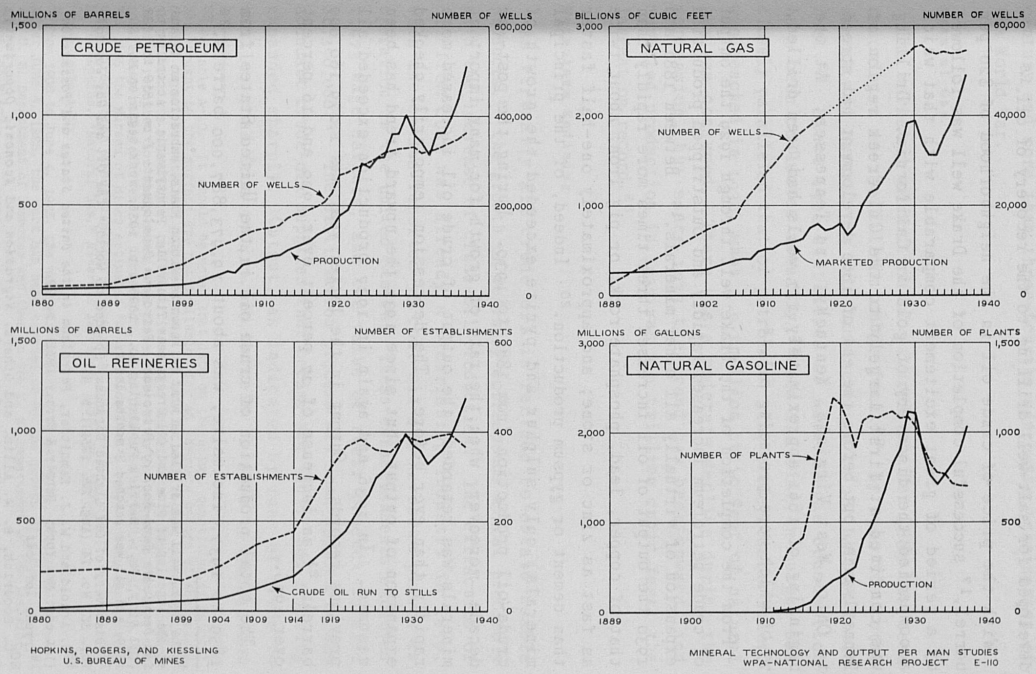
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Figure 3.- LONG-TIME TRENDS OF PRODUCTION IN THE PETROLEUM AND NATURAL-GAS INDUSTRY



HOPKINS, ROGERS, AND KIESSLING
U. S. BUREAU OF MINES

BASED ON TABLES A-6 TO A-9, A-13

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
WPA-NATIONAL RESEARCH PROJECT E-110

for his achievement in applying a technique that had been developed for salt-well drilling to the recovery of oil.[16]

With the price of crude oil in the neighborhood of $20 per barrel,[17] successful completion of the Drake well was followed by a period of great excitement comparable with that which accompanied the discovery of gold in California. Drilling was confined at first largely to the Oil Creek region of Pennsylvania, but before the end of 1860 development had spread to Ohio, West Virginia, Kentucky, and Tennessee. At the beginning of 1861 approximately 117 wells had been drilled, 73 of which were producing oil.[18]

From the completion of the Drake well through 1929 the output of crude petroleum increased rapidly and outstripped production expansion of virtually all other minerals.[19] Between 1881 and 1930 the output of oil increased three times more rapidly than that of copper, lead, phosphate rock, or pig iron; about twice as fast as zinc or stone; and approximately one-half faster than cement or gypsum production.[20] Indeed, of the principal minerals, only sulphur and pyrite exceeded the growth of crude-oil production from 1881 to 1930. During the post-war decade, moreover, when the rate of growth for many important minerals was retarded, the output of crude oil increased more rapidly than ever before. The depression temporarily checked expansion of output, but since 1932 the upward trend has been resumed. In 1936 and again in 1937 production exceeded all previous records. Output in the latter year was 1,279,160,000 barrels,[21] an increase of 27 percent over 1929 and 16 percent over 1936.

The total production of crude oil in the United States from 1859 to 1937, inclusive, was about 19,973,887,000 barrels.[22]

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[16]The Drake well was drilled on what is known as Watson Flats, embracing an island at the junction of Pine and Oil Creeks near Titusville, Pennsylvania. According to *The Derrick's Hand-Book of Petroleum: Petroleum Developments From 1859 to 1898* (Oil City, Pa.: Derrick Publishing Co., 1898), p. 1036, work began on May 20, 1859, and oil was reached 3 months later.

[17]"Discovery of Oil Lighted Darkness, Speeded up World," *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934), p. 4.

[18]R. Arnold and W. J. Kemnitzer, *Petroleum in the United States and Possessions* (1st ed.; New York: Harper & Bros., 1931), p. 79.

[19]Tryon, *loc. cit.*

[20]C. Goodrich, B. W. Allin, and Others, *Migration and Economic Opportunity* (Philadelphia, Pa.: University of Pennsylvania Press, 1936), p. 425.

[21]See table A-6.

[22]A. G. White, G. R. Hopkins, and H. A. Breakey, "Crude Petroleum and Petroleum Products," *Minerals Yearbook, 1937* (U. S. Dept. Int., Bur. Mines, 1937), pp. 1008-9. See also table A-6.

Of this total, 95 percent was produced since the turn of the century and more than three-fourths since the termination of the World War.

Natural Gas

The marketed production of natural gas for 1889 has been calculated at 250 billion cubic feet.[23] By 1902 the total quantity of natural gas sold had increased to 281 billion cubic feet.[24] Since 1906 statistics of natural-gas consumption have been collected annually,[25] and the rise in output has closely paralleled that of petroleum. The predepression record was reached in 1930, when 1.9 trillion cubic feet of natural gas was consumed. There was a moderate decline during the depression, but since 1933 the trend has been upward, and marketed production in 1937 was 2.4 trillion cubic feet, the largest on record.[26]

Petroleum Refining

As virtually all crude oil is refined to obtain usable products,[27] the growth of refining corresponds almost precisely with the increase of crude-oil production. The extraction of oil from coal was already a flourishing industry in 1859, when the census reported 78 coal-oil and kerosene plants in operation in the United States. These establishments employed 1,473 wage earners, and the value of their product totaled $6,398,000.[28] The distillation process was soon applied to the abundant crude-oil supplies that became available, and refining expanded sharply. Output, as indicated by runs of crude to stills, rose from 17,417,000 barrels in 1880 to 52,011,000

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[23] See table A-10. It should be noted that data on the actual quantities of natural gas brought to the surface are not available, for an adequate record of the losses of gas cannot be obtained. Consequently the statistical record of natural-gas output consists primarily of the quantities of gas marketed or consumed. Even such figures reported for early years - as those reported by the censuses for 1889 and 1902 - may require extensive correction, as is indicated in table A-10, ftn. u. For 1935 the Bureau of Mines estimated "gross production", representing essentially total production minus unmeasured losses at wellheads. (See F. S. Lott and G. R. Hopkins, "Natural Gas," *Minerals Yearbook, 1937*, pp. 1060-1.)

[24] See table A-10.

[25] From 1906 to June 4, 1925, the work was conducted by the U. S. Geological Survey. After June 4, 1925, the work has been carried on by the Bureau of Mines, first in the U. S. Department of Commerce and then in the U. S. Department of the Interior.

[26] See table A-7.

[27] According to A. G. White, G. R. Hopkins, and H. A. Breakey, "Crude Petroleum and Petroleum Products," *Minerals Yearbook, 1938* (1938), p. 815, the run of domestic crude oil to stills in 1936 amounted to 97 percent of the total production.

[28] *Eighth Census of the United States: 1860*, "Manufactures" (Secretary of the Interior, 1865), p. 739.

in 1899. The growth of refining continued, and by 1929 crude run to stills totaled 987,708,000 barrels. During the depression falling prices resulted in a sharp reduction of the total value of refinery products, but production was maintained remarkably well. In 1937, moreover, refinery operations exceeded all previous records, as 1,183,440,000 barrels of crude oil were processed. In recent years the throughput capacity of the refineries somewhat exceeded 4 million barrels of crude oil daily, or more than double the rated capacity at the end of the war.[29] The cost of the raw materials and supplies used by the refineries in 1937 was $2,064,000,000, and the value of products totaled about $2,547,000,000.[30]

Natural Gasoline

Even more spectacular than the long-time increase in output in other branches of the petroleum and natural-gas industry has been the comparatively recent rise of production of natural gasoline, a relatively volatile gasoline extracted from natural gas. From the end of 1911, the beginning of the continuous annual record, through 1929, production of natural gasoline grew at an average rate of 123,681,000 gallons a year. In 1929 the output was 2,233,688,000 gallons, indicating a phenomenal increase over production 18 years before.

A significant feature of natural-gasoline production is that it was affected by the depression much more seriously than other divisions of the industry. In contrast with decreases of 10 to 20 percent in the output of crude petroleum and natural gas, the production of natural gasoline declined more than 36 percent between 1929 and 1933. Although natural gasoline did not share proportionately in the subsequent recovery, production in 1937 was within 8 percent of the predepression peak.[31]

TREND OF EMPLOYMENT

The trend of employment in the oil and natural-gas industry was consistently upward through the boom year 1929. Over this period total labor requirements grew rapidly, both absolutely

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[29] E. G. Nourse and Associates, *America's Capacity to Produce* (Washington, D. C.: The Brookings Institution, 1934), pp. 88-9.

[30] *Census of Manufactures: 1937*, "Petroleum Refining" (U. S. Dept. Com., Bur. Census, mimeo., Dec. 28, 1938), p. 1.

[31] See table A-8.

and in relation to the working population as a whole. Although employment reached a high point in 1929, the most rapid increase took place during the war decade. (See figure 7.)

With reference to the drop in employment that occurred with the onset of the business depression, it appears that the decline was less sharp than in most other branches of mining. The downward movement reached a low in 1932 and by 1935 a substantial proportion of the depression losses had been recovered. From 1935 to 1937 employment showed further important gains; over this period the number of men employed directly in primary phases of petroleum, natural-gas, and natural-gasoline production, for example, increased about 17 percent, and the number of man-hours worked by the same group showed a gain of about 34 percent. Over the same years the average number of wage earners employed and man-hours worked in refining establishments increased 7 and 9 percent, respectively. Recovery of employment in pipe-line transportation between 1935 and 1937 was also indicated by an increase of 17 percent in the number of wage earners employed by oil pipe lines that reported to the Interstate Commerce Commission.

Since data are inadequate for the compilation of a long-time statistical series on over-all employment covering every department of the oil and gas industry, the course of employment trends is best observed by noting developments in the principal segments of the industry for which statistical series can be developed. This is done in the following sections, which present available indicators of employment in primary production, petroleum refining, and pipe-line transportation.[32]

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[32] Consideration on this basis eliminates employees engaged in marketing, who comprise a large proportion of the industry's labor force. The size of the labor force engaged in marketing, however, appears to be more closely related to retail-trade practices than to technological changes, as was noted in chapter I. Reliable figures on employment in marketing, moreover, are not available for an extended period. Furthermore, the development of such figures even for a single year raises difficult statistical problems regarding the classification of persons working in filling stations who may be "employees" at one census period and "active proprietors" at another because of a change in retailing policy from company-operated to leased stations or vice versa; in addition, there has been no actual count of the estimated 180,000 employees working at an estimated 140,000 garages, stores, and other enterprises that retail petroleum products as a side-line activity. (American Petroleum Institute, Committee on Labor, E. R. Lederer, chmn., "Labor," *American Petroleum Industry* [New York: 1935], pp. 177, 178.) Despite these difficulties, over-all employment has been distributed by major divisions in the industry for 1935, as far as available data permit, in table A-2 for the guidance of those who are interested in noting approximate relationships of the different branches. While it should be kept in mind that the data shown on marketing include only employment reported at establishments that market motor fuel and related products as a main activity, and that nearly 180,000 persons reported to the census as "active proprietors" of filling stations are excluded from the total, 693,611 persons are classified as "employees", including both wage and salaried workers. Of this total, 21.7 percent were employed in the primary production of oil, gas, and natural gasoline; 6.0 percent in pipe-line transportation; 13.3 percent in petroleum refining; 8.9 percent in general administrative offices; and 50.1 percent in marketing.

Oil and Gas Wells and Natural-Gasoline Plants

In harmony with the general trend noted for the industry, employment in the primary production of crude oil, natural gas, and natural gasoline showed a remarkably rapid growth from the beginning of the record until 1929. As illustrated in figure 4, the long-time trends both in number of wage earners employed and man-hours worked have been notably upward (see also table A-11). In the half-century which ended in 1929 the rate of growth was comparatively steady during the first 29 years, and from 1880 to 1909 an approximate fourfold gain took place in the number of wage earners required in primary production. A period of exceptionally rapid increase in employment opportunities occurred during the World War, when the number of men required more than doubled within the span of a single decade. Although the use of the automobile continued to expand in spectacular fashion between 1919 and 1929, employment in this period increased at a comparatively slower pace, and approximately 61 percent more wage earners were employed in primary production in 1929 than in 1919.

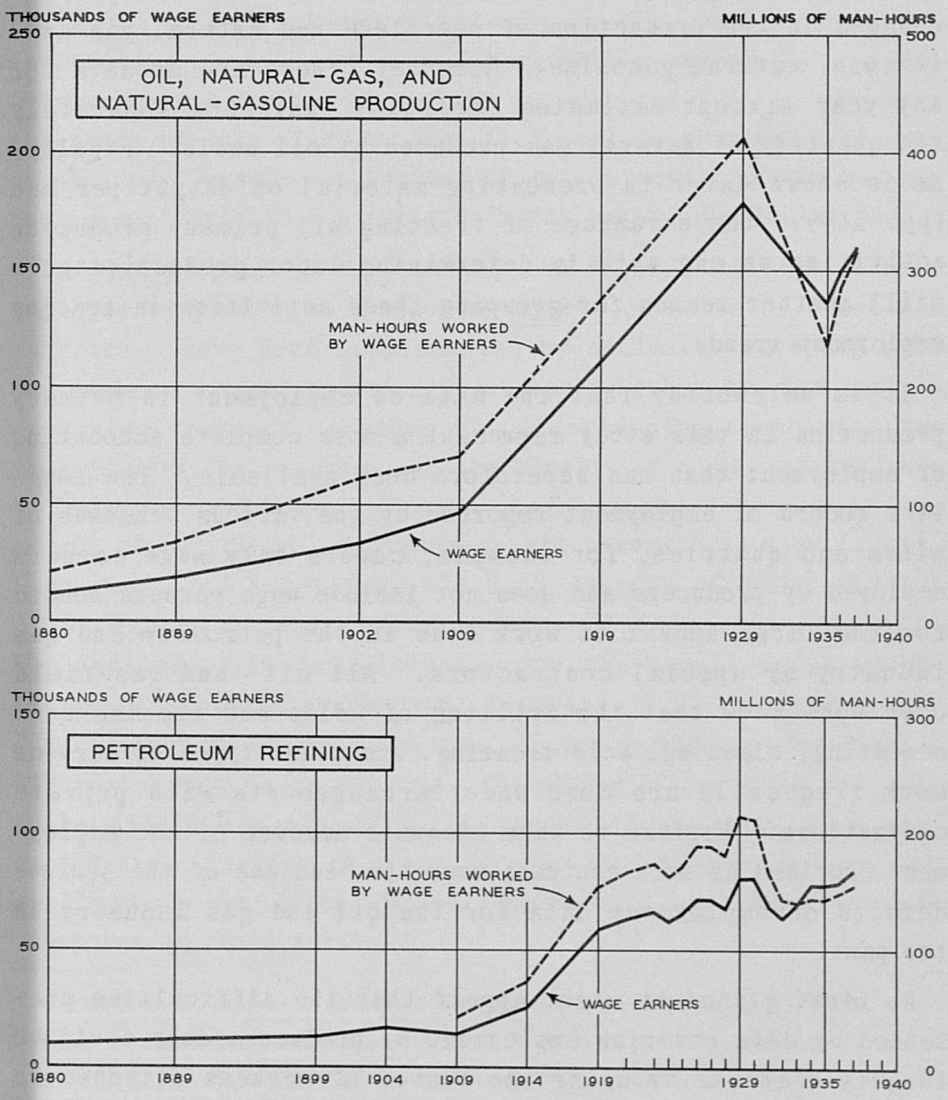
The trend of employment in petroleum and natural-gas production for 1930-34 - a period when annual figures are not available - can be followed by using the index of employment in crude-petroleum production of the U. S. Bureau of Labor Statistics.[33] Although this index covers operations producing crude petroleum mainly, a number of the establishments included in its sample also produce natural gas and natural gasoline. According to this index of the number of men on pay rolls at representative wells, employment was virtually halved between 1929 and the low point of the depression (March 1932). Much of this loss was recovered by the latter part of 1933, when a code formulated under the provisions of the National Industrial Recovery Act was approved by the President (August 19, 1933), and the employment index rose from 55.3 percent of the 1929 average in 1932 to 77.7 percent in 1934. From 1935 through 1937 employment showed additional gains as the average number of wage earners increased from 136,735 to 159,800 and as the

[33] This index, available beginning with 1929, serves many useful purposes, but it cannot be regarded as a substitute for more inclusive annual employment data that are used in this study whenever available. These annual employment figures include wage earners engaged in the production of natural gas and natural gasoline as well as those principally employed at petroleum wells; furthermore, all wage earners are included, whereas beginning with May 1935 employees engaged in drilling and rig building are excluded in the reports used in preparing the BLS index.

number of man-hours worked increased from 236,260,000 to 315,924,000 (see figure 4).

Petroleum and gas wells and natural-gasoline plants are treated as a group in presenting the long-time series on employment because these production processes are so closely related as to make desirable the consideration of employment data for the principal primary production activities as a unit.

Figure 4.- LONG-TIME TRENDS OF EMPLOYMENT IN THE PETROLEUM AND NATURAL-GAS INDUSTRY



YAWORSKI, KIESSLING, AND ROGERS
U. S. BUREAU OF MINES

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
WPA-NATIONAL RESEARCH PROJECT E-III

As is noted elsewhere in this report (p. 173), more than 40 percent of the natural gas comes to the surface in association with oil, and it is frequently difficult to separate production of natural gasoline from activity at oil and gas wells. A second reason for grouping the employment data as indicated is that the available long-time statistical record often combines primary producing activities in such a way as to make accurate separation of data for component activities impossible. A few examples will illustrate this problem. The censuses of mines and quarries for 1909 and 1919 reported a miscellaneous group of enterprises that included employees engaged in the production of petroleum and natural gas and, in 1919, natural gasoline. Moreover, there are no data for any year (except estimates for 1935) that show separately the quantity of natural gas produced by oil wells. Finally, as is shown later in presenting material on output per man (pp. 26-7), the advantage of treating all primary producing activities as one unit in determining labor productivity is still another reason for grouping these activities in tracing employment trends.

It is noteworthy that the data on employment in primary production in this study represent a more complete accounting of employment than has heretofore been available. The long-time record of employment reported by the various censuses of mines and quarries, for example, covers only wage earners employed by producers and does not include wage earners needed for the large amount of work done in the petroleum and gas industry by special contractors. All oil- and gas-field operators know that the drilling of wells and the tasks of cementing, cleaning, acid treating, and other types of service work frequently are done under arrangements with private contractors. Failure to take adequate account of the employment provided by such contract work has been one of the serious defects of employment data for the oil and gas industry in the past.

At first glance it might appear that the difficulties presented by data covering employment by producers only could be largely overcome by using the number of workers attached to the oil and gas industry as reported by the decennial census of occupations. These data, however, present difficulties of comparability as well as of understatement of the number of

wage earners actually employed. Part of the difficulty is the fact that occupations in the several decennial census reports have not always been treated alike and the occupational groupings are not entirely consistent. The classification "oil- and gas-well operatives" is more homogeneous and comparable than any other group; the number of persons reported under this classification, however, is available for only three decennial census periods beginning with 1910 (see table A-12), and the numbers of workers so reported are below the numbers of "wage earners" reported by the censuses of mines and quarries for 1909 and for 1919 (see figure A-1). This is because the classification excluded some wage earners and because the enumerative censuses of occupations were probably incomplete. Other reasons why the census of occupations data do not meet the needs of this study are that they include unemployed as well as employed persons - a serious factor in 1930 - and it has not been practicable to use these data for man-hour calculations.

For the purpose of this survey the figures on wage earners employed by producers - reported by the censuses of mines and quarries - have been supplemented by estimates covering both the number of wage earners and man-hours worked by wage earners rendering contract services.[34] In preparing these data for recent years, the authors had the benefit of a special analysis of reports submitted by contractors in connection with the census of petroleum, natural-gas, and natural-gasoline production conducted jointly by the U. S. Bureau of Mines and the U. S. Bureau of the Census (census of business) for 1935. For earlier years the estimates are the result of an unpublished statistical study by N. Yaworski, R. L. Kiessling, and J. J. Ossermann.[35] Although the precise accuracy of the derived figures cannot be determined, the probable error is believed to be slight and the data are presented and used here with confidence. Insofar as space permits, the statistical methods employed in preparing the estimates have been described in footnotes to table A-11.

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[34] Even with these estimates included, the employment data do not quite account for all persons who perform manual labor in the production of oil and gas; they exclude a number of small proprietors, mostly farmers, who devote a part of their time to operating wells on their property. For example, in 1909 and 1919, the only years for which this information was available, 2,155 and 1,987 proprietors, respectively, were reported performing such manual labor. (See table A-10).

[35] Study conducted by the "Mineral Technology and Output per Man" section of the National Research Project.

As the record of employment in petroleum and natural-gas production may be drawn upon to some extent by others, it was felt that a simplified comparison of the different employment series available and the new data presented in this study would be a useful byproduct. A comparison of this type is presented in figure A-1 for the benefit of those who are interested in the details.

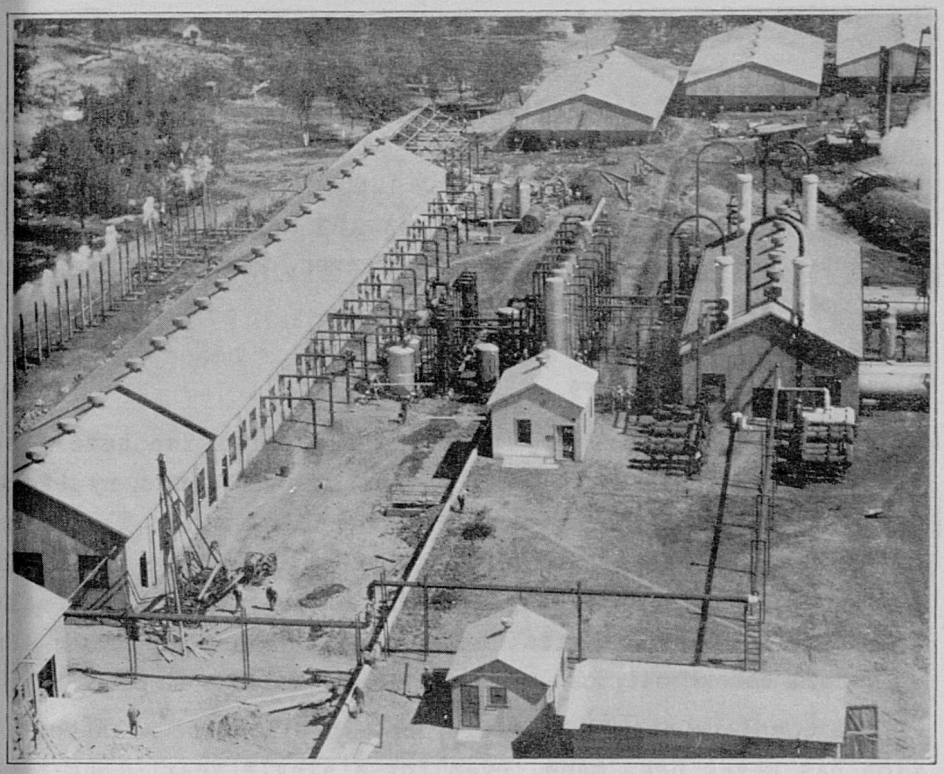
Refining

Broadly speaking, the long-time trend of employment in petroleum refining corresponds closely with that for crude-oil and natural-gas production. A period of rapid relative growth of employment which took place before 1880 was followed by a slower increase which marked the next quarter of a century; in 1904 there were 16,770 wage earners employed at refineries. The statistical record indicates that the upward trend was checked during the next 5 years, but at least a part of the small decrease in employment between 1904 and 1909 was due to a change in methods of reporting data. For example, in the 1909 census one of the largest refineries made a separate report for its box, cooperage, and tin shops,[36] whereas these activities had been previously included in a single general report. The second decade of the new century, however, witnessed a sharp advance in labor requirements, and the number of wage earners was more than trebled between 1909 and 1919. Employment continued to expand during the post-war decade, but at a much less rapid rate than in the 10 preceding years. The trend, however, was steadily upward, and by 1929 the average number of wage earners employed in petroleum refining was 80,596.

Employment in refining declined during the depression but less sharply than in almost any other major unit of the industry. According to the Bureau of Labor Statistics index of employment in petroleum refining, the number of workers employed by refineries in November 1932 - the depression low - was 78 percent of the average for 1929. This drop was much less than that already noted for employment in petroleum, natural-gas, and natural-gasoline production. Employment

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[36] W. L. Thorp, *The Integration of Industrial Operation* (U. S. Dept. Com., Bur. Census, Census Monographs III, 1924), pp. 65-6.



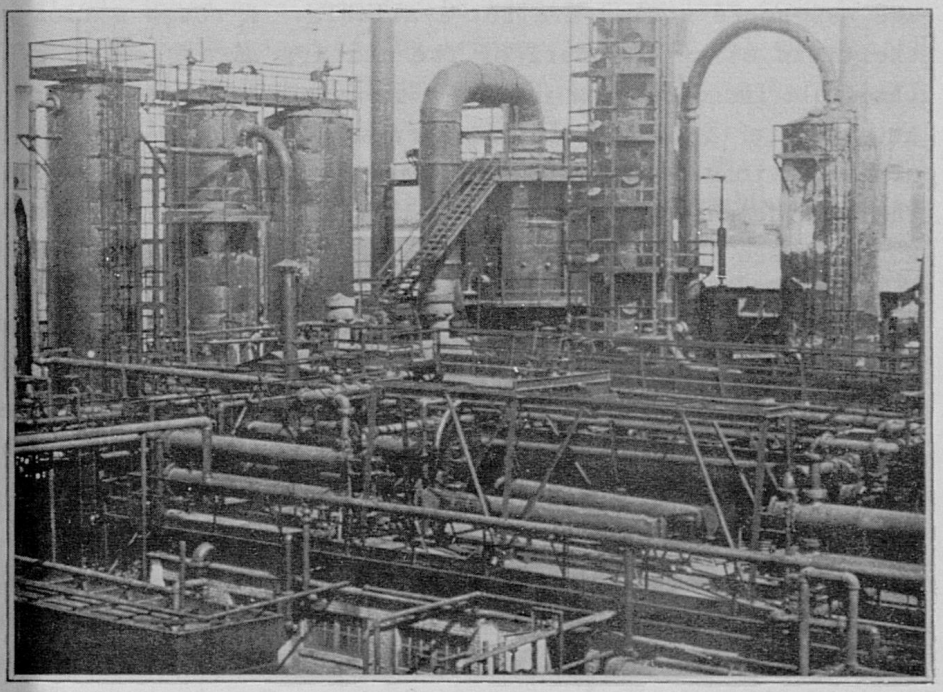


ILLUSTRATION 2.— PLANTS THAT PROCESS NATURAL GAS OR PETROLEUM APPEAR TO THE LAYMAN AS A COMPLEX COLLECTION OF VESSELS, VALVES, AND PIPING OF DIFFERENT SIZES

The upper view shows a plant for extracting natural gasoline from natural gas near Seminole, Oklahoma. The lower view shows a portion of a large modern petroleum refinery in the Chicago area.

recovered rapidly after 1932, and by 1935 the number of wage earners was only slightly short of the predepression peak. The number of wage earners continued to increase and in 1937 reached the all-time record of 83,183 men. The number of man-hours worked in the same year, however, was 28 percent less than in 1929.

Pipe-Line Transportation

Labor requirements in pipe-line transportation have also increased sharply. In this branch of the industry there were two periods of rapid growth in employment. The first coincided with the development of the pipe-line system in the late seventies and eighties,[37] and the second with the remarkable expansion that began during the World War and continued throughout most of the post-war decade.

As a complete survey of employment in pipe-line transportation has never been made, even for a single year, long-time statistical series on the number of wage earners employed and man-hours worked are not available. A rough notion of the trend since the turn of the century is suggested by a threefold increase from 1910 to 1920 in the number of *laborers* attached to the pipe-line industry as reported by the census of occupations for those years; this increase was followed in the next decade by almost a twofold gain in the same class of workers (see table A-14). Such a trend is, of course, merely suggestive, for although *laborers* comprised about 55 percent of the total gainful workers reported as attached to the pipe-line industry in 1930, the ratio of laborers to other classes of wage earners employed by pipe lines probably changed in important fashion over the period for which data of the census of occupations are available.

Beginning with 1922 it has been possible to develop indicators of transportation service rendered, employment, and output per man for the important segment of pipe-line transportation represented by oil and gasoline lines that come under the jurisdiction of the Interstate Commerce Commission. These companies represent more than 80 percent of the total mileage utilized for the shipment of crude petroleum and refined products (see table A-15).

[37] Nourse and Associates, *op. cit.*, p. 365.

As is shown in the middle graph of figure 6, the year of peak employment since 1922 was not 1929 or 1930, but 1927. Thereafter the trend was steadily downward until 1932, when the number of wage earners was only slightly more than half the 1927 high. Since the depression low there has been a vigorous upward movement, and in 1937 the number of wage earners exceeded the number employed in 1929, but was still considerably below the level of the year of peak employment.

Although these data trace recent trends in employment and output per man for pipe lines handling crude oil and refined products, it should be noted that they understate the rate of increase in the total volume of employment for the entire pipe-line system. Oil pipe lines, for example, do not include the important and more recent long-distance natural-gas pipe lines. Such lines have shown a remarkable growth since the World War, and this has tended to increase total pipe-line employment. Unfortunately, no authentic statistical series on employment by natural-gas pipe lines are available. In addition, labor data reported by regular pipe-line companies - whether or not engaged in the transportation of oil or natural gas - usually do not include much of the employment required for pipe-line construction. There are, of course, some companies that undertake their own construction, but this work is either largely or entirely done for many companies by special contractors. Reasonably complete figures on the amount of employment provided by pipe-line construction could have been obtained only by a special survey.

INCREASING OUTPUT PER WORKER EMPLOYED

The history of the petroleum and natural-gas industry represents an almost continuous record of successive economies in unit labor requirements. Although the same tendency has been a feature of virtually all branches of mining,[38] increasing output per worker in petroleum and natural-gas production is especially significant because this industry ranks second among the mineral industries as an employer of labor and because the production of oil and gas has always required a relatively small amount of labor per unit of product. In fact, it is largely due to the mushroom-like growth of the

[38] F. G. Tryon and M. H. Schoenfeld, "Mineral and Power Resources," *Recent Social Trends* (New York: McGraw-Hill Book Co., 1933), I, 67-9.

petroleum and natural-gas industry that the increased output per worker employed in mining as a whole has outstripped that of all other basic industries.[39] Despite the depression influences that operated after 1929, it is noteworthy that the trend of output per man-hour in the petroleum and natural-gas industry has continued upward strikingly.

Oil and Gas Wells and Natural-Gasoline Plants

An outstanding reduction in manpower requirements per unit of product has taken place over an extended period in the primary producing segment of the industry. As is shown in figure 5, output per man-hour increased more than 850 percent between 1880 and 1935 (see table A-16).[40]

A feature of the long-time record of output per man-hour for primary producing activities is the large share of the aggregate increase that has taken place in relatively recent years. Gains in unit yield, it is true, approximately tripled in the 30 years which ended in 1909. A more than threefold gain was recorded, however, in the relatively short span from 1919 to 1935. Of great significance, also, is the continued increase in labor productivity between 1929 and 1935, when output per man-hour increased 72 percent. Slightly lower output per man-hour in the two years after 1935 is explained by the expanding drilling campaign that required additional workers.

The data on output per man-hour presented in accompanying figures and tables treat activities at oil and natural-gas wells and natural-gasoline plants as a group for the same reasons that have already been discussed in connection with employment trends (see pp. 19-20). In addition to the problems noted in developing comparable figures on employment, unit worker output of joint products is more useful and less apt to be misleading if expressed in terms of a common denominator.

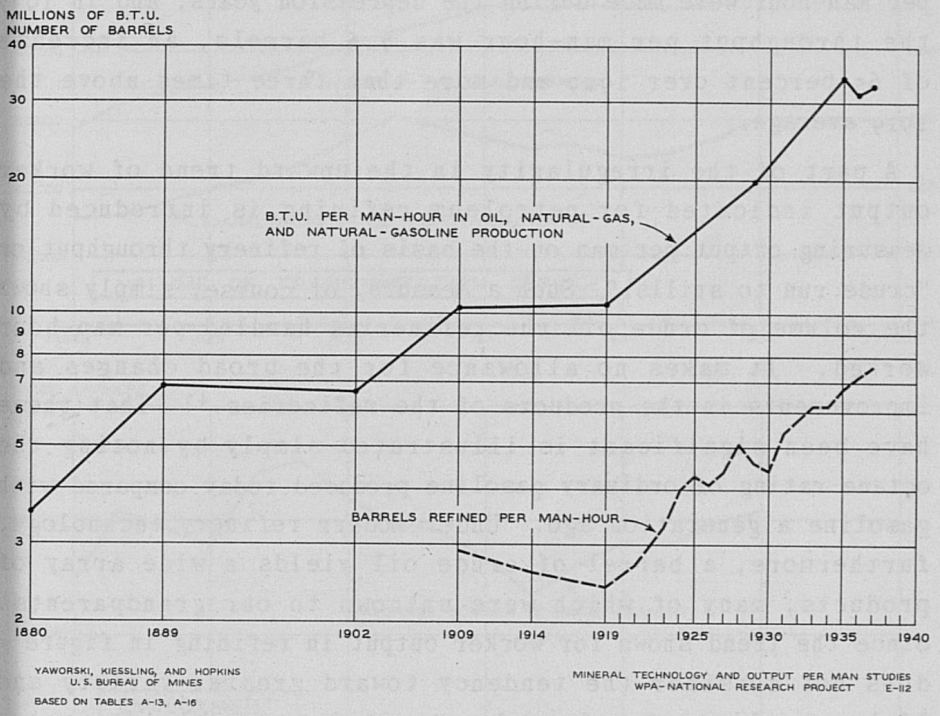
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[39] W. Thomas, "The Economic Significance of the Increased Efficiency of American Industry," *The American Economic Review*, Vol. XVIII, No. 1 (Mar. 1928), "Supplement," p. 125.

[40] The few irregularities in the long-time upward trend of output per man are explained mainly by unusual conditions that prevailed in census periods. From 1889 to 1902, for example, there was a notable increase in output per man-hour in petroleum production that was more than offset by a decline in productivity in natural-gas fields as gas-well pressures dropped notably and production failed to keep pace with employment; this development, vividly recorded in the census results for 1902, was soon remedied by new discoveries. Likewise, failure to show more of an increase in unit output during the decade which ended in 1919 is associated with wartime factors of high prices, urgent demand, extensive drilling, and the operation of properties that would have been submarginal under more normal economic conditions.

Figure 5.- RISE IN OUTPUT PER MAN-HOUR IN THE PRODUCTION OF OIL, NATURAL GAS, AND NATURAL GASOLINE AND IN PETROLEUM REFINING

(Ratio scale)



For the purposes of this study such unlike units as barrels of crude petroleum, cubic feet of natural gas, and gallons of natural gasoline are converted to their B. t. u. equivalents in developing the output-per-man-hour series. The factors used in making these calculations are indicated in table A-16, and it will be noted from figure A-2 that there is little difference in a trend of output per man as determined on the basis of heat value of products and a trend determined on the basis of quantities weighted by value.

Refining

A similar, although somewhat more irregular, trend is shown for output per man in petroleum refining. Using refinery throughput of crude oil per man-year as an approximate indicator of worker output in the early years (see table A-13 and figure A-3), output per man more than quadrupled between 1880 and 1909, when the record of worker output is first available

on a man-hour basis. The upward movement of output per man was checked during the war decade but was resumed after 1919. By 1929 throughput of crude per man-hour was 4.6 barrels, a gain of 92 percent over 1919. Additional increases in output per man-hour were made during the depression years, and in 1937 the throughput per man-hour was 7.6 barrels, an increase of 65 percent over 1929 and more than three times above the 1919 average.

A part of the irregularity in the upward trend of worker output indicated for petroleum refining is introduced by measuring output per man on the basis of refinery throughput or "crude run to stills." Such a measure, of course, simply shows the volume of crude oil the refineries handled per man-hour worked. It makes no allowance for the broad changes and improvements in the products of the refineries.[41] That these have been significant is illustrated simply by noting the octane rating of ordinary gasoline produced today compared with gasoline a generation ago. Under modern refinery technology, furthermore, a barrel of crude oil yields a wide array of products, many of which were unknown to our grandparents. Since the trend shown for worker output in refining in figure 5 does not consider the tendency toward greater variety and higher quality of end products, it is a highly conservative measure of the increase in output per man-hour that has taken place.

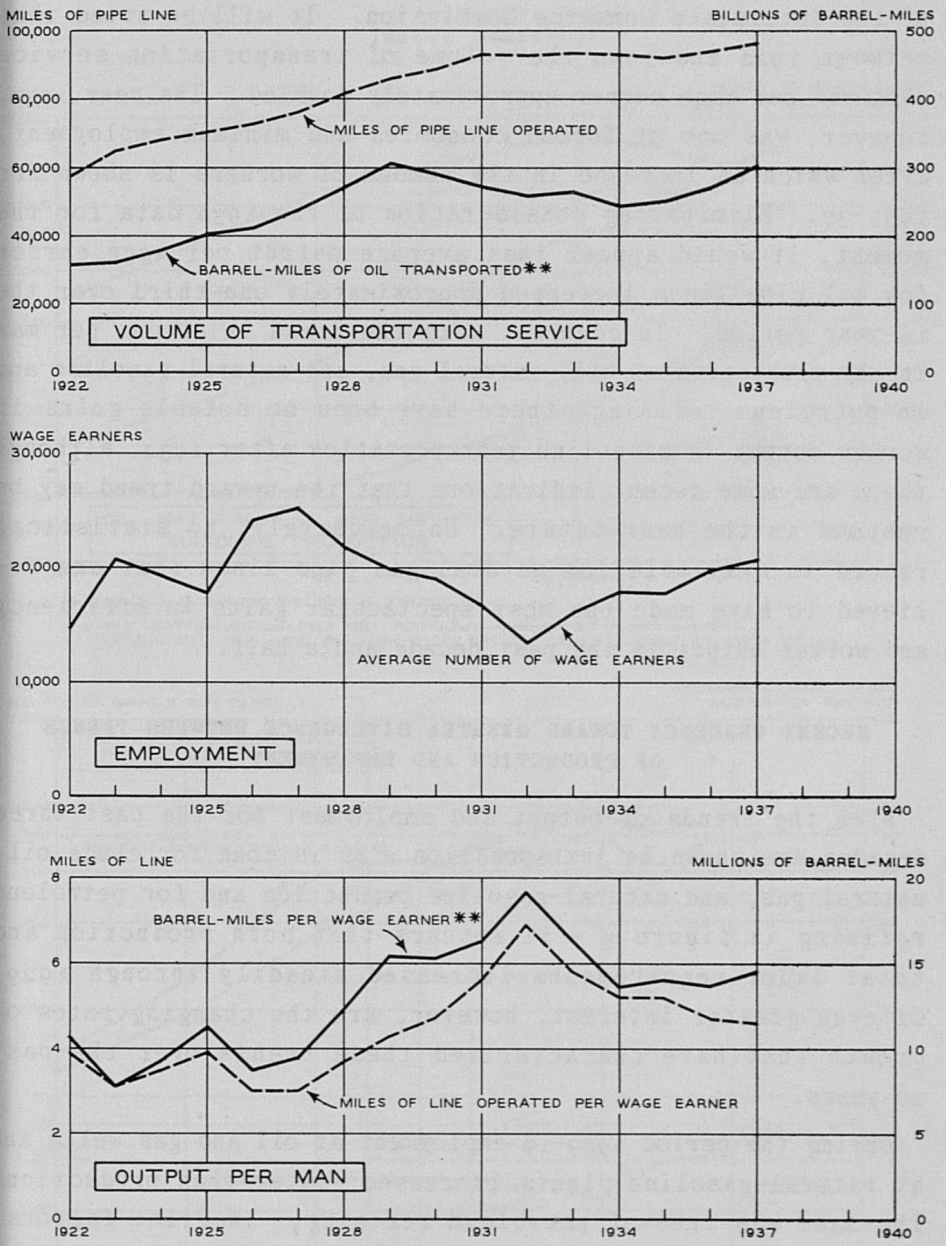
Pipe-Line Transportation

Such scattered indicators as are available suggest that the long-time trend of output per man in pipe-line transportation has also been upward. In fact, it is probable that the increase in worker output on pipe lines has been fully as great as in any branch of the industry, for there has been a spectacular mechanization of tasks that in an earlier period required large numbers of workmen.

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[41] Even in such a period as 1914-19, when the throughput of crude oil per man-hour was dropping, notable advances were being made in the number and type of products obtained; this is one of the important reasons why output per man in refining - as measured by crude run to stills per man-hour - did not show an increase. (See Thorp, *op. cit.*, p. 66.) Certainly, the apparent decline in output per man shown for refining over 1909-19 is partly a product of the wartime influences noted in ftn. 40 and partly a statistical refraction that results from using *throughput* as a measure of *output* at a time when each barrel of crude oil was being processed more intensively to obtain a larger volume of finished products.

Figure 6.– VOLUME OF TRANSPORTATION SERVICE, NUMBER OF WAGE EARNERS, AND OUTPUT PER MAN IN TRANSPORTATION OF OIL BY PIPE LINES,*1922-37



*DATA COVER LINES UNDER THE JURISDICTION OF THE INTERSTATE COMMERCE COMMISSION.

**BARREL-MILES WERE REPORTED FOR 1935-37 AND ESTIMATED FOR 1922-34.

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BASED ON TABLE A-15

Figure 6 presents the trend in output per man for the comparatively recent period 1922-37 for pipe lines, transporting crude oil and refined products, that are under the jurisdiction of the Interstate Commerce Commission. It will be noted that between 1922 and 1932 the volume of transportation service rendered per wage earner approximately doubled. The year 1932, however, was one of forced economies and minimum employment, after which an increase in the number of workers is shown for 1933-37. Eliminating consideration of the 1932 data for the moment, it would appear that average output per wage earner for oil pipe lines increased approximately one-third over the 16-year period. In contrast with the trend in output per man in the production of oil, natural gas, and natural gasoline and in petroleum refining, there have been no notable gains in worker output in pipe-line transportation after 1932, although there are some recent indications that the upward trend may be resumed in the near future. Unfortunately, no statistical record is available for natural-gas pipe lines that are believed to have made the most spectacular gains in efficiency and worker output in the past decade and a half.

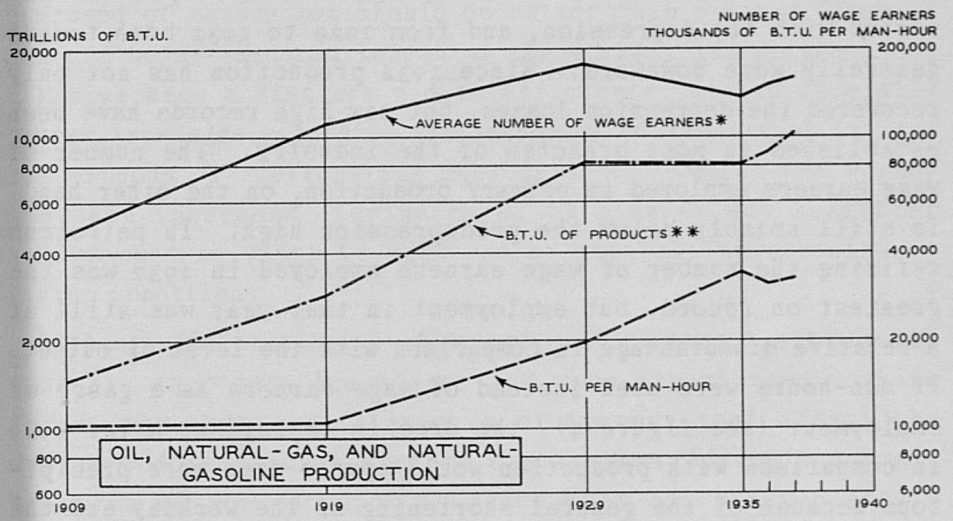
RECENT TENDENCY TOWARD GREATER DIVERGENCE BETWEEN TRENDS OF PRODUCTION AND EMPLOYMENT

When the trends of output and employment for the past three decades are shown in juxtaposition - as is done for crude oil, natural-gas, and natural-gasoline production and for petroleum refining in figure 7 - it appears that both production and total labor requirements increased steadily through 1929. Of even greater interest, however, are the changing rates of growth that have characterized these trends over the past 20 years.

During the period 1909-19 employment at oil and gas wells and at natural-gasoline plants increased faster than production. The same was true of petroleum refining. (Wartime factors, plus statistical problems in measuring the output in refining, explain the failure of output per man to increase in this period, as already noted in footnotes 40 and 41.) In the decade which ended in 1929, however, there was an important change. Although employment continued to increase in primary production activities, the rate of increase lagged notably behind the

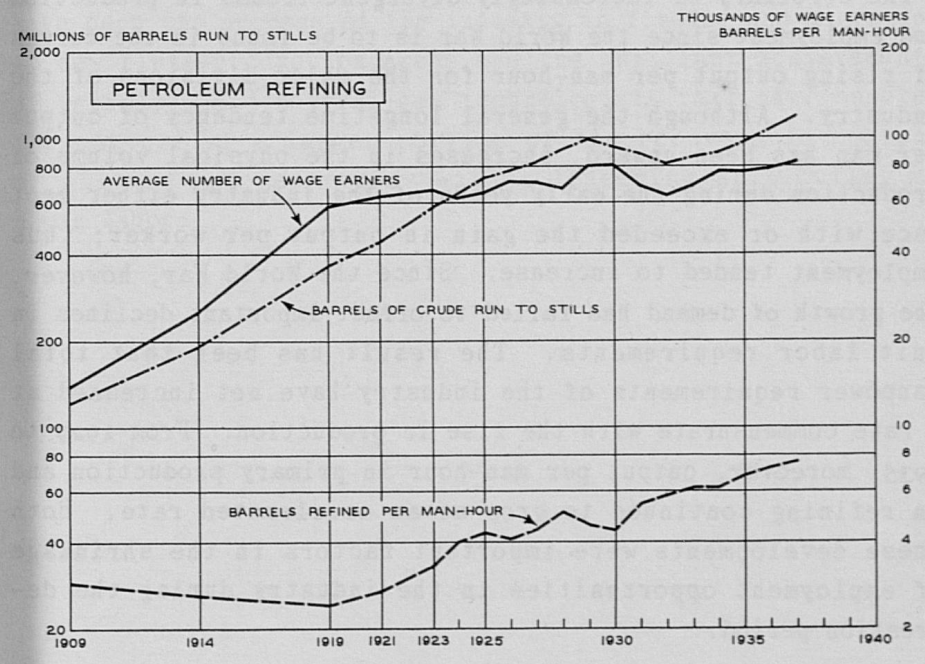
Figure 7.- CONTRASTING RATES OF CHANGE IN PRODUCTION, EMPLOYMENT, AND OUTPUT PER MAN FOR MAJOR PRODUCING DIVISIONS OF THE OIL AND GAS INDUSTRY, 1909-37

(Ratio scale)



*INCLUDES WAGE EARNERS EMPLOYED BY CONTRACTORS.

**UNIT HEAT VALUES EMPLOYED ARE: PETROLEUM, 6,000,000 B.T.U. PER BARREL; NATURAL GAS, 1,000 B.T.U. PER CUBIC FOOT; NATURAL GASOLINE, 120,000 B.T.U. PER GALLON.



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BASED ON TABLES A-11, A-13, A-16

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growth of output. Petroleum refining showed similar development, except that the shrinkage in employment opportunities was proportionately greater than in oil, natural-gas, and natural-gasoline production.

The upward movement of both employment and output was arrested with the depression, and from 1929 to 1932 both trends generally were downward. Since 1932 production has not only recovered the depression losses, but new high records have been established in most branches of the industry. The number of wage earners employed in primary production, on the other hand, is still notably below the predepression high. In petroleum refining the number of wage earners employed in 1937 was the greatest on record, but employment in that year was still at a relative disadvantage in comparison with the level of output. If man-hours were used instead of wage earners as a gauge of employment (see figure 4), the drop in employment after 1929 in comparison with production would appear even more precipitous because of the general shortening of the workday and the workweek in the past 6 years.

The corollary of increasingly divergent trends in production and employment since the World War is to be found in the curves of rising output per man-hour for the major divisions of the industry. Although the general long-time tendency of output per man has been upward, increases in the physical volume of production during the early years of the industry either kept pace with or exceeded the gain in output per worker; thus employment tended to increase. Since the World War, however, the growth of demand has failed to offset important declines in unit labor requirements. The result has been that total manpower requirements of the industry have not increased at a rate commensurate with the rise in production. From 1929 to 1935, moreover, output per man-hour in primary production and in refining continued to grow at an accelerated rate. Both these developments were important factors in the shrinkage of employment opportunities in the industry during the depression period.

Over an extended period many things have happened that have tended to raise the productive efficiency of individual workers employed in the oil and gas industry. One important influence of this character has been the improvement in the quality of

the industry's working force. Restriction of immigration, for example, has permitted broader general education and has raised the industrial skill of the working population as a whole. Another significant factor has been an increase in the average permissible working age for minors; certainly a labor force composed of mature men should do better than a labor force of men and boys. Reduced length of the workday and workweek has likewise been a distinct aid to efficiency, as has generally better knowledge regarding the incidence of industrial fatigue and methods of ameliorating such fatigue. Output per worker has been increased, furthermore, by a safer and healthier environment in which to work and by general improvements in living conditions.

Although the cumulative effect of such changes has given the industry an older, healthier, and more experienced working force, the combined influences of factors that affect the welfare of individual workers can account for only a small fraction of the enormous increase that has taken place in output per man. The overshadowing reasons why the trend in output per man has outstripped both production and employment have been the success of the industry in finding and migrating to new flush-production areas and the brilliant achievements of petroleum and natural-gas technologists that have enabled the capture of a larger portion of the recoverable content of oil and gas reservoirs with a lessening unit outlay of human labor.

CHAPTER III

INFLUENCE OF MIGRATION TO NEW FLUSH-PRODUCTION AREAS*

Peculiar to all mineral exploitation is the characteristic of exhaustibility and a consequent distinctive life cycle through which every mining district tends to pass.[1] Although the history of a few famous metal mines extends over several centuries, sooner or later production dwindles, and even the richest pass into oblivion. To such an end came the Nubian mines that supplied the Pharoahs of Egypt with gold, the almost mythical mines of Ophir that showered King Solomon with riches, and the silver mines of Laurium whose treasure was said to be responsible for altering the course of human history. Even in the United States, where large-scale mining has been carried on for somewhat less than 100 years, there are numerous towns in the Western States - Goldfield, Tonopah, Virginia City, Leadville, Cripple Creek, Aspen, and Tombstone - where pristine vigor has waned. These towns, as well as the many almost completely deserted "ghost camps", bear mute testimony to the ephemeral character of mining localities.

Although depletion is a characteristic feature of all mining, oil and gas pools are notoriously short-lived. For example, the Fountain oil well, whose daily production of 300 barrels[2] was largely responsible for breaking the market in 1861, has long been only a memory to a few ancient survivors of the pioneer era. Similarly, the Big Moses gas well in Tyler County, West Virginia, has been almost entirely forgotten, but in the early days of the industry it was one of the greatest of all wells and produced 35 million cubic feet a day.[3] Even in the past few decades scores of famous oil pools have come

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*By G. R. Hopkins; R. L. Kiessling, Economic Analyst, WPA National Research Project; and H. O. Rogers.

[1] H. O. Rogers and F. G. Tryon, "Mining: History, Technology, and Economics," *Encyclopaedia of the Social Sciences* (New York: The Macmillan Co., 1933), X, 500; see also D. F. Hewett, "Cycles of Mineral Production: Youth, Maturity, and Old Age," *Mineral Economics: Lectures Under the Auspices of the Brookings Institution* (1st ed.; New York: McGraw-Hill Book Co., Inc., 1932), pp. 62-90.

[2] G. W. Stocking, "The American Petroleum Industry," in H. T. Warshow, ed., *Representative Industries in the United States* (New York: Henry Holt and Co., 1928), p. 536.

[3] F. H. Oliphant, "Natural Gas," *Special Reports of the Census Office, Mines and Quarries: 1902* (U. S. Dept. Com and Labor, Bur. Census, 1905), p. 772.

and gone. Among these Cushing (1912), Ranger (1917), Smackover (1922), Mexia (1922), and Hendricks (1926) are outstanding examples.[4] Not one of these great pools, moreover, was a significant producer for longer than 5 years. Active development of new areas was undertaken as rapidly as old pools failed, and the almost continuous process of migration of the industry to new flush-production areas was an important factor in maintaining output per man. The fact that the new fields were generally more productive than the old ones accounted for part of the long-time increase in unit output.

SHIFTING CENTERS OF OIL AND GAS PRODUCTION

As a result of the evanescent quality of the contents of oil and gas pools once they are in production, particularly when exploited under the wasteful practices of competitive drilling referred to in chapters VI and VIII, the geographic frontiers of the industry have been constantly redrawn. Today the computed centers of oil and gas production are far from the areas where the industry was first important[5] (see figure 8). The line of march has been to the west and south, following closely in the wake of discovery.

In the past, nearer in time than in opinion, the geographic center of petroleum production was in Pennsylvania. In fact, the center of crude-oil production 20 years after the completion of the Drake well was still in that State. During the following half-century, however, production moved across the country with giant strides. By 1889 the center of production was in northeastern Ohio, and a decade later it had moved diagonally across Ohio to a point close to the Indiana border. But the most spectacular shift of all occurred during the first decade of the present century, when the computed center of production moved almost 1,000 miles across the country from western Ohio to central Kansas. More recently the rate of movement has been slowing down, and the direction of the march has changed. As a result of the discovery of the great East

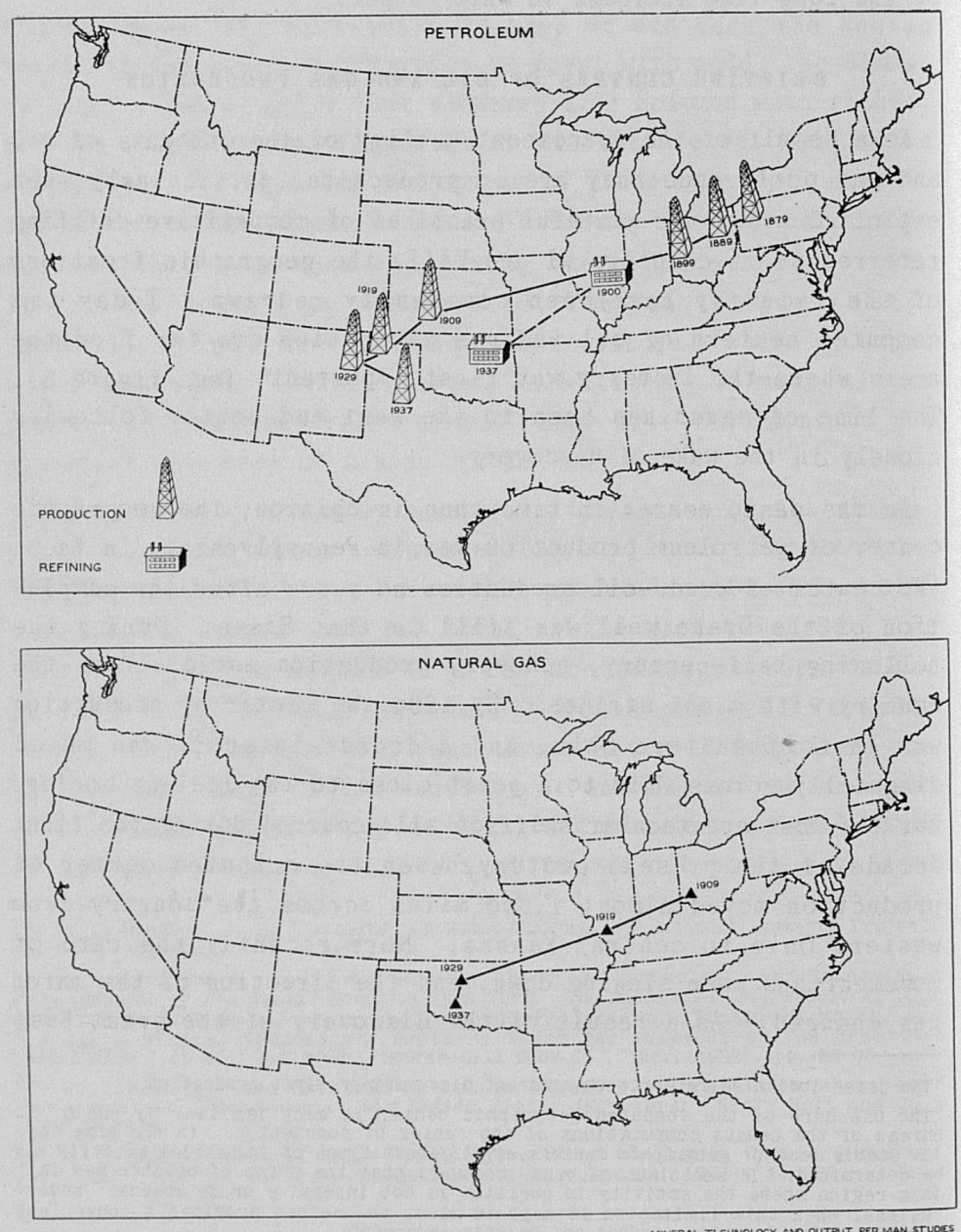
[4] The dates indicated refer to the year of discovery or first production.

[5] The use here of the computed geographic center is made familiar by the U. S. Bureau of the Census computations of the center of population. In the same way, the statistical or geographic centers of different types of industrial activity may be determined. It sometimes happens, however, that the point of balance may fall in a region where the activity in question is not intensive or is absent. Nevertheless, when this limitation is kept in mind, the method provides a convenient way of tracing long-time trends and relative movements.

Texas field, the center of crude-oil production has shifted southward and in 1937 it was in the Texas Panhandle.

A closely similar shift has occurred in natural-gas production. In 1909 the center of natural-gas output was in southwestern Ohio. By 1919 it had shifted to southern Illinois and in 1937 it was in south-central Oklahoma.

Figure 8.- SHIFTING CENTERS OF PETROLEUM AND NATURAL-GAS PRODUCTION



Refinery centers, too, have shifted about. During the early stages of the industry's development the refineries were located in proximity to the oil fields.[6] Today, however, a complicated network of pipe lines and a great fleet of tankers enable many principal refineries to be established in or near main consuming areas. The occurrence of petroleum deposits and facilities for transportation appear to be dominant factors determining refinery location. In 1937 the computed center of the refining industry was northeastern Oklahoma, not far from the center of crude-oil production; in 1900, by contrast, the center of the refining industry was central Illinois.

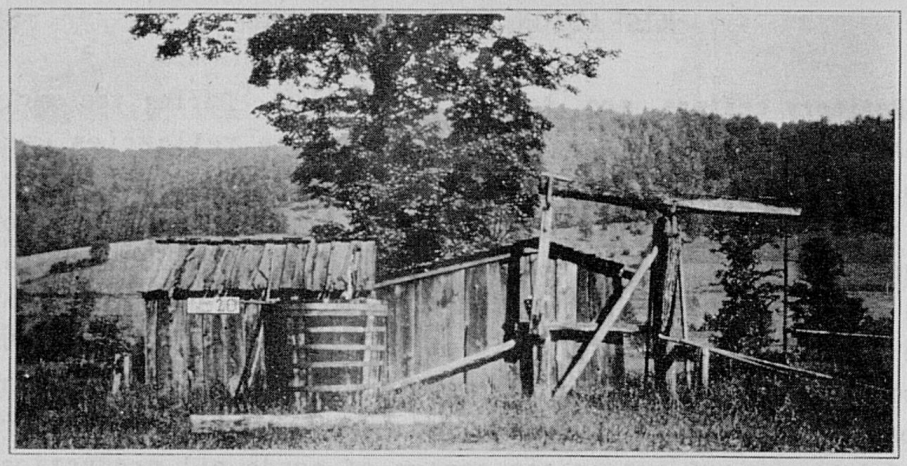
RISE AND FALL OF PRODUCING STATES

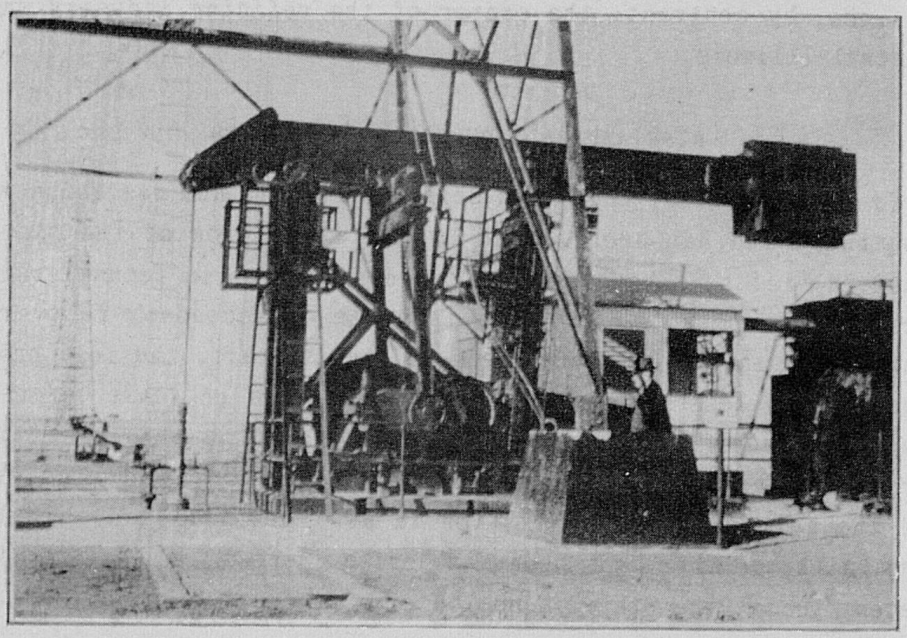
To a large extent the broad shift of the oil and gas industry southwestward has been forced by the exhaustion of the older eastern fields. The output of crude petroleum in Pennsylvania reached its peak in 1891 and, in spite of secondary-recovery activities in the Bradford field in recent years, the 1937 production was less than two-thirds the total of 46 years before. The high record for New York was established in 1882, when it produced over a fifth of the national total. During the course of the next 30 years production in New York dwindled sharply and, although there has been a moderate increase of activity in recent years, the State is no longer a producer of importance.

In Ohio, West Virginia, and California the commercial production of crude petroleum dates from 1876. Ohio's all-time peak was reached in 1896 and West Virginia's 4 years later In both these States production declined sharply in subsequent years. Indiana became a commercial producer in 1889 and from 1898 to 1905 was comparatively important. Meanwhile, production in California was increasing rapidly, and Texas became an important producer almost overnight as a result of the discovery of Spindletop early in 1901. Oklahoma did not become a substantial producer until after 1905, but after the Glenn pool was developed in 1906 and 1907 its rise was rapid. About the same time Illinois suddenly advanced to a place of prominence, production increasing from 181,000 barrels in 1905 to a peak of 33,686,000 barrels in 1908, when it ranked third

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[6] American Petroleum Institute, Committee on Refining, N. Robinson, chmn., "Refining," *American Petroleum Industry* (New York: 1935), p. 69





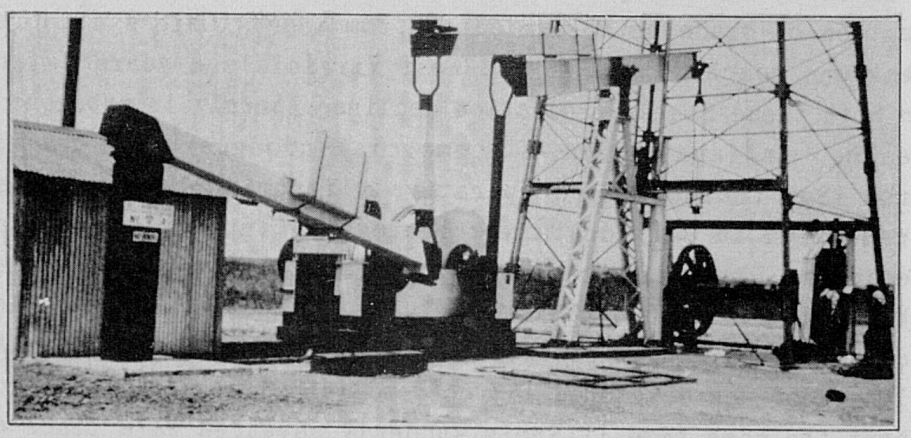


ILLUSTRATION 3.— THE OVERWHELMING PROPORTION OF OIL IN MOST AREAS IS PRODUCED BY PUMPING

Old-type pumping gear, still used in some Appalachian fields, is shown in the upper view. The middle view shows a modern pumping unit in use in Oklahoma. The lower view shows a pumping well in West Texas fitted with a "grasshopper" counterbalance.

among the producing States. The decline of Illinois, however, was almost as precipitous as its rise, and production dropped 60 percent during the next decade. In 1937 the output of the State was less than a quarter of the total in the year of peak production, but a recent expansion of drilling promises a new high output record in the near future.

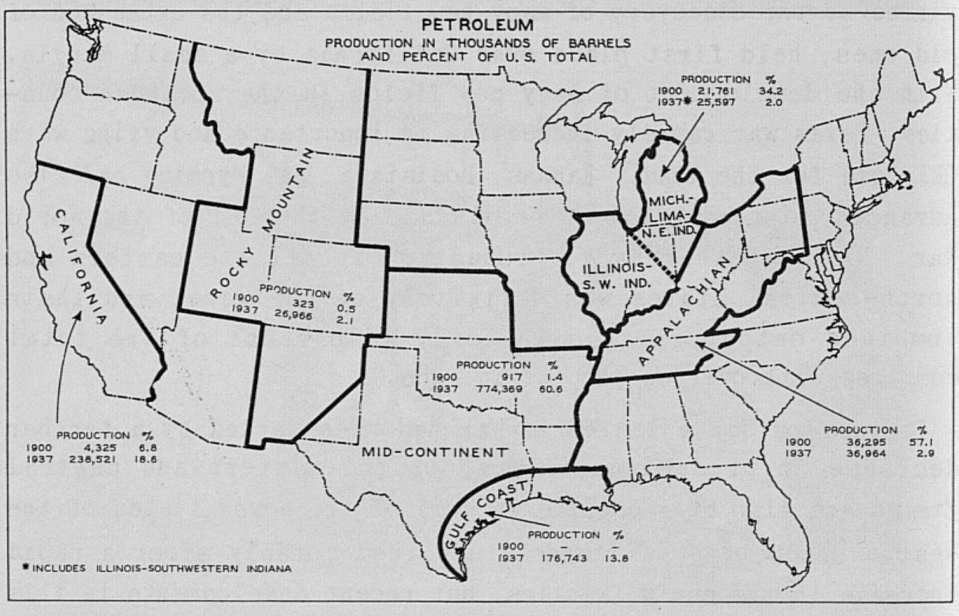
Further significant changes in the status of the producing States occurred during the war decade; in 1920 Oklahoma, by virtue of the discovery of many new fields and the extension of old ones, held first place over California by a small margin. With the development of many new fields in the northern counties, Texas was rapidly increasing in importance and vying with Oklahoma for the lead. Kansas, Louisiana, and Wyoming had also advanced to a position of prominence by the end of the World War. On the other hand, production in all the eastern and north-central States was definitely on the wane, and their combined output in 1920 was only 10 percent of the total compared with over 90 percent in 1900.

The period since the World War has been marked by a further decrease in production in most of the eastern and central States and also by a decline in some of the newer fields of the West. Production in Arkansas declined notably after a rapid increase in the early twenties, but recent developments in this State have been accompanied by rising output. In Wyoming and Montana, production reached its peak in the middle twenties and declined sharply in succeeding years. In Texas, Louisiana, New Mexico, and Kansas, however, new discoveries apparently continue to keep production in the ascendant, and output is maintained at high levels in Oklahoma and California. Important fields developed in these States since the war include Kettleman Hills and the flush fields of the Los Angeles Basin in California; Tonkawa, Burbank, Seminole, Oklahoma City, and Fitts in Oklahoma; and the East Texas, Conroe, and the fault-line pools in Texas.

The shifting character of regional contributions to the Nation's oil and gas output is illustrated by figure 9, which compares the relative importance of the major oil- and gas-producing districts in 1937 with their status at the turn of the century. In 1900 considerably more than half the national requirements of crude petroleum came from the Appalachian

area, slightly more than a third from the Lima, northeastern Indiana, and Michigan district, and the small remainder from California, Mid-Continent, and Rocky Mountain fields. In 1937, by contrast, over three-fifths of the crude-oil production was produced by the Mid-Continent fields, almost one-fifth by

Figure 9.- CHANGES IN RELATIVE IMPORTANCE OF MAJOR PETROLEUM AND NATURAL-GAS PRODUCING DISTRICTS



G. R. HOPKINS AND R. L. KIESSLING
U. S. BUREAU OF MINES

BASED ON RECORDS OF THE BUREAU OF MINES

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California, and over one-eighth by the Gulf Coast fields. The Appalachian area's share of the total in 1937 was 2.9 percent, and only 2.0 percent was furnished by the Lima, northeastern Indiana, and Michigan field and the Illinois and southwestern Indiana field.

There have likewise been broad changes in the relative importance of the major gas-producing regions over recent decades. At the longest, the life of a gas well is a matter of only a few years. Many of the eastern and middle-western fields that played a prominent part in stimulating the commercial use of natural gas are almost forgotten, and the communities that they served are now using either manufactured gas or natural gas from the newer fields of the Southwest.

As was true for oil, Pennsylvania was the leading State in the earliest period of natural-gas production. West Virginia, in 1909, stepped into first place and remained in the lead until 1923, when it produced about one-fifth of the country's total output. In the following year Oklahoma became the leading producer, and in the same year Pennsylvania receded from fourth to sixth place; thus 1924 marked the passing of the supremacy of the eastern States in the production of natural gas and a closer approach in rank of the States producing natural gas to those that produce petroleum, emphasizing the growing production of casing-head gas (gas produced with oil or obtained from oil wells). In 1929 Texas surpassed Oklahoma as the leading producer, and in recent years the Texas output has been more than double that of any other State. The rise and fall of leading States simply reflected a development noted in other major producing States, including Arkansas, Illinois, Indiana, Ohio, Wyoming, and Kansas. In Ohio, however, output has been relatively well maintained; in Kansas, production has been increasing after an earlier decline. Other major producing States in which production appears to be expanding are California, Kentucky, Montana, New Mexico, and Louisiana. The largest recent single source of natural gas is the region extending across three States from Amarillo in the Texas Panhandle to Hugoton in southwestern Kansas.[7]

Figure 9 illustrates the declining importance of the old fields of the eastern region and the spectacular rise of

[7] C. Goodrich, B. W. Allin, and Others, *Migration and Economic Opportunity* (Philadelphia, Pa.: University of Pennsylvania Press, 1936), p. 291.

western producers. In 1937 nearly two-thirds of the marketed production of natural gas came from the Mid-Continent and Gulf Coast fields, almost a fifth from California and the Rocky Mountain regions, and about one-sixth from the Appalachian fields. Three decades ago, however, more than three-fourths of the commercial output was supplied by the Appalachian fields, and the Mid-Continent-Gulf Coast area produced less than a fifth. The combined output of California and the Rocky Mountain fields in 1906 amounted to less than 0.1 percent of the total.

Although the subject of shifting geographic centers of production is introduced at this point in the discussion mainly in connection with an explanation of increasing output per man, other results of the rise and fall in the importance of producing States are noted in a shifting volume of employment opportunities for different areas. After a study of the 10-year cross sections of the census record of employment at oil and gas wells, by State, from 1870 to 1930, one observer reported:

> In Pennsylvania . . . . employment reached its peak in 1890 and declined nearly 50 per cent in the course of the next twenty years. . . . . employment . . . . reached its peak in Ohio and Indiana about 1900, in Illinois about 1910, and in West Virginia, Kentucky, Kansas, Louisiana, and Wyoming about 1920. In all of these states there followed a significant decline. In Oklahoma, Arkansas, Texas, and California . . . . new discoveries continued to expand employment up to 1930, the year of the last record.[8]

INCREASING SIZE OF PRODUCING UNITS

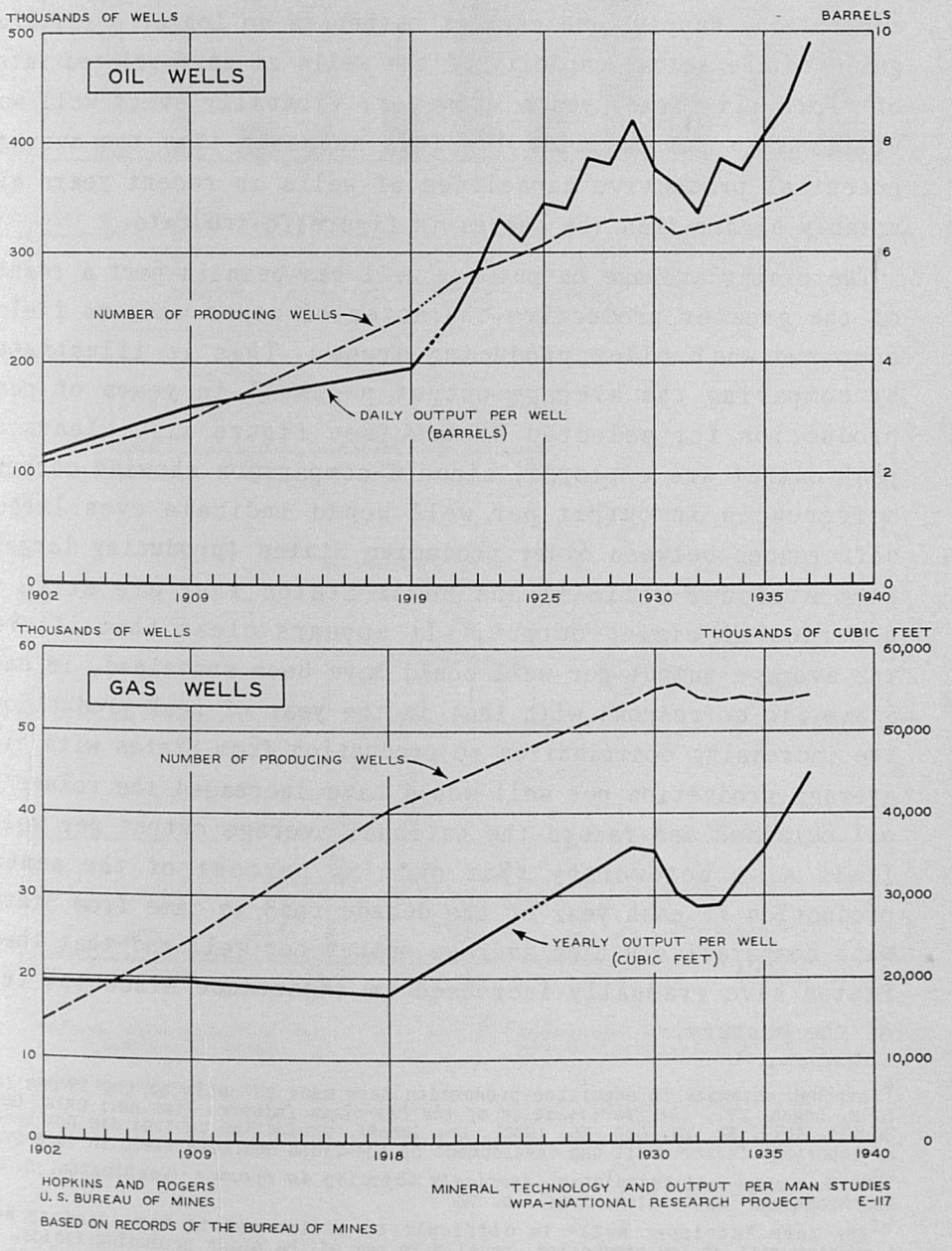
The westward march of oil and gas production has been attended by a marked increase in the average size of the producing wells (see figure 10). This development is due partly to the larger initial production of western wells (which are generally deeper and produce under higher pressures than those in older areas) and to the application of a constantly improving technology both in drilling and production. The net result has been that the average production of both oil and gas wells has increased materially.

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[8] *Ibid.*, pp. 270-1.

For the oil wells the average production per well in 1937 was 9.8 barrels a day, a small increase over 1929 when the average output was 8.4 barrels; compared with the average in 1899, the present average yield represents a gain of about 350 percent. Meanwhile, the average daily initial production of new wells drilled has increased from roughly 50 barrels in 1908 to 480 barrels in 1937.

Figure 10.– TREND OF NUMBER AND AVERAGE OUTPUT OF OIL AND NATURAL-GAS WELLS, 1902-87



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Since the turn of the century there has also been a general upward trend in the average output of natural-gas wells. Whereas the average annual output was 19,555,000 cubic feet per well in 1902, the average was 44,960,000 in 1937, an increase of 130 percent.

This record of increase in the size of wells is even more remarkable when viewed against the background of the proration program[9] used during the past decade to hold in check the output of flush-production areas. As will be noted in chapters VI and VIII, proration is now a dominant factor in controlling supply, and current output is no longer a faithful guide to the actual capacity of the wells at unrestricted rates of flow. In former years, however, virtually every well was utilized to its capacity.[10] This suggests that the average potential productive capacities of wells in recent years are notably higher than the curves in figure 10 indicate.

The rising average output per well has been in part a result of the greater productive character of newer western fields compared with older producing areas. This is illustrated by comparing the average output per well in years of peak production for selected States (see figure 11). Years of peak output are employed, since a comparison showing current differences in output per well would indicate even larger differences between older producing States (producing largely from stripper wells)[11] and newer States that are still in a period of rising output. It appears clear that if even the average output per well could have been sustained, in each State, to correspond with that in the year of peak production, the increasing contribution to production from States with high average production per well would have increased the volume of oil obtained and raised the national average output per well. It is also noteworthy that over 85 percent of the annual production in each year of the decade 1928-37 came from States with comparatively high average output per well and that these States have gradually increased in importance since the turn of the century.

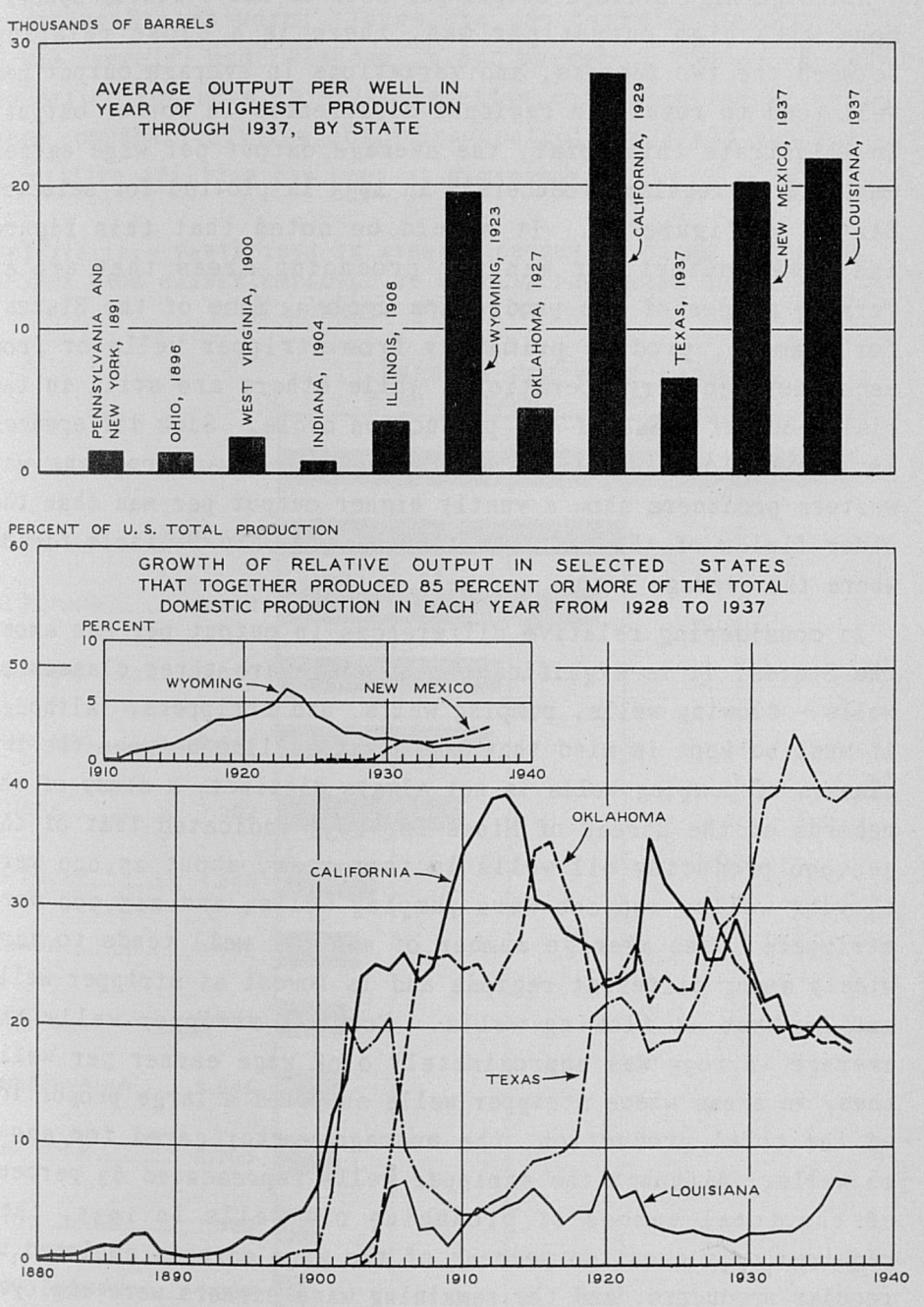
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[9] Although attempts to stabilize production were made as early as the 1870's (see L. M. Logan, Jr., *The Stabilization of the Petroleum Industry* [1st ed.; Okla. Geol. Survey, Bull. No. 54, Oct. 15, 1930], pp. 125-8), production control did not become an important factor until the development of the flush Seminole field in 1926-27.

[10] E. G. Nourse and Associates, *America's Capacity to Produce* (Washington, D. C.: The Brookings Institution, 1934), p. 73.

[11] The term "stripper well" is difficult to define and is here used to mean a pumping well of low production, usually in one of the older producing fields.

Figure 11.- IMPETUS GIVEN PETROLEUM PRODUCTION BY GREATER AVERAGE OUTPUT PER WELL IN NEWER PRODUCING STATES AND BY THE INCREASING IMPORTANCE OF STATES WITH RELATIVELY HIGH AVERAGE PRODUCTION PER WELL



HOPKINS, KIESSLING, AND SETTLE
U. S. BUREAU OF MINES

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
WPA-NATIONAL RESEARCH PROJECT E-118

BASED ON TABLES A-17, A-18

REGIONAL DIFFERENCES IN OUTPUT PER MAN

Although high average output per well is not strictly synonymous with high output per man, there is a close relation between the two factors, and variations in average output per well tend to result in regional differences in worker output. To illustrate this point, the average output per wage earner employed by regular producers[12] in 1935 is plotted for selected States in figure 12. It should be noted that this figure indicates output per man for producing areas that are at varying stages of the production cycle. Some of the States, for example, produce primarily from stripper wells or from secondary-recovery operations, while others are still in the rising-output phase of the production cycle. Such differences in production conditions are among important reasons why western producers show a vastly higher output per man than the older fields of the East and the Indiana-Ohio-Illinois fields where the average output per well is low.

In considering relative differences in output per man among the States, it is significant that there are three classes of wells - flowing wells, pumping wells, and strippers. Although it must be kept in mind that the dividing line between the two classes of pumping wells is not always distinct, a study of the records of the Bureau of Mines for 1935 indicated that of the 340,990 producing oil wells in that year, about 25,000 were flowing wells, 100,000 were pumping wells, and 215,990 were strippers. The average number of men per well tends to vary widely among different regions and is lowest at stripper wells and highest at flowing wells. For all stripper wells the average in 1935 was approximately 0.08 wage earner per well; thus, in areas where stripper wells supplied a large proportion of the total production, the average worker cared for about 12 wells. Although the stripper wells represented 63 percent of the total number of producing oil wells in 1935, they required only about 20 percent of the wage earners employed by regular producers, and the remaining wage earners were employed at the more productive pumping and flowing wells.[13]

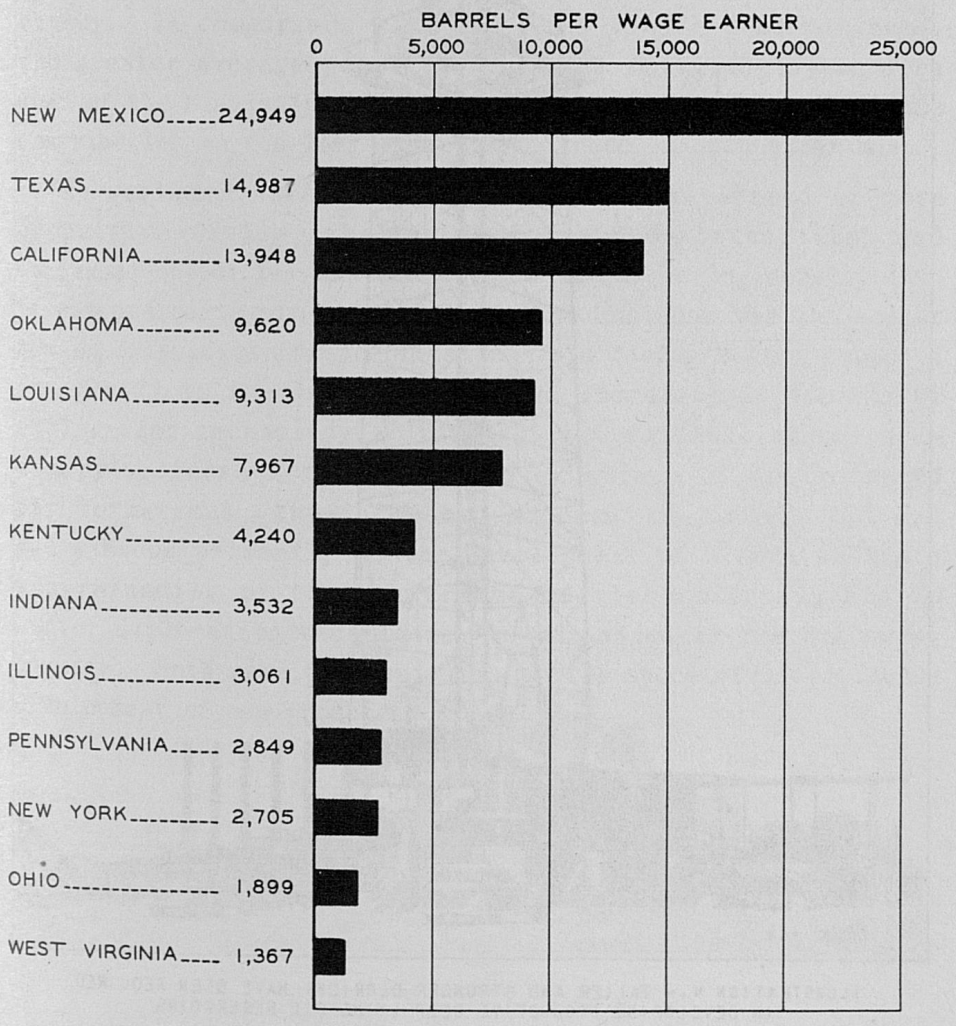
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[12] The data cover wage earners at oil wells only and exclude workers rendering contract services.

[13] For additional data on average number of wage earners per producing well see table A-19.

Annual average output per wage earner in 1935 was highest in New Mexico. Averages per man for the three most important producing States were: Texas, 14,987 barrels; California, 13,948 barrels; and Oklahoma, 9,620 barrels. The record for New Mexico reflects chiefly the efficient operation at Hobbs where comparatively few companies control the field and where competitive drilling has been at a minimum.

Figure 12.- VARIATIONS IN AVERAGE OUTPUT OF CRUDE PETROLEUM PER WAGE EARNER EMPLOYED BY REGULAR PRODUCING COMPANIES IN SELECTED STATES IN 1935



HOPKINS AND ROGERS
U. S. BUREAU OF MINES

BASED ON TABLE A-19

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
WPA-NATIONAL RESEARCH PROJECT E-119

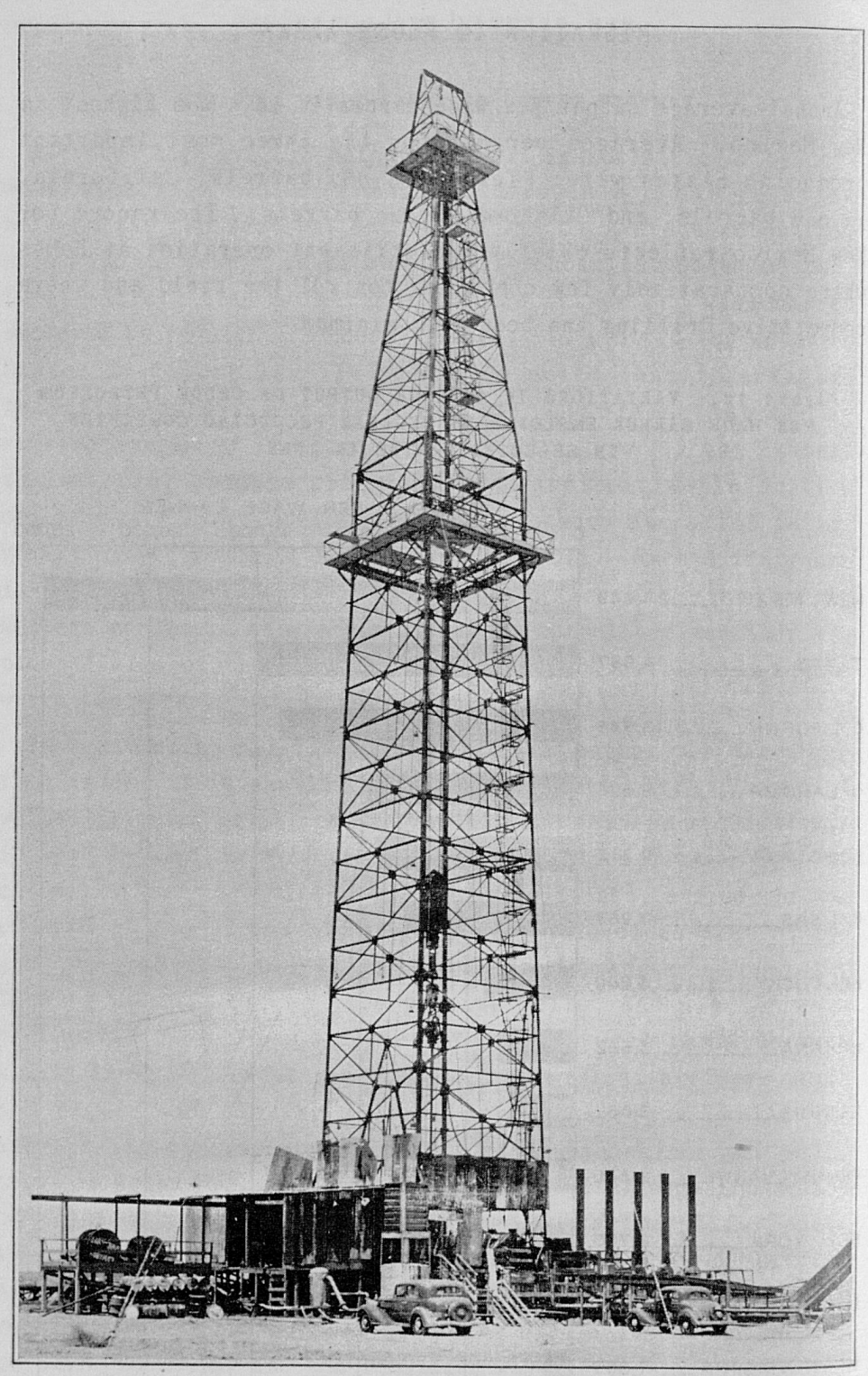


ILLUSTRATION 4.- TALLER AND STRONGER DERRICKS HAVE BEEN REQUIRED IN DEVELOPING PRODUCTIVE DEEP-LYING OIL RESERVOIRS

This picture illustrates a recently developed steel derrick, known as a "double-taper" rig, used in one of the world's deepest oil fields in California. The total height is 178 feet and the "break" is 128 feet above the foundations. High derricks are an economy in deep drilling because the drill pipe can be pulled in longer "stands", requiring fewer breaks. The type of design shown facilitates the racking of a large number of stands. This picture was kindly supplied by the Kern County Chamber of Commerce, Bakersfield, California.

Compared with the relatively high averages for many of the western States, the output per man for older producing areas - in which stripper operations are important - appears low. In Pennsylvania, for example, the average output per man in 1935 was 2,849 barrels, or less than one-fifth of the average for Texas. The average was still lower in New York, Ohio, and West Virginia. Of all fields east of the Mississippi the average output per man per year was highest in Michigan - 17,279 barrels. Although this average exceeded that of many western States, the annual contribution from the Michigan fields has never been more than 1.6 percent of the national output. In comparison with the older fields just reviewed, the greater average production per man obtained in the area west of the Mississippi River appears as an important influence contributing to the long-time upward trend in output per man.

The westward movement of production that opened up more productive fields, shifted employment opportunities, and increased output per man was not a self-generating development. It was due partly to the initiative of business men who sought new opportunities for profit as the old fields became depleted and partly to the development of an increasingly successful exploration technology. Granting the existence of the necessary business motives and the existence of undiscovered pay formations, the increased success in finding oil and gas was due primarily to the development of a more adequate understanding of the occurrence of these minerals and to better exploration techniques, as explained in the following chapter. Both were prerequisites to the successful continuous development of new producing areas.

CHAPTER IV

DEVELOPMENT OF EXPLORATION AND DISCOVERY TECHNIQUES*

The industry has been able to migrate to new fields and production has been kept articulated with demand only because new discoveries constantly are being made. During the past quarter-century proved reserves of oil never have sufficed to supply our domestic needs for more than a decade or two.[1] Consequently, if discoveries were to cease suddenly, the result within a very short time would be a shrinkage of supplies and rising prices, for the stream of new sources must be kept continuous to replace the waning production of fields that are being depleted. It is true that the producing life of oil pools ranges from 4 to 30 years and sometimes even longer, depending on many factors involved in individual reservoir conditions and extraction programs, but the peak of the production curve for most fields embraces a relatively short period. Exploration therefore is an essential phase of oil and gas production and is much more important than in any other branch of the mineral industry.

What happens when discovery fails to keep pace with demand is exemplified by experience gained during the World War. In 1915 the discovery and rapid development of the famous Cushing (Oklahoma) pool caused an acute economic situation in the industry caused by overproduction, but this glut swiftly was transformed into a serious shortage with the rise of war demands and the suspension of Russian supplies.[2] Measured in terms of days' supply, United States stocks of crude fell from an average of approximately 260 in 1915 to a low of 98 in 1920,[3] and the weighted average price of crude oil rose from 64 cents a barrel in 1915 to $3.07 a barrel in 1920.[4]

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*By J. Brian Eby, Consulting Geologist, Houston, Texas; Lew Suverkrop, Engineer and Geologist, Bakersfield, California; H. O. Rogers; and O. E. Kiessling.

[1]National Resources Board, *A Report on National Planning and Public Works in Relation to Natural Resources and Including Land Use and Water Resources, With Findings and Recommendations* (Dec. 1, 1934), p. 405.

[2]E. G. Nourse and Associates, *America's Capacity to Produce* (Washington, D. C.: The Brookings Institution, 1934), pp. 80-1.

[3]*Ibid.*, p. 81.

[4]J. E. Pogue, "Price of Crude Oil in Perspective," *Bulletin of the American Association of Petroleum Geologists*, Vol. 20, No. 6 (June 1936), p. 813.

So serious was the shortage that "gasolineless" Sundays were instituted in an effort to conserve motor fuel for essential needs.[5] The situation was relieved only by a succession of major discoveries in the early twenties.

Even in periods of oversupplied markets the margin of excess has been comparatively narrow. The late twenties, for example, was a period of chronic excess production; yet had it not been for the discovery of the East Texas field, a serious shortage might have developed during the early thirties (provided no other discoveries of equal importance had been made) because the output of all fields producing in 1929 had decreased 40 percent by 1934[6] while domestic requirements were only 10 percent below the level of 1929. Conditions such as this have not been unusual in the industry because, at any given time, a large share of the supply comes from relatively few major pools in their early production stages.[7] The decline in output, however, usually is precipitous after the first years of operation. In the Seminole field, for example, production declined 70 percent in the period 1927-31, and a decrease of more than 80 percent occurred in the aggregate production of four important fields of West Texas (Big Lake, Church-Fields-McElroy, Hendricks, and Chalk) from the sum of their peak productions to 1933.[8] Even under present curtailment programs a major burden of supplying market requirements falls on new fields, and the importance of maintaining the rate of discovery is readily apparent.

Despite the critical importance of discovery, until relatively modern times random drilling was the standard technique employed in the search for oil and gas. This method was successful as long as surface indications to attract the prospector were abundant and major pools were accessible at comparatively shallow depths. Indeed, for nearly half a century the wildcatters,[9] who drilled with little or no

[5] H. C. Fowler and R. A. Cattell, "Influences of Petroleum Technology Upon Composite Interest in Oil," *Minerals Yearbook, 1935* (U. S. Dept. Int., Bur. Mines, 1935), p. 777.

[6] L. C. Snider and B. T. Brooks, "Probable Petroleum Shortage in the United States and Methods for Its Alleviation," *Bulletin of the American Association of Petroleum Geologists*, Vol. 20, No. 1 (Jan. 1936), pp. 22-3.

[7] Nourse and Associates, *op. cit.*, p. 75.

[8] Snider and Brooks, *op. cit.*, p. 23.

[9] The word "wildcat" is used here to mean a hole drilled for oil or gas and sufficiently far from any developed production to be a test of unknown subsurface conditions. As is noted later in this discussion, an exploratory well may be located with or without the benefit of technical logic.

scientific advice, usually were able to discover new pools considerably faster than they were required. As unexplored places where there were visible surface indications to serve as guides became fewer and it became necessary to tap the deeper horizons to reach oil, random drilling began to show signs of declining effectiveness. For that reason the industry in recent years has turned increasingly to scientific knowledge for aid, and the contribution of technology in exploration probably has been greater than in any other branch of the industry.

EARLY EXPLORATION METHODS

Surface Indications

The history of oil exploration in the United States dates from the discovery of the Drake well in 1859. This well was drilled in proximity to oil seepages; for many years afterward seepages of oil actually were an important, and probably the most important, factor considered in drilling for oil. Other surface indications that helped the early prospector were gas and salt-water seepages, deposits of asphalt, paraffin waxes, bituminous outcrops, and the presence of burnt-out shales. Although these indications generally were reliable means of determining the presence of petroleum in the associated strata, they did not offer conclusive evidence that it existed in commercial quantities.[10] Moreover, localities where surface indications were to be found were limited, and prospectors soon were forced to seek oil in localities that had the same general appearance as those that had proved productive. In the absence of any appreciable geologic knowledge, the criterion was chiefly topographic. As a result exploration sometimes was carried on in areas where the sedimentary beds were shallow or where the formations were pre-Cambrian, crystalline-metamorphic, or igneous rocks - formations now known to be unproductive of oil.

Apart from surface indications and topographic features, which for the most part were helpful, the early prospectors frequently were governed by other considerations that often

[10] H. C. Miller and B. E. Lindsly, "Report on Petroleum Production and Development," *Petroleum Investigation* (U. S. Congress, House of Representatives, Hearings on H. Res. 441, 73d Cong., Recess, 1934), part 2, p. 1109.

impeded discovery. At first the general impression prevailed that there was a definite relationship between the course of the streams on the surface and oil underground. Consequently, for several years after the Drake discovery the drilling of wells was confined almost exclusively to the beds or valleys of streams.[11] This notion was upset, however, when one adventurous prospector found oil by drilling a well with a derrick perched on a hilltop. A period followed in which the art of discovery was fitted out with all the trappings of an occult science; witch sticks, necromancy, sorcery, divining rods, and even an occasional fervent prayer to Providence were from time to time regarded as reliable means of finding oil.

Meanwhile, however, considerable knowledge was being developed as a result of these early drilling activities regarding geologic structures that were favorable to petroleum and natural-gas accumulations.

Rising Importance of Geology

Although the theory explaining the occurrence of oil and gas in anticlines and domes was developed by T. Sterry Hunt as early as 1861,[12] it won little or no credence among oil operators. Not even the revival of the theory 20 years later by I. C. White and its endorsement by most geologists made an appreciable impression upon the producers, who continued to rely largely upon clairvoyants, spiritualists, "doodle-bugs", and dreams until after the turn of the century.[13]

One reason for the tardiness with which the industry turned to geology was that for many years the geologists failed to recognize that other structural forms besides the anticline favored the accumulation of oil and gas. These other structures include monoclines, synclines, domes, and lenses of coarse sand in beds of shale.[14] Consequently, when random

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[11] R. Arnold and W. J. Kemnitzer, *Petroleum in the United States and Possessions* (1st ed.; New York: Harper & Bros., 1931), p. 24.

[12] "Notes on the History of Petroleum or Rock Oil," *The Canadian Naturalist and Geologist*, Vol. VI, No. 4 (Aug. 1861), pp. 245-55.

In 1842, prior to Hunt's clear statement of the anticlinal theory of the accumulation of petroleum, William Logan observed the occurrences of oil in anticlines near Gaspé and in 1860 H. D. Rogers noted that the newly discovered fields in Pennsylvania were located on anticlines. See H. D. Miser, "Our Petroleum Supply," *Journal of the Washington Academy of Sciences*, Vol. 29, No. 3 (Mar. 15, 1939), p. 97.

[13] D. White, "Geology and Occurrence of Petroleum in the United States," *Petroleum Investigation* (U. S. Congress, House of Representatives, Hearings on H. Res. 441, 73d Cong., Recess, 1934), part 2, pp. 893-4.

[14] Miller and Lindsly, *op. cit.*, pp. 1108-9.

drilling repeatedly found oil in areas where the anticlinal theory did not apply, the geologists generally were discredited. Largely on this account comparatively few geologists were employed by producing companies prior to 1900. The research work of the geologists continued, however, and as the anticlinal theory gradually was augmented by the structural theory that did not limit accumulations to anticlines, geology gained in prestige. By 1908 some of the more important companies were employing geologists, and by 1920 most of the principal producers and an increasing number of the smaller operators considered geologists an essential part of the operating staff.

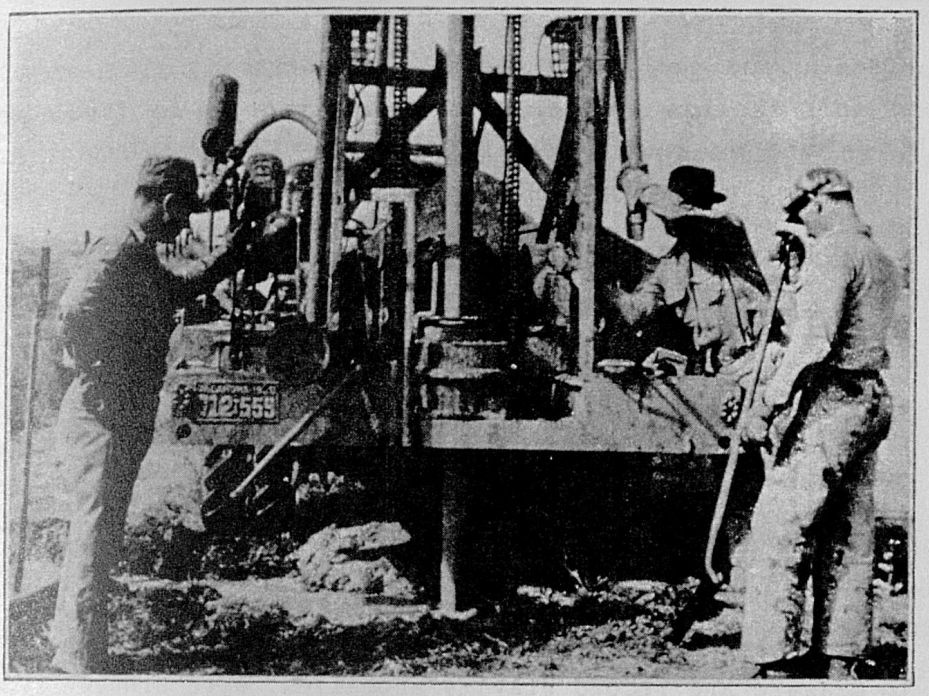
Geologic Mapping

Although geologists were for the most part disregarded, early exploration was aided to some extent by the development of a method of geologic mapping. By means of the plane table and alidade the topographic features of large areas were determined, and by comparing the surface structure of unproved areas with those of productive fields a number of important discoveries were made. Such fields as Humble, Jennings, and West Columbia were found on the basis of these criteria. Structure contouring did not become a factor of great importance in discovery, however, until after the turn of the century.[15]

MODERN EXPLORATION AND DISCOVERY METHODS

In the last decade and a half the art of discovery in the oil and gas industry has virtually been remade. By the end of the World War localities where there were surface indications of oil and gas had for the most part been prospected thoroughly, and it was relatively clear that haphazard methods of exploration were failing to keep pace with the growth of demand. As already noted, prices of crude oil at the wells rose from an average of less than $1 a barrel in the years immediately preceding the war to an average of $3.07 a barrel in 1920. Stimulated by the high prices, the principal producing companies hastily recruited large staffs of geologists. Their remarkable performance is attested to by the rapid succession

[15] White, *op. cit.*, p. 886.



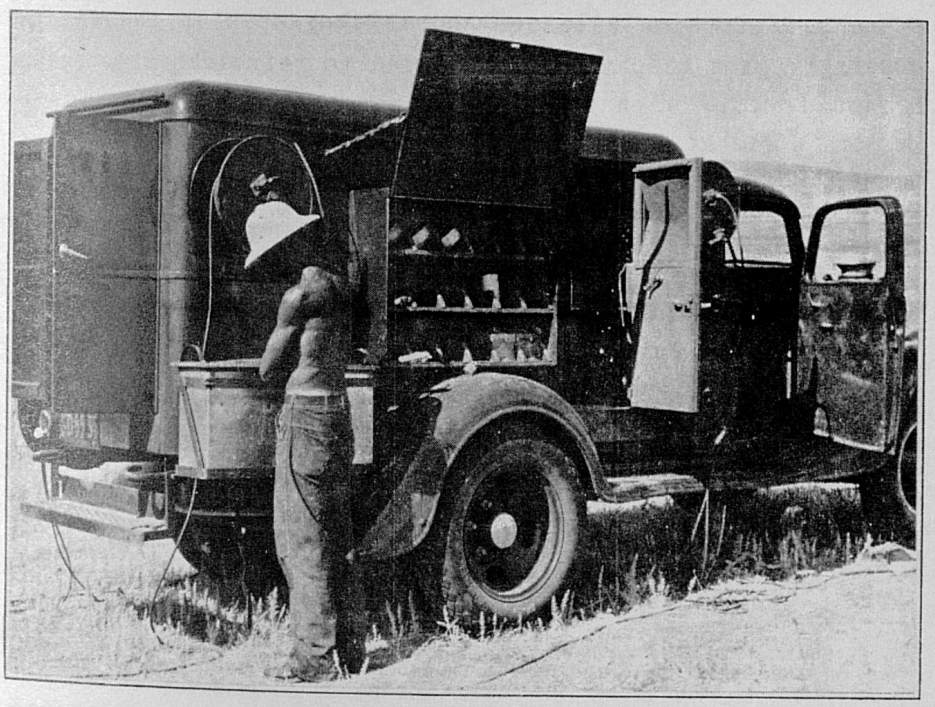


ILLUSTRATION 5.— SOME MAJOR STEPS IN EXPLORATION WITH A REFLECTION SEISMOGRAPH

The seismograph drilling crew in the upper view is drilling a hole in which a light charge of dynamite is to be detonated. The shot is fired by a "shooter" who is advised by telephone from the recording truck, usually at a distance of several hundred yards from the shot hole. The seismic waves originated by the blast are reflected by underlying layers of rock and are picked up by receptors and recorded electrically by instruments in the recording truck shown in the bottom view. The geophysicist studies the data thus obtained and from them seeks to understand the underlying geological structures.

of major oil pools that they have discovered. As a result of this success the geologists - reinforced by knowledge of seismic and other geophysical phenomena, micro-paleontology, and aerial photography - today are entrenched firmly in the petroleum industry.

Development of Geophysics

As its name implies, the science of geophysics concerns the physics of the earth. Geophysical instruments are used to determine the physical properties of subsurface formations and were first applied in the discovery of bodies of iron ore.[16] The refraction seismograph, which employs the principle of determining the velocity of sound (actually the shock or compressional wave) in subterranean rock strata, was introduced in the Gulf Coast field in 1923.[17] Torsion balances, used to measure and record gravity anomalies, were brought into the coastal region in the latter part of 1922. The immediate success of torsion balances and seismographs in the coastal country[18] gave geophysics as applied to petroleum prospecting a firm footing with the oil companies of the United States and the world at large.

Experiments with the reflection seismograph, which virtually has replaced more expensive refraction methods, were being conducted as early as 1926. By this means sound waves are directed vertically or nearly vertically downward into the earth, and seismic records of the returning "echoes" are made. By properly identifying these echoes from station to station, knowledge of the depth of the reflecting bed is obtained. Reflection seismograph investigations remained in the experimental stage for 2 or 3 years, but numerous structural discoveries have been made by this method since 1930. The discovery and development of the Hastings oil field

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[16] K. C. Heald, "The Technique of Exploration," *Technology and the Mineral Industries* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-1, Apr. 1937), p. 8.

[17] For a detailed historical summary of the introduction of geophysical methods in the United States see D. C. Barton, "Applied Geophysical Methods in America," *Economic Geology*, Vol. XXII, No. 7 (Nov. 1927), pp. 649-68. See also J. B. Eby, "Geophysics - Its Application to Petroleum Prospecting," *The Petroleum Engineer*, Vol. VIII, No. 5 (Feb. 1937), pp. 113-34.

[18] The success of geophysics in the coastal country from 1922 to 1931 is discussed in considerable detail in a paper by J. B. Eby, "The Economic Relation of Geophysics to Geology on the Gulf Coast," *Economic Geology*, Vol. XXVII, No. 3 (May 1932), pp. 231-46.

in December 1934 and of the Anahuac oil field in March 1935 brought the method into prominence.

Other methods of geophysical exploration that have had considerable or partial success in the exploration for oil fields in the United States include the gravitometer, the magnetometer, and various types of electric earth-resistivity apparatus. The reflection seismograph, however, is at present by far the dominant method, and its use apparently continues to increase.

Aerial Photography

Improvements in mapping methods since 1920 have been greater than in the entire previous history of the industry, owing largely to the introduction of aerial photography, a technique developed by army fliers during the World War. Large areas can be mapped more quickly, more cheaply, and in more useful detail by this means than by any other method or combination of methods. The speed and low cost of the method are suggested by the fact that the entire State of Connecticut was photographed in about 150 flying hours.

Many topographic details are disclosed by airplane photographs that often cannot be discovered by any other means, even direct observation. Aerial maps made from photographs reveal many structural features, such as faults and other details, that otherwise would escape the attention of the geologist.[19] Mapping by plane table has continued, but less extensively than formerly, because aerial photographs - in presenting a direct picture of the terrain - usually make it possible for the geologist to establish his position relative to the objects on the ground. These may be located by other means of surveying. Thus, surveying continues as a necessary supplement to much aerial mapping, particularly for such purposes as tracing beds of rock having a small angle of dip in areas of slight topographic relief. Platting by means of the stereocomparator, and especially the stereocartograph, originally developed in Europe, has been introduced in this country and has resulted in more precise maps than were formerly feasible.

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[19] Miller and Lindsly, *op. cit.*, p. 1110.



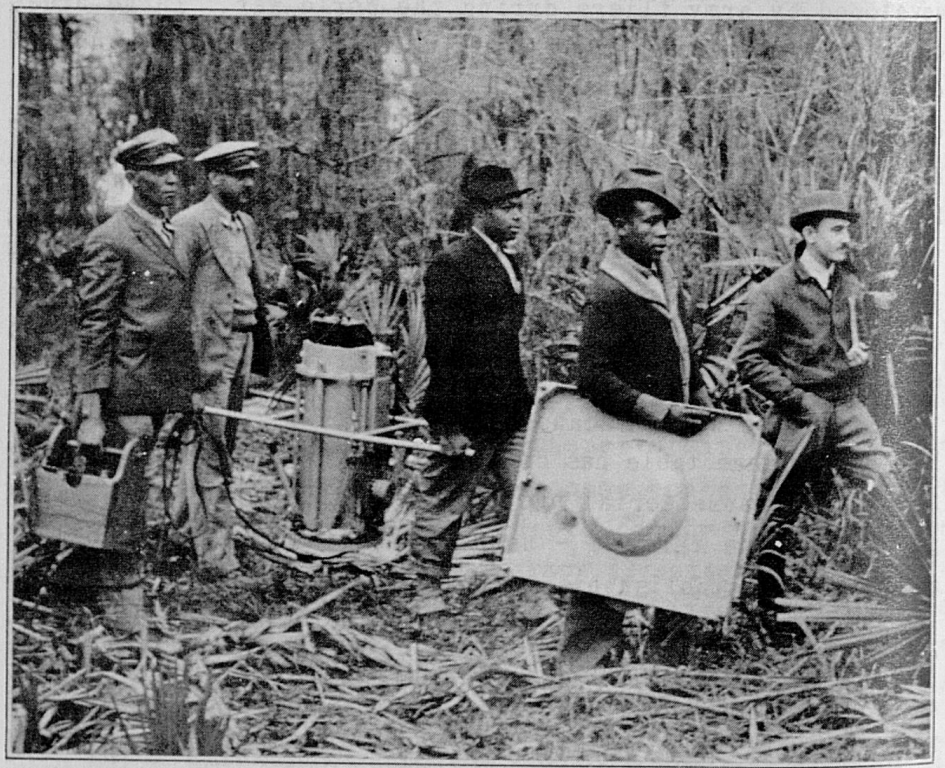


ILLUSTRATION 6.— GEOPHYSICAL EXPLORATION IS CONFRONTED WITH UNUSUAL DIFFICULTIES IN AREAS WHERE THE TERRAIN PRESENTS SPECIAL OBSTRUCTIONS

The upper view shows two "marsh buggies" traveling in 8 to 10 feet of water. They are special transportation units, with inflated tires approximately 10 by 3 feet in size, developed to aid geophysical exploration work in the marshy areas of the Gulf coast. These unusual vehicles are equipped to travel either on land or water. The lower view shows a gravimeter being transported by manpower in a Louisiana marsh area. This picture was kindly supplied by the American Askania Corp.

Paleontology Turned to Practical Account

Discovery also has been aided materially by making use of stratigraphic data from cores and other samples. In this, great credit is due economic paleontologists. Their work has increased greatly the knowledge of stratigraphy without which many producing areas would not have been discovered and many more would have been developed improperly. The growing importance of this work is indicated by the fact that in 1935 about 100 full-time paleontologists and assistants were employed in the California fields alone, whereas in 1920 there were none. Although exploration is the principal beneficiary of the application of paleontology, the latter has also contributed to development work. Electric logging methods,[20] however, have made paleontology somewhat less important in this field.

ACHIEVEMENTS OF SCIENTIFIC EXPLORATION

The achievements of scientific exploration methods can be demonstrated by classifying oil fields according to whether the discovery wells were located on the basis of geological or geophysical work or whether they were simply the result of random drilling (the last term is used in this report to mean the location of exploratory wells without the benefit of technical advice). The accompanying analysis presents such a classification for oil fields discovered in the United States from 1922 to 1938, inclusive. Before the data are examined in detail, however, it should be noted that the use of the term "discoveries" is confusing, for oil reserves have also risen in consequence of such other factors as lateral and vertical extensions of old fields and increases in the recovery factors applicable to old areas.[21] For the purposes of this discussion, a discovery is the finding of a new oil-producing area; deep-sand production obtained by deeper drilling in older fields - irrespective of the importance of the new development - is not considered a new discovery but is used to revise the estimate of ultimate production from the older field. Consideration by method of discovery is limited further

[20] See pp. 105-7.

[21] N. Ely, "The Conservation of Oil," *Harvard Law Review*, Vol. LI, No. 7 (May 1938), p. 1211.

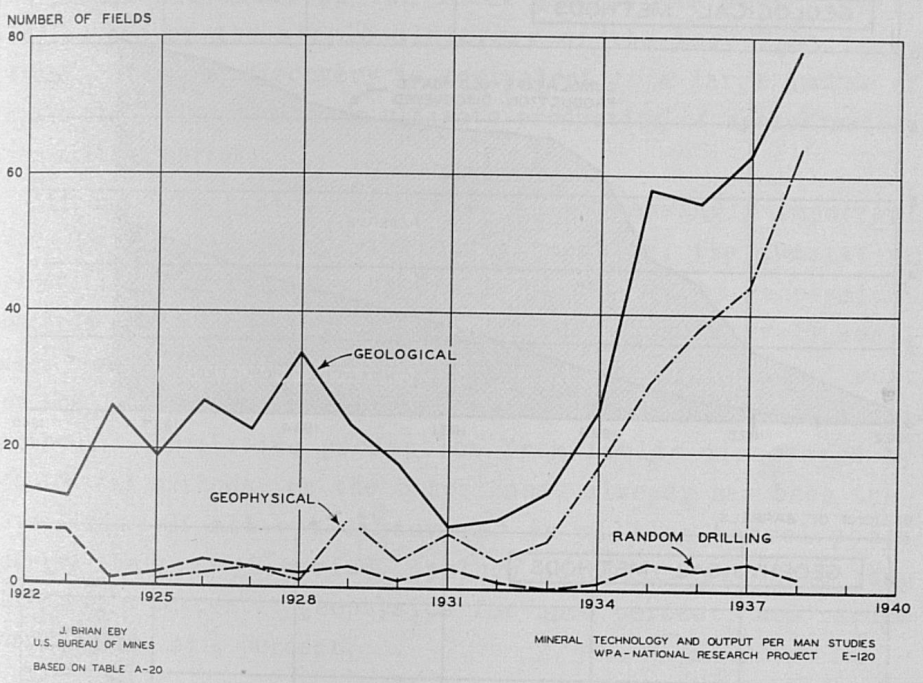
to those oil fields for which the potential output is estimated at a million barrels or more.

With reference to the finding method credited with the discovery of each field, it is recognized that there are instances where the dominant factor in bringing about a specific discovery cannot always be distinguished clearly; an attempt to earmark the method primarily responsible for finding every oil field must of necessity be somewhat arbitrary. For this reason the views of both geologists and geophysicists were solicited in classifying the different fields, and mention of a few fields will illustrate the classification employed. Geology is given credit for discovery of the Van and Yates pools in Texas; Oklahoma City and Seminole in Oklahoma; Ritz-Canton in Kansas; Rodessa in Louisiana; Kettleman Hills, Dominguez, and Inglewood in California; Cutbank in Montana; Oregon Basin in Wyoming; and Iles in Colorado. Geophysics was given credit for discovery of the Iowa, Hastings, Anahuac, Thompsons, and Tomoconnor pools in the Louisiana-Texas Gulf Coast and Monument in New Mexico. As already noted, the term "wildcat" is used in this discussion to denote any exploratory well in unproved territory, regardless of the reasons for its specific location; the less inclusive term "random drilling" is used here to describe the drilling of exploratory wells without the benefit of technical logic, a practice that is also sometimes improperly called "wildcatting" to the exclusion of other methods of locating exploratory wells. Random drilling is credited with the discovery of the East Texas, Conroe, and Hendricks pools in Texas and Smackover in Arkansas.

Contribution of Various Methods of Discovery to Production and Reserves

From the beginning of 1922 to the end of 1938, 796 oil fields that rated more than a million barrels of recoverable oil were discovered in the United States. These fields have been classified on the basis of whether geology, geophysics, or random drilling was primarily responsible for their discovery. The number of discoveries made each year by the different methods is indicated by figure 13, showing that the number of major oil fields found by scientific knowledge far exceeds those found by random drilling and that the importance of scientific methods has increased enormously in recent years.

Figure 18.- NUMBER OF MILLION-BARREL OIL FIELDS, BY METHOD OF DISCOVERY, 1922-38

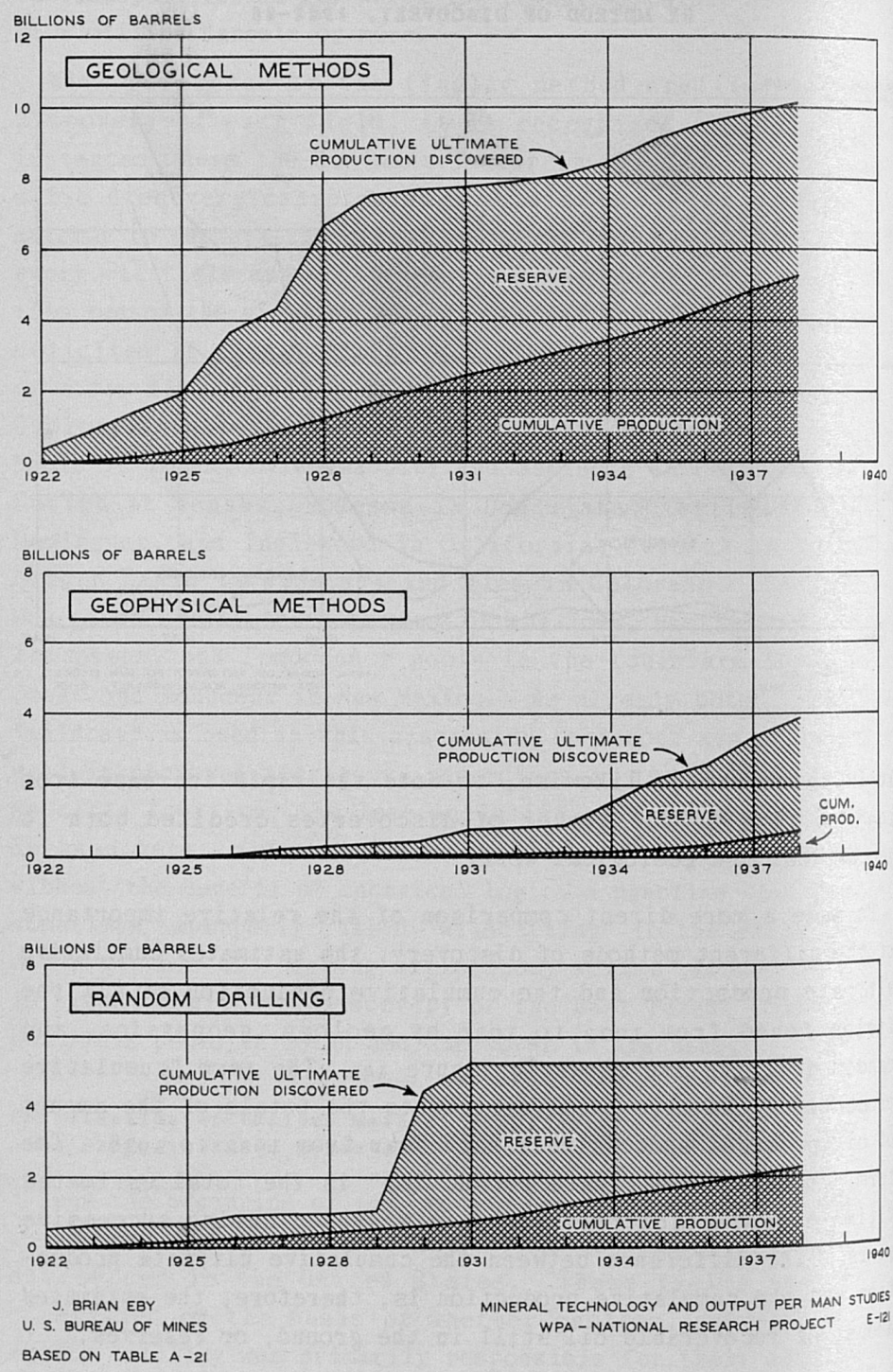


It is interesting, likewise, to note the rapid increase from 1933 to 1938 in the number of discoveries credited both to geophysical and geological work.

To make a more direct comparison of the relative importance of the different methods of discovery, the estimated cumulative ultimate production and the cumulative production of all the fields found from 1922 to 1938 by geology, geophysics, and random drilling are shown in figure 14. The term "cumulative production", as here used, represents the totals of the amount of oil produced successively each year from 1922 to 1938. The term "cumulative ultimate production" is the total estimated ultimate production from fields discovered during successive years. The difference between the cumulative ultimate production and the cumulative production is, therefore, the estimated amount of recoverable oil still in the ground, or reserves.

The upper graph of figure 14 shows that geologically discovered oil reserves rose rapidly from 1922 to 1929 and have approximately kept pace with withdrawals between 1929 and 1938. With the finding of Anahuac and Hastings and several other smaller but highly important oil fields by geophysics, reserves

Figure 14.- CUMULATIVE PRODUCTION AND CUMULATIVE ULTIMATE PRODUCTION OF MILLION-BARREL OIL FIELDS, BY METHOD OF DISCOVERY, 1922-38



J. BRIAN EBY
U. S. BUREAU OF MINES
BASED ON TABLE A-21

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credited to geophysical methods increased considerably between 1933 and 1938 (see middle graph). The contribution of random drilling, indicated in the lower graph, has been greatly influenced by the single discovery of the huge East Texas field. This one discovery is equivalent to a large number of small fields, each with an ultimate production of approximately 100 million barrels.

Although geophysics has played an increasingly important role in discovery since the early twenties, the cumulative production accounted for by fields discovered by geophysical methods down to the end of 1938 has been comparatively small (see figure 14). This is due in part to the proration of most of the larger fields found in recent years by geophysical methods. Cumulative production from fields discovered by geological methods, on the other hand, already has been substantial. Of all oil discovered in million-barrel pools during the 1922-38 period, geology accounted for more than half (52.6 percent); geophysics for 20.0 percent; and random drilling for 27.4 percent.

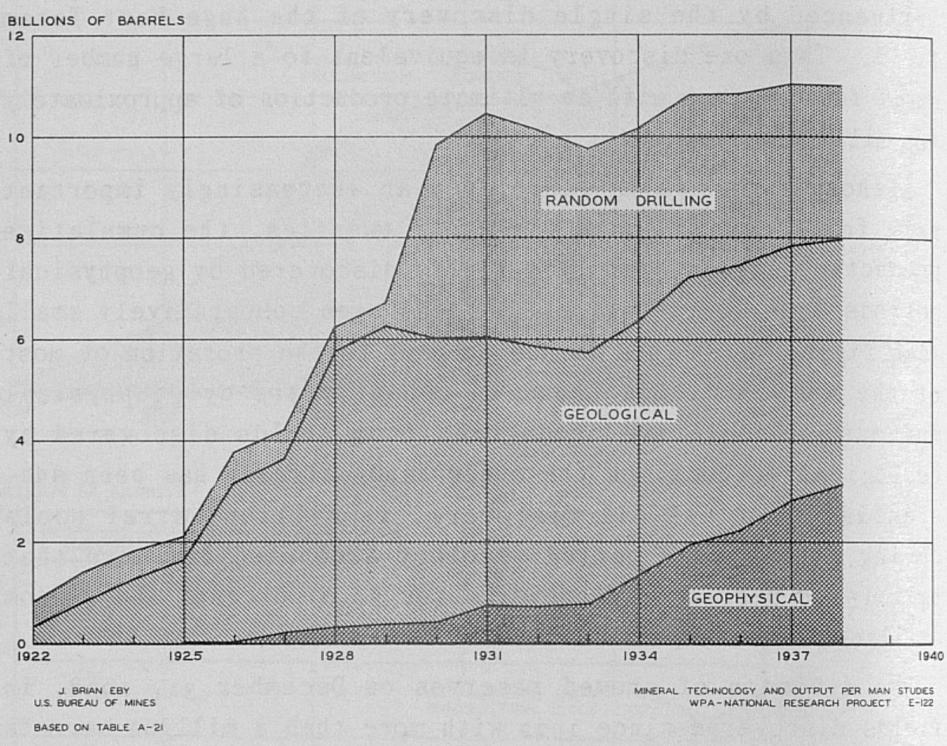
The division of proved reserves on December 31, 1938, in fields discovered since 1922 with more than a million barrels of ultimate production indicates that geology was responsible for 44.1 percent, geophysics for 28.5 percent, and random drilling for 27.4 percent. Figure 15 demonstrates that total reserves in million-barrel fields have not been increased notably since 1930. Rapidly growing cumulative demand has just about kept pace with increasingly successful exploration technology.

Although it is true that neither geology nor geophysics has advanced to a point where the presence of oil in commercial quantities can be determined without actually completing a well, the newer scientific techniques of exploration have greatly enhanced the chances for success, once drilling is undertaken. This is demonstrated conclusively by Lahee's studies of exploratory wells drilled in unproved territory in 1937 and 1938, indicating that locations based on technical advice were at least three times as successful as locations made without such advice.[22]

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[22] F. H. Lahee, "Further Data on Wildcat Drilling in 1937," *Bulletin of the American Association of Petroleum Geologists*, Vol. 22, No. 9 (Sept. 1938), p. 1235 and "Wildcat Drilling in 1938," *The Oil and Gas Journal*, Vol. 37, No. 45 (Mar. 23, 1939), p. 46.

Figure 15.- RESERVES AT THE END OF EACH YEAR IN FIELDS WITH MORE THAN A MILLION BARRELS OF ULTIMATE PRODUCTION, BY METHOD OF DISCOVERY, 1922-38



Cost and Employment Involved in Finding Oil

It has been estimated that 200 to 300 million dollars have been spent annually during recent years in the search for new oil pools.[23] Information on the amounts spent by producing companies in finding oil is fragmentary, however, and data covering the cost of different types of geophysical exploration in the years 1934-38 presented in figure 16 are of special interest.

Over the 5-year period the outlay for geophysical field crews engaged in exploration was about 77 million dollars. Nevertheless, this amount is not the total cost of the work, for it does not include the expenses of staff overhead, geophysical research, leasing or drilling developments, or seismic damage claims as a result of geophysical operations. It is also roughly estimated that over the same 5 years approximately 54 million dollars were spent in strictly geological exploration.

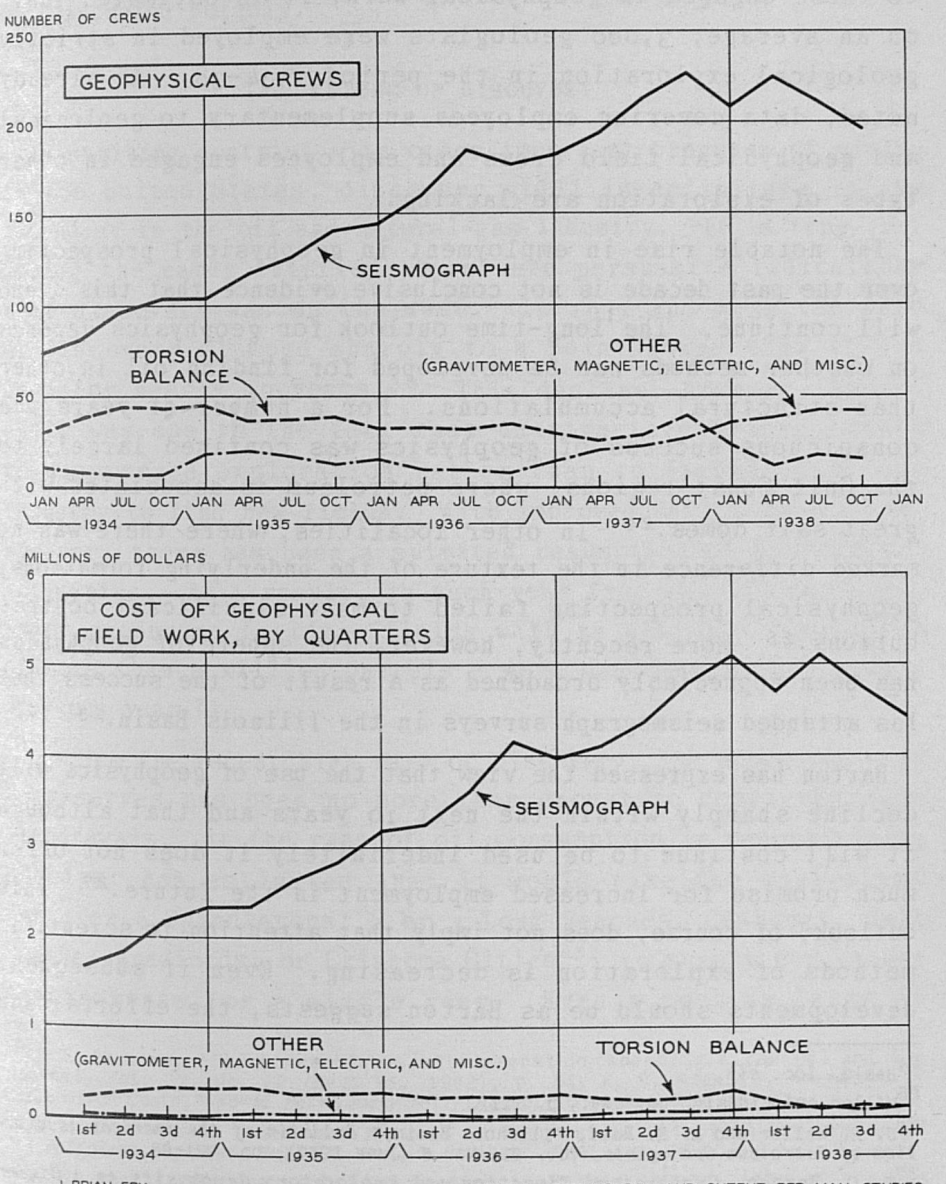
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[23] American Petroleum Institute, Special Committee on Petroleum Production and Supply, J. E. Pew, chmn., "Petroleum Production and Supply," *Bulletin of the American Association of Petroleum Geologists*, Vol. 20, No. 1 (Jan. 1936), p. 7.

This figure is comparable with the outlay for geophysical work noted above. An overwhelming proportion of the amount required for geophysics has been spent for seismographic work.

Adequate figures on employment in exploration are also lacking. Employment in geophysical exploration from 1934 to

Figure 16.- NUMBER OF GEOPHYSICAL CREWS AND COST OF GEOPHYSICAL FIELD WORK FOR PETROLEUM EXPLORATION IN THE UNITED STATES, 1934-38



J. BRIAN EBY
U.S. BUREAU OF MINES

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
WPA-NATIONAL RESEARCH PROJECT E-123

BASED ON TABLES A-22, A-23

1938, however, is reflected quite accurately by the trend in the number of geophysical crews at work, as shown in figure 16. These data are also interesting because they are separated for the different types of geophysical exploration. In the period covered, employment reached a maximum in October 1937, when 226 seismograph crews were in the field, with an average of 12 field employees per crew. In April 1938, 225 seismograph crews were active, but since that date there has been a definite reduction in the number of parties operating. In addition to those engaged in geophysical work, it is estimated that, on an average, 3,000 geologists were employed in strictly geological exploration in the period 1934-38. As already noted, data covering employees supplementary to geological and geophysical field crews and employees engaged in other types of exploration are lacking.

The notable rise in employment in geophysical prospecting over the past decade is not conclusive evidence that this trend will continue. The long-time outlook for geophysics depends on whether methods can be developed for finding oil in other than structural accumulations. For a number of years the conspicuous success of geophysics was confined largely to the Gulf Coast regions, where petroleum is associated with great salt domes.[24] In other localities, where there was no marked difference in the texture of the underlying formations, geophysical prospecting failed to make significant contributions.[25] More recently, however, the sphere of geophysics has been appreciably broadened as a result of the success that has attended seismograph surveys in the Illinois Basin.[26]

Barton has expressed the view that the use of geophysics will decline sharply within the next 10 years and that although it will continue to be used indefinitely it does not offer much promise for increased employment in the future.[27] This outlook, of course, does not imply that attention to scientific methods of exploration is decreasing. Even if subsequent developments should be as Barton suggests, the efforts made

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[24] Heald, *loc. cit.*

[25] Miller and Lindsly, *op. cit.*, p. 1111.

[26] J. M. Weller and A. H. Bell, "Illinois Basin," *Bulletin of the American Association of Petroleum Geologists*, Vol. 21, No. 6 (June 1937), pp. 771-88.

[27] D. C. Barton, *Geophysical Education and Exploratory Geophysics As a Career* (American Institute of Mining and Metallurgical Engineers, Tech. Pub. No. 950-V, Aug. 1938), p. 1; see also National Youth Administration of Texas, J. C. Kellam, Director, *Employment Opportunities in the Oil Industry in Texas* (Austin, Tex.: Industrial Study No. 1, mimeo., Sept. 1, 1938), pp. 14-5.

in scientific exploration would doubtless continue to increase. Already attention has been called to several interesting possibilities, including more adequate stratigraphic studies[28] and soil analysis.[29] Whether the suggestions made up to the present will be those that lead to needed new discoveries only the future can disclose. There appears, however, to be no uncertainty in the fact that an ever-widening variety of scientific techniques will be used in future exploration and that the aggregate employment for this purpose probably will increase notably.

FUTURE OF DISCOVERY

In striking contrast with other important branches of mining in the United States, discovery still is definitely in the ascendant in the oil and natural-gas industry. It is true that during the early thirties there were persuasive indications that discovery was on the wane. In 1931 and 1932 the rate of discovery slumped sharply to a point lower than it had been for nearly 20 years.[30] This decline, however, apparently was due to the fact that unattractive prices tended to discourage exploration rather than to inability of the industry to find new fields. With improved market conditions, however, there has been a spirited resumption of exploration activities. As a result, in each year from 1935 to 1938 more major producing fields - fields with an ultimate production of more than a million barrels - were discovered than in any previous year.[31]

Despite the recent high rate of discovery, the accretion made to reserves has been no more than enough to counterbalance withdrawals. At the rate of oil consumption in recent years, DeGolyer has estimated that it would take the equivalent "of 5 or 6 Spindletops; 2 or 3 Long Beaches, Cushings, Salt Creeks, Bradfords, or Oklahoma Cities"[32] to supply our market requirements for a single year. Even a pool as large as

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[28] E. E. Rosaire, "Stratigraphic vs. Structural Prospecting," *The Oil and Gas Journal*, Vol. 37, No. 32 (Dec. 22, 1938), p. 54; E. E. Rosaire, "Paradox of Exploration Costs," *World Petroleum*, Vol. IX, No. 10 (Oct. 1938), p. 39.

[29] J. B. Eby, "Newer Trends and Methods in Geophysical Petroleum Exploration," *The Petroleum Engineer*, Vol. IX, No. 10 (Midyear 1938), pp. 37-40.

[30] W. E. Pratt, "Future of Oil in America as Viewed in the Light of Present Developments," *The Oil and Gas Journal*, Vol. 34, No. 16 (Sept. 5, 1935), p. 25.

[31] See table A-20.

[32] E. DeGolyer, "Future of Petroleum Exploration in United States," *Bulletin of the American Association of Petroleum Geologists*, Vol. 21, No. 6 (June 1937), p. 706.

East Texas is capable of satisfying current market requirements for no more than 3 or 4 years. How long can we expect to find new pools large enough to replace the production of the dead and dying fields? Are there more East Texas, Seminole, Yates, Kettleman Hills, and Conroe fields still undiscovered? If so, where are they likely to be found? These are critical questions upon which the future of the industry hinges.

Chances of Random Drilling

The prospects of important contributions to reserves being made in future by old-time random drillers who locate wells without the benefit of technical advice are not encouraging. As already noted, virtually all discoveries before the turn of the present century either resulted from elementary surface indications of the presence of oil or gas or from random drilling with no criteria that warranted exploration. Between 1930 and 1938, by contrast, less than 4 percent of the million-barrel fields found were discovered by these methods. The areas where obvious surface indications are present have been thoroughly prospected, and it is noteworthy that during the 5 years 1931-35 not a single major oil pool was discovered as a result of wells drilled in the vicinity of obvious surface indications.[33] In the absence of these guides random exploration is seriously handicapped.

Another obstacle to small independent operators and to wildcatters who drill without detailed knowledge of subsurface conditions is that in most of the areas that now offer the greatest promise for discoveries of considerable magnitude, the oil horizon lies at depths that involve huge expenditures for development and operation.[34] Over so short a span as the past 4 years the average depth of wildcat holes increased from 3,540 feet in 1935 to 4,132 in 1938.[35]

Although the outlook for the random-drilling type of exploration is not promising, the possibility of new major discoveries being made by this method of exploration cannot be dismissed. Even within the past decade the random driller has ventured into areas discounted by the geologists and has found pools

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[33] W. E. Pratt, "Discovery Rates in Oil Finding," *Bulletin of the American Association of Petroleum Geologists*, Vol. 21, No. 6 (June 1937), p. 700.

[34] National Resources Board, *loc. cit.*

[35] Lahee, "Wildcat Drilling in 1938," p. 46.

of major importance, such as Hendricks, Smackover, East Texas, and Conroe. As long as such successes as these are achieved, random drilling remains a factor to be considered in oil and gas exploration.

Prospects for Scientific Exploration Methods

Notwithstanding the occasionally brilliant successes of random drilling, geology, aided by its allies, geophysics and paleontology, appears to have the most inviting future prospects. In fact, the potentialities of highly specialized sciences when used in conjunction with one another upon oil exploration are now generally appreciated. Since it is expected that further progress will be made in adapting science to the task of oil exploration, discovery is not expected to end abruptly in the near future.

Will the discoveries of the future be large enough to supply our national requirements? How long can we continue to find oil at the rate of a billion barrels a year and natural gas at the rate of somewhat more than 2 trillion cubic feet a year? To meet this demand we need more great pools like Midway-Sunset, Seminole, and East Texas. Some observers doubt whether more pools comparable with these in size will be found, and it is certainly true that in the past similar discoveries have been made infrequently. Other observers, although agreeing that major discoveries cannot be projected indefinitely into the future, believe that we may safely count on further great additions to reserves as a result of outstanding discoveries. The existence of large pools remaining to be discovered plus the continued refinement of prospecting techniques are two major postulates, frequently unstated, to the latter view.

The more hopeful outlook is supported primarily by the fact that although whole regions have been eliminated as possible sources and many other parts of the country have been so thoroughly prospected and developed that there is virtually no possibility of future discoveries of importance,[36] there remain large areas underlain with sedimentary rocks that have been inadequately explored.[37] Indeed, there are some sections, such as the Gulf Coast of Mississippi, Alabama, and western

[36] National Resources Board, *loc. cit.*

[37] American Petroleum Institute, Special Committee on Petroleum Production and Supply, *op. cit.*, p. 8.

Florida and the Plains area north of the Texas Panhandle, that are still almost virgin territory.[38] Likewise, there are the deep formations in a number of the present producing fields as well as in localities where neither oil nor gas is now being produced that remain to be explored.[39] It is recognized, however, that structural traps (anticlines, domes, and faults), which in the past have been virtually the only geological guides in oil and gas discovery, are definitely limited in number.[40] Even those that are still untested are rapidly being found as a result of recent developments in seismic methods, and within a few years all the structural accumulations that can be located by prevailing techniques probably will have been found.[41] In consequence, the chances for new major discoveries appear to depend principally on our ability to find oil and gas in other types of accumulations.

Although the search of geologists for new production has been confined almost exclusively to the location of closed structures, approximately a third of the oil that has been produced in the United States has come from pools of the stratigraphic type.[42] Of the 22 most important oil fields that have been discovered in this country thus far, 9 have been fields in which the chief trap-forming element was a stratigraphic change from porous to nonporous conditions within the reservoir rocks.[43] These fields are the Midway-Sunset, Coalinga, and Kern River in California; Glenn, Burbank, and Bristow-Slick in Oklahoma; East Texas in Texas; Smackover in Arkansas; and Bradford in Pennsylvania. Not only were all of these found as the result of random drilling, but none of them could have been discovered through the application of the structural theory.[44] Partly because of the growing recognition of this fact and partly because of the increasing difficulty of finding unexplored structural traps, it seems certain

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[38] C. Goodrich, B. W. Allin, and Others, *Migration and Economic Opportunity* (Philadelphia, Pa.: University of Pennsylvania Press, 1936), pp. 258-9.

[39] K. C. Heald, "Deep Well Drilling Problems and Their Solution," *The Oil Weekly*, Vol. 81, No. 13 (June 8, 1936), p. 20.

[40] A. I. Levorsen, "Stratigraphic versus Structural Accumulations," *Bulletin of the American Association of Petroleum Geologists*, Vol. 20, No. 5 (May 1936), p. 523.

[41] "I. P. T. Is Told Future Geological Data to be Secured by Exploratory Wells," *The Oil and Gas Journal*, Vol. 35, No. 1 (May 21, 1936), p. 27. This statement was reported from an address of E. DeGolyer made at a dinner of the Institution of Petroleum Technologists, Tulsa, Oklahoma, May 15, 1936.

[42] Levorsen, *op. cit.*, p. 524.

[43] *Ibid.*, p. 525.

[44] *Ibid.*

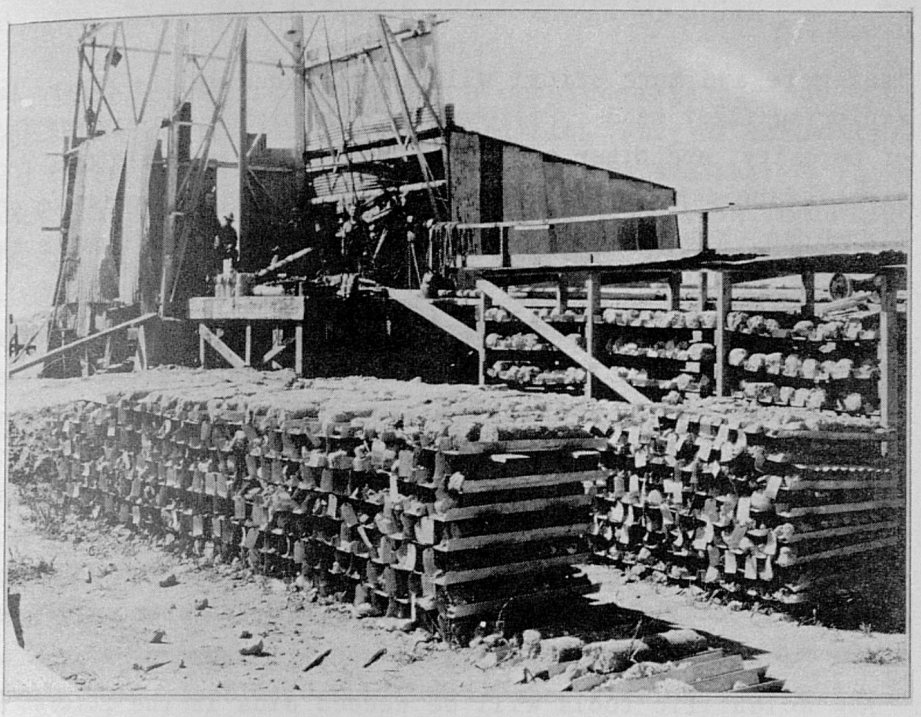




ILLUSTRATION 7.- CAREFUL STUDY OF DRILL CORES IS AN IMPORTANT SOURCE OF VALUABLE INFORMATION REGARDING POTENTIALLY PRODUCTIVE FORMATIONS

Four thousand feet of large-diameter cores of formations penetrated in drilling a well for exploratory purposes only are shown in the upper view. Each section of core is carefully labeled and is examined for identification by paleontologists and geologists. The lower view shows the careful attention given to cores at a regular drilling operation. Immediately upon being withdrawn from the hole, sections of the core are placed in sealed containers, properly labeled, and are then taken to a nearby field laboratory for preliminary study, usually followed by detailed analysis at a central laboratory.

that more and more effort will be expended in the future in exploring flank sands, regional unconformities, up-dip wedging of porosity, and other conditions that offer possibilities for stratigraphic accumulations. With the possible exception of Minnesota, Wisconsin, Arizona, and Nevada, conditions such as these exist in most parts of the country.

It is improbable that only a few scientific tools or theories will dominate exploration in the future. An outgrowth of the continued study of conditions under which oil and gas have been found has been broader knowledge of the many different factors concerned in oil and gas accumulation. The trend is definitely toward more complete understanding of the occurrence of oil and gas and toward employment of an ever-widening variety of complicated finding techniques, each with a specific preferred application.

New scientific tools will be needed aids in the future,[45] for rising demand has given technologists a constantly heavier task of finding oil and gas. It is significant that up to 1930 discoveries were more than adequate to provide for a growing production and permitted net additions to reserves. From 1930 to the present, however, new discoveries have just about paced the growth of demand.[46] The maintenance of an expanding output has by itself required a rising number of discoveries, and the range in the annual number of new fields discovered increased from 26 to 51 in the 1922-29 period to a range from 70 to 223 for the years 1934-38 (see table A-20). The general character of changing demand is discussed in chapter XI, so that it suffices here to note that discovery will be appraised as "successful" in the future only if new fields continue to be found in number and size adequate to supply at least the essential needs of an enlarging body of consumers. The task is much greater than simply doing as well as has been done in the past.[47]

Despite the hazards that influence exploration and demand, the authors believe that discovery will continue to meet

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[45] L. G. E. Bignell, "New Methods Required to Find Future Reserves," *The Oil and Gas Journal*, Vol. 36, No. 6 (Dec. 23, 1937), pp. 18-9.

[46] Although there have been recent additions to the indicated proved reserve, one of the main reasons for this has been revision of earlier estimates "brought about by the increased efficiencies of improved technique and delayed production." See J. E. Pogue, *Economics of the Petroleum Industry* (New York: Chase National Bank, Mar. 1939), p. 15.

[47] C. K. Leith, *Mineral Valuation of the Future* (1st ed.; New York: American Institute of Mining and Metallurgical Engineers, 1938), pp. 87-8.

our national requirements for a considerable period. The inevitable increase in the technical efficiency of exploration and the existence of large areas underlain by sedimentary rocks that remain to be more fully explored[48] will be important factors in this development. The discovery of new oil fields with more than a million barrels of ultimate production reached a peak in 1938, and there are no indications that the rate of finding is lagging (see table A-20). Although the short-time outlook is for ample supplies, over the longer view the prospects are tempered by recognition that the area in which new great finds may be made is constantly being narrowed and that many of the new techniques of exploration encounter baffling obstacles of observation and interpretation. Over the very long run, which extends largely beyond the scope of this study, the prospect is one of growing difficulties in which exploration technology will find it more difficult to overcome the handicaps of nature.

Future Employment in Exploration

The point that future employment throughout the oil and gas industry in its present form hinges upon continued success in discovery is noted in chapter XI. Thus the following comments are limited to certain aspects of employment in discovery work only.

Changing techniques of exploration are almost certain to involve much more drilling for discovery, as it will be necessary to drill many wells simply to obtain geological information.[49] The practicability of doing more drilling doubtless will be facilitated by the evolving technique of boring "slim holes" at reduced costs (see pp. 114-5).[50] Such holes may be simply in the nature of "post holes" for exploration purposes[51] or they may be drilled for development and production, as in Illinois fields at present. Increased drilling of this type will supplement regular drilling programs, and it is anticipated that the extra labor required will increase the aggregate number of workers employed in discovery work.

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[48] American Petroleum Institute, Special Committee on Petroleum Production and Supply, *op. cit.*, pp. 8-9.

[49] DeGolyer, *op. cit.*, p. 712.

[50] F. H. Lahee, "Wildcat Drilling in 1937," *Bulletin of the American Association of Petroleum Geologists*, Vol. 22, No. 6 (June 1938), p. 847.

[51] Miller and Lindsly, *op. cit.*, p. 1112.

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[48] American Petroleum Institute, Special Committee on Petroleum Production and Supply, *op. cit.*, pp. 8-9.

[49] DeGolyer, *op. cit.*, p. 712.

[50] F. H. Lahee, "Wildcat Drilling in 1937," *Bulletin of the American Association of Petroleum Geologists*, Vol. 22, No. 6 (June 1938), p. 647.

[51] Miller and Lindsly, *op. cit.*, p. 1112.

Not only will more wage earners be required, but a large expansion is also anticipated in the demand for skilled technicians. First there is likely to be an active demand for experts in stratigraphic analysis. At the same time additional geologists will be needed partly because most wells will be drilled under close geologic supervision and partly because it will be necessary to rework the surface geology of many areas, with the principal emphasis on stratigraphic variations.[52] Finally, the services of specialists in geophysics will be needed,[53] as well as specialists in other branches of science.

Looking ahead, DeGolyer[54] suggests that search for oil in the future will be organized as follows:

> The exploration department of the future will include geological work (subsurface studies, surface studies, stratigraphy, paleontology, geophysics), scouting, engineering, and land leasing, as it does effectively in many of the best organized companies of today; and it will also include organization for the drilling of exploratory wells. Its business will be strictly that of securing oil reserves, and, for greater effectiveness, it will be relieved of all other duties insofar as possible.

The task of providing ample reserves of petroleum and gas is of major importance to the individual company and to the industry, and increased attention to prospecting with greater employment in exploration work may be expected in the future.

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[52] Levorsen, *op. cit.*, p. 529; see also DeGolyer, *loc. cit.*
[53] Levorsen, *ibid.*
[54] DeGolyer, *op. cit.*, p. 711.

CHAPTER V

DEVELOPMENT OF DRILLING TECHNIQUES*

Concomitant with the ability of the petroleum industry to find new flush pools and to migrate to new rich fields, the development of more efficient techniques for drilling wells and for the recovery of oil from producing strata made important contributions to the growth in output per man. The net effect of such technologic victories was to permit the capture of an increasing proportion of the recoverable content of existing reserves with a reduced outlay of human energy per unit of product. The principal technologic advances in drilling and production that contributed to this result are described briefly in this and the succeeding chapter.

Oil-well drilling technology began with the heritage of certain skills developed by artisans engaged in an older industry. Long before the birth of the oil industry, man, in sinking holes into the earth for the production of salt brine, developed boring methods. Their counterparts are found in modern drilling techniques. The early Chinese drillers utilized churn-drilling methods in which simple tools, suspended by a rope from the end of a spring pole, were given an up-and-down churning movement. This primitive method - frequently improved in different ways and varied in adaptation to special drilling conditions - was widely used in the salt-brine industry in the United States as far back as 1806 and in prospecting for minerals at an early date.[1] From this method evolved what is known as the cable-tool system of drilling oil and gas wells.

It is thus true that most of the tools and the basic technique of cable-tool drilling were at hand when "Col." E. L. Drake drilled for oil at Titusville, Pennsylvania, in 1859.[2] The derrick used in drilling this epochal well was constructed

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*By J. S. Ross, Consulting Petroleum Engineer; R. E. Heithecker, Petroleum Engineer, U. S. Bureau of Mines, Bartlesville, Oklahoma; Lew Suverkrop; and O. E. Kiessling.

[1]For a description of the use of the hand churn-drill in hard-rock mining see C. E. Nighman and O. E. Kiessling, "Mineral Technology and Output Per Man Studies: Technologic Progress in Rock Drilling" (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, in preparation).

[2]An account of the drilling of the Drake well and of other early developments in the petroleum industry is given in the Diamond Jubilee of the Petroleum Industry number of *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934).

of pine poles cut from timber near the site. It was 30 feet high, 12 feet square at its base, and 3 feet square at its top. A steam engine of the type then in use on the river steamboats furnished the motive power. The engine was provided with a heavy flywheel and a crank was attached at the end of the flywheel shaft. The pitman or connecting link between this crank and the end of the working beam (later known as the walking beam) gave the beam what was called a "grasshopper" motion. The working beam extended through the derrick and was attached to a vertical upright post set outside the derrick. As the crank rotated, the pitman lifted and dropped the end of the beam and gave a churning motion to the tools suspended by the drilling rope attached to the center of the beam. This working beam supplanted the old spring pole. In later practice its center was supported by a "sampson post", and the drilling rope was suspended from the end of the walking beam.

The pulleys and sheaves, and their shafts, were hand-fashioned from wood, as was most of the other equipment used by the early pioneers. The light iron tools, consisting of the drilling bits, jars, reamer, and bailer, as well as the light "rig-irons" were forged by local blacksmiths.

Although steam was used for drilling, the drilling tools were run in and out of the hole by manual operation of a hoisting drum, known as the "bull wheel", which was set in the side of the derrick. With this equipment the Drake well was sunk to a depth of $69\frac{1}{2}$ feet. Casing, made of cast-iron pipe, was driven to a hard ledge 39 feet below the surface. From this level to the bottom of the hole the rate of drilling was reported to be 2 to 3 feet a day.

Completion of the Drake well precipitated a frenzy of oil-well drilling that created a heavy demand for labor. Because of the shortage of equipment many of the shallow wells sunk during this period were hand-drilled by the primitive spring-pole method. Although the rapid development had a depressing effect upon the price of oil,[3] drilling continued to expand. Men from all walks of life were attracted, and most of them were unfamiliar with drilling methods. Many of the skilled drillers were recruited from the salt-brine industry; their

[3]The price of oil dropped from about $20 a barrel in August 1859, to 50 cents a barrel in May 1861. See *The Derrick's Hand-Book of Petroleum: Petroleum Developments From 1859 to 1898* (Oil City, Pa.: Derrick Publishing Co., 1898), pp. 706, 712.

helpers, the tool dressers, after serving a period at the latter occupation, became drillers. This system of training men on the job has continued to modern times.

EARLY DRILLING PRACTICES

The early rigs were small, light, and often operated by manpower, for the wells were shallow and drilling was not difficult. Such equipment soon proved inadequate, however, when it became necessary to drill deeper or when more difficult drilling conditions were experienced. Important changes were made as soon as new and better tools were added, rigs were made larger and heavier, and steel replaced wood parts. The steam engine became the universal source of motive power for driving the various pieces of mechanical equipment,[4] such as the band wheel, bull wheel, calf wheel, and sand-line reel, used in drilling and bailing, and for performing other tasks formerly done by hand labor. During the gradual development of the cable-tool method of drilling, the various parts used in the construction of the rigs became standardized, and there evolved what is known today as the American standard cable-tool system.

The cable-tool system of drilling was in general use for nearly half a century after the Drake well and reached its zenith about 1910, when operators began to employ the rotary drill more widely. Although the art of drilling with cable tools underwent progressive development, the essential features of the early practices were retained. It was used most successfully in the comparatively shallow fields of the Appalachian region, where the formations were chiefly indurated shales and hard sandstones, and in certain western and middle

[4] A wooden band wheel, ranging from 9 to 12 feet in diameter, mounted on suitable jack posts, was placed between the engine house and the derrick, and the engine was belted directly to this wheel. A crank on the band-wheel shaft was connected to the power end of the walking beam by means of the pitman, which made possible the up-and-down motion necessary to produce the churning action of the tools suspended on the drilling cable. An endless rope, connected from the band wheel to the bull wheel, transmitted mechanical power for pulling the drilling tools from the hole, an operation formerly performed by hand and foot. Another hoist, called the calf wheel, was installed in the side of the derrick next to the band wheel and connected to it by means of a chain, sprocket, and clutch. A cable was wound on this hoist and was threaded between the sheaves in the crown block in the top of the derrick and the traveling block, thus multiplying the hoisting power for raising and lowering the casing. Behind the band wheel a smaller hoist was mounted on which was spooled the sand line, a smaller cable, used in running the bailer in and out of the hole. This sand reel, as it was called, received its power from a friction pulley, brought in contact with the rim of the band wheel. Even after the introduction of steel drilling lines many drillers preferred and used manila ropes, or "rag" lines, as they were called.

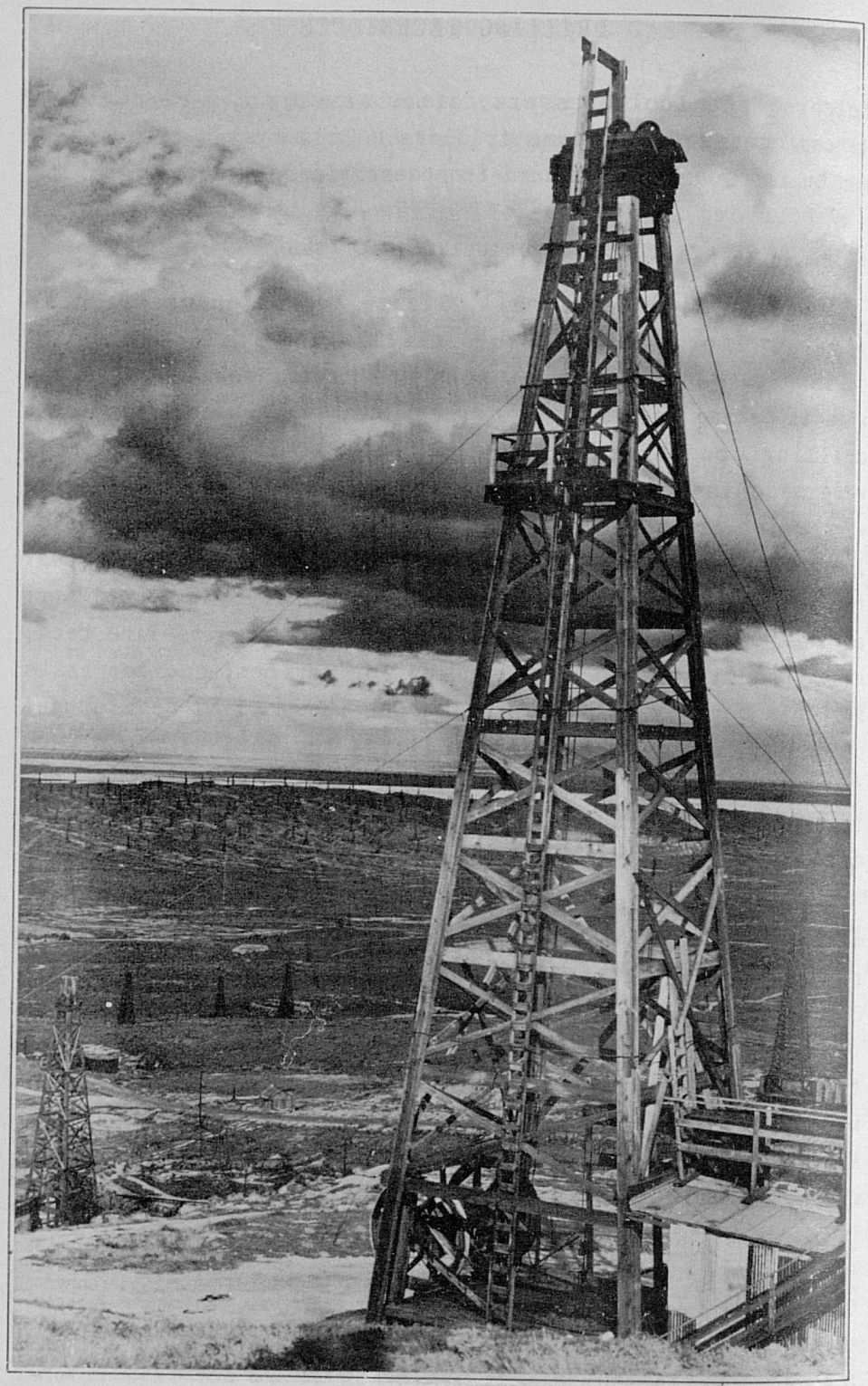


ILLUSTRATION 8.— A WOODEN DERRICK TYPICAL OF THOSE USED FOR CABLE-TOOL DRILLING IN CALIFORNIA ABOUT 1910 TO 1920

This derrick, 84 feet high, is in definite contrast with a recent-type steel derrick shown in illustration 4. The picture was courteously supplied by the Automobile Club of Southern California.

western areas, where relatively shallow wells were drilled through hard formations.

The usual cable-tool drilling crew consisted of two men, the driller and the tool dresser; in drilling the well two crews were employed, each working 12-hour shifts or "tours." Working continuously for 24 hours each day, two crews,[5] for example, spent 8 to 15 days in drilling 600- to 1,000-foot wells in Pennsylvania in 1889. The length of the drilling shift began to change from a 12- to an 8-hour tour about 1923, and the 8-hour shift is now the general practice.

In addition to the drillers, the other principal groups of skilled laborers in the oil fields were the rig builders, tank builders, casing crews, and pipe-line crews. Roustabouts and helpers served all these groups. After the wells were completed and the principal items of equipment had been installed by the crews, pumpers and lease men handled the equipment and serviced the wells. There were also skilled workmen in all oil fields who worked as blacksmiths, machinists, pipe fitters, and in the various building trades, but these were not looked upon as "oil-field workers", as were the men who drilled for and produced the oil. In addition to the skilled workers, a large number of unskilled workers was engaged in a wide variety of tasks.

Because of the spasmodic nature of the oil-field drilling operations, characterized by "boom" periods of intensive drilling, most oil-field workers sought employment by migrating from one field to another as new fields were discovered. These migrations, however, always left behind a large number of laborers, both skilled and unskilled, to service the producing wells and to do such work as was required in maintenance of the oil field. As the productive power of the field declined, employment opportunities decreased. For most fields the cycle of peak employment in early drilling and flush production, followed by rapidly declining employment, was completed in a relatively short span of years.

TECHNICAL ADVANCES IN DRILLING

Cable-tool drilling is still the preferred method in some areas, especially in older regions where the drilling depths

[5] *Eleventh Census of the United States: 1890*, "Report on Mineral Industries in the United States" (U. S. Dept. Int., Census Office, 1892), p. 452.

are shallow enough to permit the use of portable drilling rigs and drilling machines. These are compact units, mounted on wheels, that have been improved greatly and are driven by steam or internal-combustion engines. Cable tools have a definite application where the drilling is in hard, cavernous limestone that is likely to give trouble because of lost circulation of rotary-drilling muds, and in regions where the formations are hard and the depths are comparatively shallow.

Steel has replaced wood to a large extent in the construction of rig equipment. Walking beams, bull wheels, calf wheels, and band wheels are made predominantly of steel, and for several years the trend has been to build derricks of this material also. Sand reels now are driven by chain and sprocket wheels. Recent advances in cable-tool drilling have been ascribed particularly to the use of superior alloy steels in the manufacture of tools and rig parts and to the development of heavier and better machines where such equipment is used.

The ability to "rig up" or assemble the equipment used on a cable-tool well in less time and with less labor, and to carry on drilling operations with fewer men (though the drilling speed is slower in comparison with the heavy rotary rig) are important advantages in favor of the standard and portable cable-tool systems of drilling where well depths are shallow or moderate and where the subsurface formations are hard.

Except in wildcat or exploratory drilling, present-day practice calls for drill bits to be heated and dressed (for the restoration of hardness and cutting edge) in centrally located machine shops instead of on the derrick floor, thus permitting the tool dresser and the driller to pursue their work of drilling without interruption. The term "tool dresser", however, still is applied to the driller's helper.

Shift From Cable to Rotary Drilling

The introduction of the rotary drill early in the present century marked the beginning of a new drilling technique which, through several decades of development, has reached a high degree of effectiveness and in most areas has largely replaced the older cable-tool method. In 1901 the rotary drill was used for the first time expressly for oil-well drilling by Capt. J. F. Lucas at Spindletop, Texas, in drilling the discovery well of the Spindletop field; previously, however, this

equipment was used for drilling artesian water wells as early as 1882, and it was while drilling for water that the old Corsicana field was discovered in 1896. Completion of the first Spindletop well as a "gusher" attracted attention to the rotary, as it provided a new method for penetrating the soft, caving shales and unconsolidated formations in which the use of cable tools had been unsuccessful.

This rotary method of drilling differed from the older cable-tool system in that the formations through which the wells were drilled were abraded and chipped by an augerlike steel, "fishtail" bit attached to a rapidly rotating pipe, instead of being hammered and pulverized into small particles by the pounding of heavy tools suspended by a cable. The drill cuttings were washed from the hole while drilling progressed by fluid pumped down the hollow drill pipe or "stem" and circulated to the surface outside the rotating pipe. This distinctly different type of drilling provided employment for a new group of drillers and assistants, more skilled in many respects than those required for the older method.

The first rotary pipe used for drilling consisted of ordinary steel tubing rotated by means of clamps or gripping rings attached to a round table made of steel, set over the well and rotated by a system of gears, sprockets, and chains connected to a steam engine. A hoist, called the "draw works", was provided for raising and lowering the drill pipe. Pumps, connected to the rotating pipe by means of a swivel and hose, circulated water down the drill stem, out through ports in the bit, and up the annular space outside the drill pipe. As development progressed it was observed that the water deposited mud sheaths on the walls of the soft formations through which the wells were drilled and that these sheaths, together with the weight of the column of fluid, tended to prevent the holes from caving. The mud fluid, being denser than plain water, improved the carrying property of the circulating system. The returned drilling fluid passed through a system of surface ditches and pits, in which the drill cuttings settled out, and was then pumped back through the drill pipe.

As rotary drilling went deeper and as greater difficulties were experienced, larger and heavier rigs were developed and new improvements were made in the design of various parts

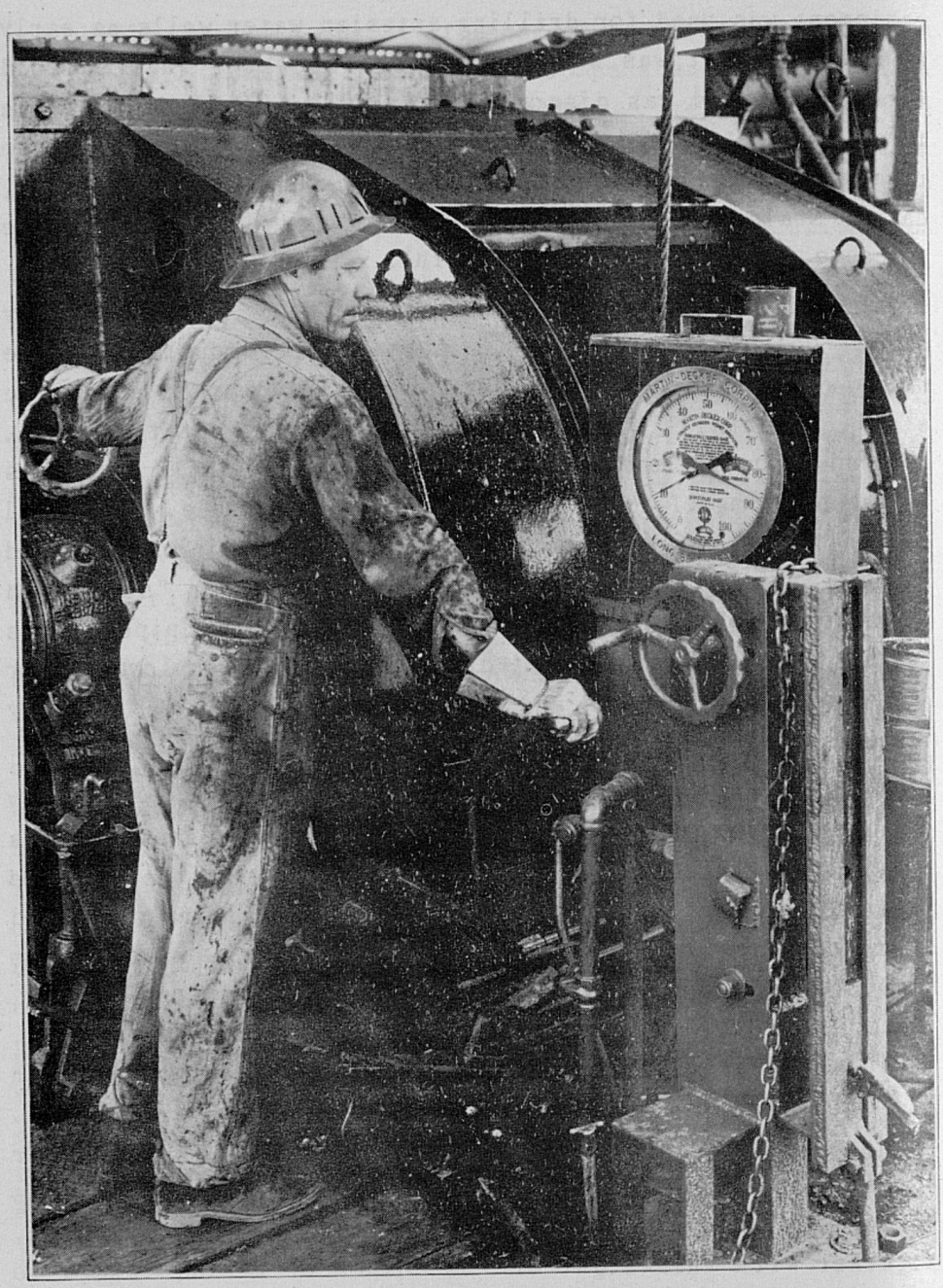


ILLUSTRATION 9.— A DRILLER AT THE CONTROLS OF A MODERN ROTARY RIG USED IN DRILLING DEEP WELLS

Deep drilling, despite the heavy equipment used, is a more delicate operation than one might think. Too much weight on the bit may cause a "twist off", buckle the drill pipe, or make for a crooked hole, or a string of tools may "freeze" in the hole so it cannot be moved. Thus the driller must be constantly on the alert; he operates many mechanical controls guided by indicating and recording instruments that show the weight on the bit, the r. p. m. of the rotary table, and the mud pressure in the hole. These facts, plus his own experience, give the driller clues to what is happening at the bottom of the hole.



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of the equipment. Special drill pipe with thick walls, coupled at intervals by "tool joints", replaced ordinary tubing in forming the drill stem. A square section of drill pipe, called a "kelly" joint or "grief" stem, designed to pass through a square-drive bushing in the rotary table, replaced the older round-pipe clamping method. Probably this is the first major change in the early rotary rig that increased the speed of drilling, for it eliminated frequent interruptions that were formerly necessary for changing position of the rotary clamps on the round drill pipe, an operation that required a considerable amount of hand labor. Introduction of the "cat-head" or spool on the end of one of the rotating shafts of the draw works for spooling a few turns of a loose end or tug rope, commonly called the "cat line", enabled the drillers to use mechanical power for "making up" or "breaking down" the joints of drill pipe, decreasing the amount of labor these operations involved.

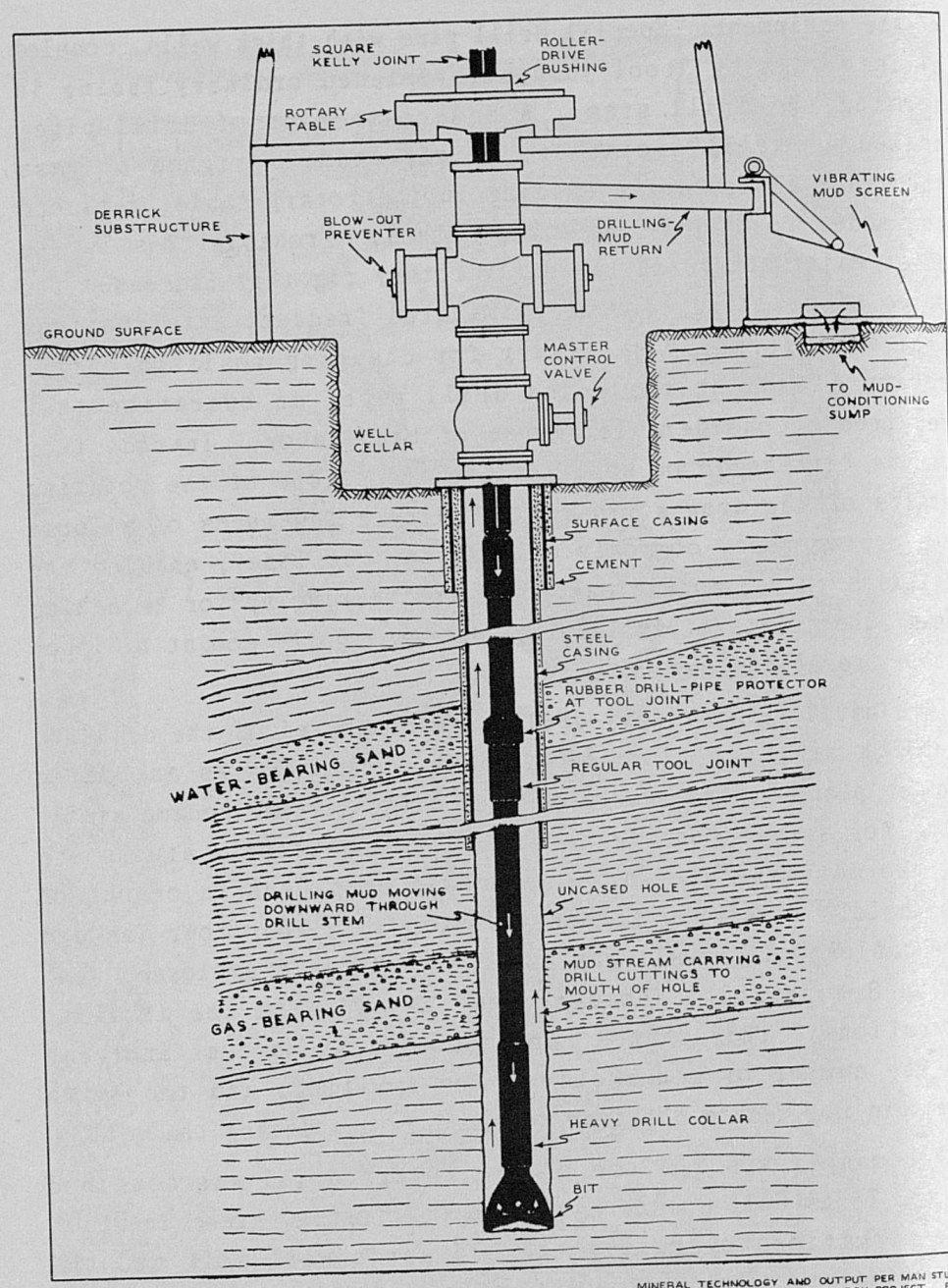
The usual 5-man rotary-drill crew consisted of the driller, derrick man, two floor men, and a fireman.[6] As automatic boiler-plant controls were developed the fireman became available for service on the derrick floor, generally at the end of the cat line when drill pipe was being run in or out of the hole. This crew formerly worked a 12-hour tour (as did the cable-tool crews), but as other oil-field employees went on an 8-hour shift another crew was added to the drilling operations. This change represented a 50-percent increase in the number of men required for drilling, and the extra crew did not reduce the time consumed in completing the well.

For many years the use of the rotary drill was confined to the Texas Gulf Coast region and California, areas in which the formations overlying the oil sands were soft and unconsolidated. The development of hard-rock bits of the roller and cone type and the introduction of hard alloy for facing the cutting edges of the older-type bits, however, made possible the use of the rotary drill in other areas. Except under special conditions, as already noted, rotary equipment has rapidly replaced cable tools throughout the industry.

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[6] "To operate one drilling rig twenty-four hours a day, seven days a week, on a thirty-six to forty-hour workweek schedule, as many as twenty-five employees may be required. A crew of five men is normally on the drilling rig each working shift: a driller, a derrick man, a fireman, a pipe racker, and a 'boll weevil.'" (National Youth Administration of Texas, J. C. Kellam, Director, *Employment Opportunities in the Oil Industry in Texas* [Austin, Tex.: Industrial Study No. 1, mimeo., Sept. 1, 1938], p. 30.)

Figure 17.- IMPORTANT FEATURES OF A HOLE BEING DRILLED BY MODERN ROTARY METHODS



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In rotary drilling, power from surface equipment is transmitted to the bit by a rotating hollow drill-stem through which is circulated mud-laden fluid. This fluid - ejected from the stem into the hole through ports in the bit - cools the bit, reinforces the walls of the hole until steel casing is inserted and cemented (thus confining the contents of underground strata to their native beds) and transports drill cuttings to the surface. Before the well is completed, according to the usual engineering practice, the uncased portion of the hole, shown in the lower half of the figure, would be protected by casing set and cemented to a point directly above the oil-bearing strata. As indicated in the accompanying discussion, blow-out preventers and master valves are important devices in achieving more effective control. To obtain clarity, the drawing is a simplified presentation and the diameter of the drill hole and the size of equipment are shown in distorted proportion to the length of the hole and to other underground features. Surface equipment, including the rig, required for such modern drilling is shown in figure 19.

Greater speed is an important advantage of the rotary drill. It is not uncommon for modern rotary rigs to drill as much as 1,000 feet of soft formation in 1 day. In the East Texas field, for example, wells 3,600 feet in depth sometimes were drilled and completed in 8 days. Such remarkable speed is due largely to the ease with which soft, unconsolidated formations are drilled with a rotating bit, and to the hydraulic jet action of the circulating fluid that erodes the soft formations ahead of the bit. In the drilling of hard formations that require the use of rock bits, the rotary is as fast as, and often faster than, cable tools.

Because the walls of the hole are coated with mud during rotary drilling, thus sealing water sands and other porous strata, a hole of comparatively uniform size may be maintained at desired depths. Moreover, the hole may require only one string of casing, in addition to the customary surface or conductor pipe. In cable-tool drilling, by contrast, the use of successively smaller-diameter casing strings for excluding the various water strata eventually leads to "running out of hole", a condition wherein the reduced size of the hole prohibits further drilling. This feature of the rotary - to finish with a large-size hole - is particularly advantageous in deep drilling, for it not only exposes a larger drainage face in the producing sand but also permits more freedom of action for the tools. Another advantage of the rotary is that high pressures met during drilling are controlled by the weight exerted by the column of mud-laden fluid, and the danger of a blow-out is minimized.

Technique of Water Exclusion

The technique of water exclusion began when the pioneer oil drillers cased their wells with cast-iron pipe and used seed bags for sealing the annular opening between the tubing and casing, or the walls of the borehole. These early seed bags were made of leather and filled with dry flaxseed or other cereal and were attached to tubing and lowered into the hole or were maneuvered behind the casing. Upon wetting, they would swell and prevent the entrance of water. Later practices involved the use of various types of fibrous material, such as chopped rope, cottonseed hulls, and lead wool, which eventually

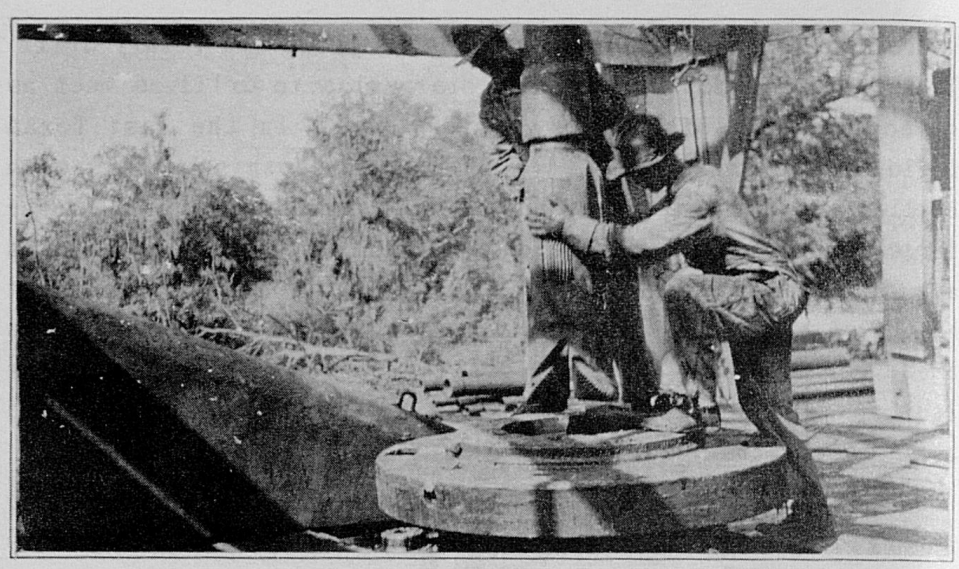




ILLUSTRATION 10.- LOWERING A LARGE ROCK BIT THROUGH THE ROTARY TABLE AND A UNITIZED DRAW WORKS AND ENGINE

The bit shown in the upper view is a type frequently used in drilling hard-rock formations. In the lower view a unitized draw works and engine is shown mounted on a truck. The mud pump and connected engine are also mounted together on skids for easy transportation.

led to the development of special types of mechanical packers of burlap, canvas, or rubber.

For many years before cementing practices were introduced, a method for excluding water, known as the "formation shut-off", was in general use. The casing, fitted with a hard steel shoe, was landed on a suitable hard shale bed or "shell", into which a small pocket had been drilled. The effectiveness of this method of water shut-off depended largely upon the composition of the impervious stratum into which the casing was wedged; today a careful operator would not be satisfied with this precarious method of protecting the producing formations.

To withstand the greater pressures and strains incident to deeper drilling, steel pipe, which supplanted cast-iron pipe, was made heavier and stronger, and older butt- and lap-welded longitudinal pipe seams were eliminated by seamless casing, which had greater strength. The length of joints of casing was increased from 20 to 30 feet. For special applications, flush-joint casings without collars are available. Recently welded strings of casing with joints 40 feet long have appeared in a number of fields. Various types of float shoes and float collars were developed that prevented fluid from entering the casing and enabled the casing to be "floated in", thus relieving the surface equipment of a part of the heavy strain of supporting a long string of casing and at the same time facilitating cementing of the casing.

The introduction of cementing methods and the remarkable advances in cementing technique have contributed materially to the success of modern drilling technology. In early practice cement frequently was dumped in the bottom of a well by means of a "dump bailer" and forced behind the casing (the lower end of which was held several feet above the bottom of the hole) by filling the casing with water.[7] Then the casing was plugged at the top and lowered into the cement. Under some conditions this proved objectionable, so cement shoes that prevented the cement from entering the casing when the pipe was lowered were devised. Another common method employed was to pump the cement through tubing to the bottom of the well and force it back of the casing.

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[7] F. B. Tough, *Methods of Shutting Off Water in Oil and Gas Wells* (1st ed.; U. S. Dept. Int., Bur. Mines, Bull. No. 163, Oct. 1918), pp. 27-8.

At early wells cementing required mixing only a comparatively few sacks of cement; this was done by the drilling crew at the well and did not entail employment of much additional labor. As wells became deeper, however, greater quantities of cement were required, not only to accomplish the necessary water shut-off but also to reinforce the casing against collapsing pressures and against corrosion and to protect and conserve the contents of shallow oil or gas sands that lie above the bottom of the casing. Consequently, as more extensive cementing was needed new methods were developed that involved pumping the cement down through the casing between two moving plugs in such a way that it did not come into contact with the well fluid until it reached the lower end of the casing and was forced upward behind the pipe. During the early use of this method the cement - several hundred sacks or less - was mixed by hand in large vats, an operation that was not only cumbersome and inefficient but also required a large amount of labor. As many as 30 men in addition to the well crew frequently were needed on a "deep cement job." By the prevailing water-nozzle and hand-hoe method, one man could mix about 20 sacks of cement in approximately 2 hours.

To speed the mixing time and increase the amount of cement that could be handled at one operation, power mixers were developed, of which the hydraulic-jet type became most widely used. This device is simply a high-pressure jet placed immediately beneath a cone-shaped hopper into which dry cement is dumped. The regulated volume of water passing through the jet under high velocity, through the medium of high-pressure pumping equipment, causes the water and cement to mix in the proper proportion and consistency for delivery to the well. This mixer, although weighing only 150 pounds, is highly efficient and can mix continuously large quantities of cement. Through these improved cementing methods and the skills developed in their application, large quantities of cement slurry for use behind long strings of casing can be mixed and pumped within the relatively short time before the initial set of the cement. A recent record may be cited:[8] 1,500 sacks (roughly 70 tons) of cement were pumped behind $7\frac{5}{8}$-inch casing 11,342 feet deep in 52 minutes - a remarkable feat that would

[8] F. L. Singleton, "Longest, Heaviest String of $7\frac{5}{8}$ Inch Casing Ever Run," *The Oil and Gas Journal*, Vol. 36, No. 16 (Sept. 2, 1937), p. 25.

have been physically impossible with the older methods of a few years ago. Not infrequently as many as 3,000 sacks of cement are pumped into a well in one operation. This improved cementing technique probably has been one of the most important technologic developments in drilling of oil and gas wells. A modern cementing job on a deep well requiring several thousand sacks is a scene of great activity, as about 10 times as much work is accomplished with the present equipment in the short period of approximately 1 hour as was possible before its introduction.[9]

A decade ago, when a drilling well was "standing cemented", all work on the well ceased for 2 to 3 weeks while the cement was permitted to set and harden. This is now changed, for the use of special oil-well cements and quick-setting reagents reduces the time of waiting to a few days. Finer grinding in manufacture now produces cements for oil-well use that have rapid setting and hardening properties.[10] The speeding-up of the setting time of cement obviously shortened the period for completing wells and naturally reduced the amount of labor employed. On the other hand, where occasion demands, reagents are available that tend to retard the setting of cement, as this may be necessary to place the cement behind the casing properly before the initial set begins. Retarding reagents naturally increase the over-all drilling time. Slow-setting but quick-hardening cement is sometimes used in especially difficult cementing operations where speed is not a factor of importance, where the cementing operations are necessarily prolonged or, in deep wells, where high earth temperatures tend to accelerate the setting rate of regular cement. Gel-cements, with highly viscous properties, are being used in oil fields where ordinary cement, due to its greater fluidity, might be lost in cavernous or unusually porous formations or where it would mix too easily with drilling fluids. Experiments are being conducted with fibrous material, such as paper pulp, which is added to the cement for the same purpose. These special cementing applications tend to increase the employment

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[9] Personal communication from C. P. Parsons, Vice President, Halliburton Oil Well Cementing Company, Duncan, Oklahoma, December 15, 1937.

[10] N. Yaworski, V. Spencer, and Others, *Fuel Efficiency in Cement Manufacture, 1909-1935* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-5, Apr. 1938), p. 55.



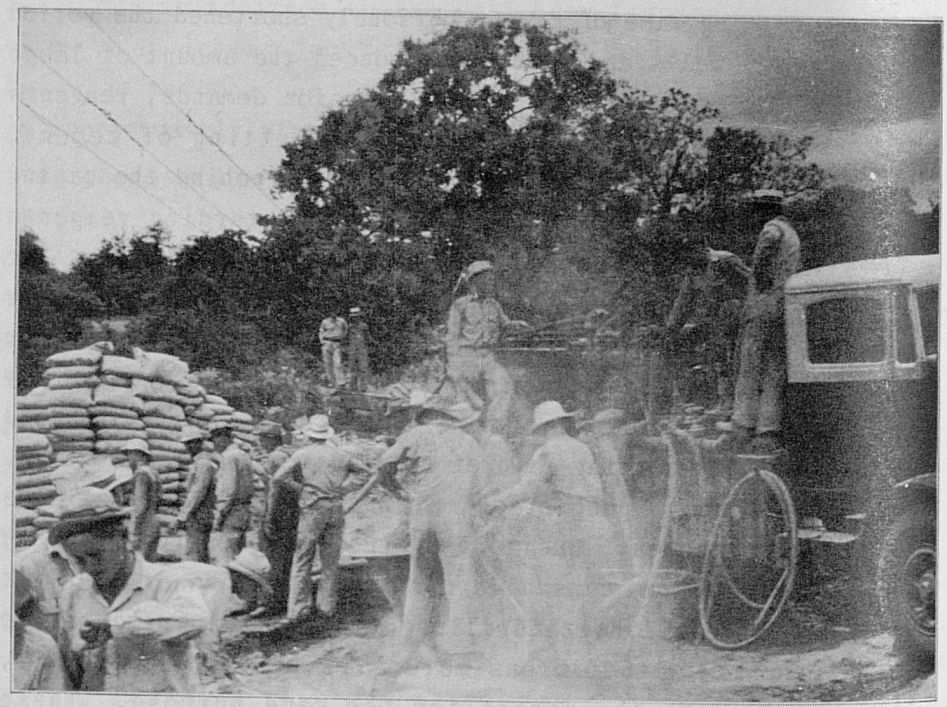


ILLUSTRATION 11.- THE TECHNIQUE OF CEMENTING WELLS HAS CONTRIBUTED MATERIALLY TO THE SUCCESS OF MODERN DRILLING TECHNOLOGY

Cementing wells is standard practice to exclude water from porous strata above the productive sand and for other purposes. The upper view shows cement being dumped in a special mixing hopper in the Rio Bravo field, California; high-pressure pumps, mounted on the truck, force the cement into the well. At this operation, $7\frac{5}{8}$-inch casing, landed at about 11,000 feet - more than 2 miles deep - was being cemented. The total time for mixing and placing 2,000 sacks of cement was 55 minutes. The lower view shows a cementing operation in the East Cement field of Oklahoma. This view was taken just before 5,000 sacks of cement were pumped into the well.

of men engaged in the industries that furnish the materials used with the cement and to some extent the amount of labor actually required to perform the cementing operation; they are used so seldom, however, that their influence in this respect is negligible and is more than overshadowed by the labor saved by the general use of quick-setting, quick-hardening reagents.

Ingenious use of an electric thermometer permits accurate determination of the height or position of the cement jacket behind the steel casing. This procedure takes advantage of the fact that cement in the process of hardening generates and emits heat, which is registered by the thermometer as it is lowered in the well. Taking the thermometer readings and interpreting them are, of course, tasks for technically trained personnel.

Additional refinements of cementing technique have been developed. The multistage cementing method, tried for the first time a few years ago, is frequently employed. It involves introducing cement behind the casing through perforations or special ports at two or more points in the casing string, thus eliminating the necessity of pumping all the cement around the shoe of the casing. This method is particularly applicable to deep-well drilling, because lower pumping pressures are required and less time is consumed in performing the operation. Another advantage is that batches of fresh cement can be placed behind the casing at points high in the hole or at strategic points where the formations prove particularly troublesome. In another recently developed process, called the "squeeze" method, cement under high pressure is forced back into porous sands to seal them.

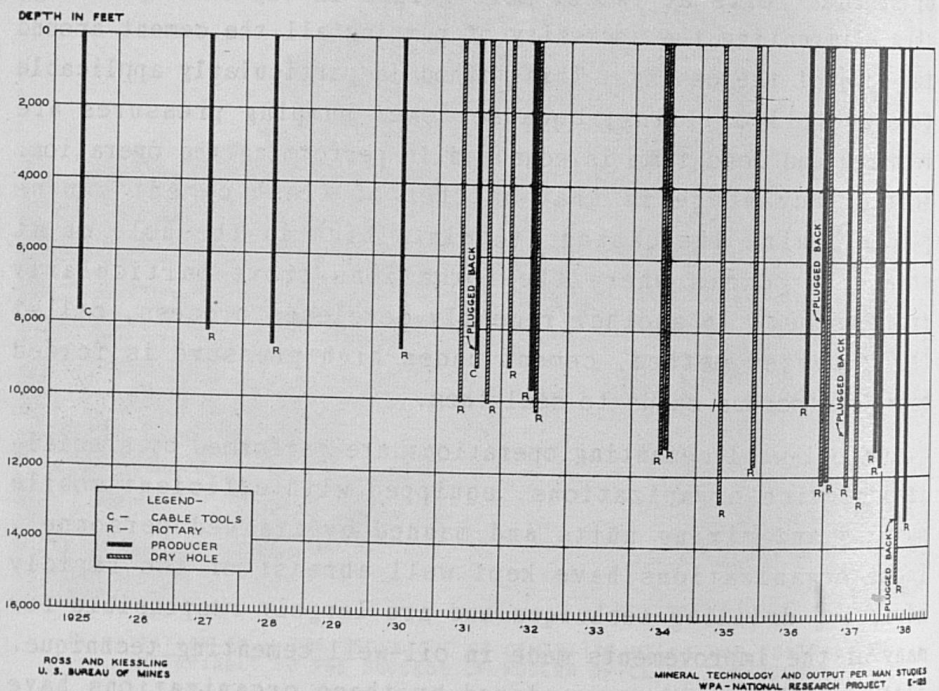
Most oil-well cementing operations are performed by specialized service organizations, equipped with efficient mobile pumping and mixing units and manned by trained personnel. These organizations have kept well abreast of the rapidly advancing drilling technique and are largely responsible for many of the improvements made in oil-well cementing technique. Although the services rendered by these organizations have very materially reduced the over-all time required for drilling a well, they provided employment for a large personnel supplementing the men actually engaged in drilling.

Trend Toward Deeper Drilling

In the search for new oil reserves to replace those being depleted with great rapidity, the general tendency has been toward deeper drilling. The depths to which wells could be successfully and economically sunk at any period in the industry's history, however, have been restricted by the limitations of the existing mechanical equipment. Owing to the remarkable advancement in rotary drilling, wells today are drilled to depths quite unknown a few years ago (see figure 18). This trend toward deeper drilling was accelerated by the increasing difficulty of finding new productive shallow sands and by discoveries of prolific oil sands lying at greater depths.

Although drilling depths have increased from less than 100 feet to 15,000 feet in the last three-quarters of a century, the average for the last 10 years is approximately

Figure 18.- RECORD OF INCREASING DEPTH OF DRILLING IN THE UNITED STATES, 1925-38



One of the results of technologic developments in drilling has been the ability to reach productive sands at increased depths. The deepest well in the world was recently drilled in the Rio Bravo field, Kern County, California, to a depth of 15,004 feet and plugged back to produce at 13,092 to 13,175 feet. The deepest producing well, however, is one in the Dulac field, Terrebonne Parish, Louisiana, that penetrates the producing formation 13,254 to 13,266 feet.

Adapted from data published in *The Oil and Gas Journal* and *The Oil Weekly*.

3,000 feet.[11] However, many fields west of the Mississippi River produce from sands lying below 6,000 or 7,000 feet. In the Gulf Coast region of Texas and Louisiana and in California oil is being produced from the remarkable depths of 10,000 to 13,266 feet, the deepest producing well being in the Dulac field, Terrebonne Parish, Louisiana. The search for oil, moreover, has extended to even greater depths. One well in Kern County, California, penetrated formations to a depth of 15,004 feet, establishing an all-time record for drilling before being plugged back to 13,175 feet to become a producing well at that depth. Exploratory wells of this type take a long time to drill, require a large capital outlay, and provide a relatively large amount of employment. Deeper drilling has been responsible for the discovery of new fields in areas where shallow drilling had proved unsuccessful and of new sands underlying older producing fields in which the existence of such sands, if known, was previously considered beyond the limit of drilling.

The work of developing deep producing fields has been an important factor in absorbing the labor released from the exhausted shallower areas. Although the speed of drilling has been greatly increased by modern methods, the deep wells require a longer time to drill, demand greater care, and involve the use of more advanced drilling technique than wells in shallow fields. Besides the regular drilling crews, deep-drilling operations also require the employment of a larger amount of service labor (as in cementing) and of a larger number of specialists, engineers, and technicians than were formerly required.

Directional Drilling

In the earlier days of rotary drilling little attention was paid to straight-hole drilling, for the main objective was to make footage regardless of whether the hole was vertical or inclined from the vertical. Consequently, mechanical troubles due to crooked holes were abundant, not only during drilling but also during the later pumping stage of production. It was not an uncommon occurrence for a crooked rotary-drilled well to deviate as much as a thousand feet or more from its

[11] L. J. Logan, "More Footage," *The Oil Weekly*, Vol. 88, No. 8 (Jan. 31, 1938), p. 48.

vertical course; to intercept a neighboring well, damaging the casing of the latter or stopping its production; to drift away from the producing area and enter a water-bearing formation instead; or to pass entirely through the productive sands because geological data obtained from earlier crooked wells were misleading. Furthermore, the location of the derrick did not indicate with accuracy where the hole entered the pay sand, and this made difficult the interpretation of the geological characteristics of the field. The industry became cognizant of the "crooked-hole problem" at the time Seminole, Oklahoma, was developed, for this field produced some of the most outstanding examples of crooked-hole drilling.[12] Since the drilling contractors were paid on a footage basis, their revenue increased with the increased footage of hole, and verticality was sacrificed to increased speed and greater footage per drilling-crew shift. Because much more hole was drilled than was necessary to reach the pay sands, crooked-hole drilling sometimes required more labor than would have been needed had the holes been vertical.

With the development of a number of well-surveying devices, ranging from the simple "acid-bottle"[13] to intricate but dependable instruments requiring the services of skilled operators, closer attention was paid to the matter of maintaining verticality of well drilling. Studies to determine the causes of accidental deflection of the bit indicated that much of the difficulty could be eliminated by using heavier drill collars above the bit and maintaining a reasonable weight on the bit itself, the weight being shown on a weight-indicator gauge. Consequently, heavier, larger drill collars were used above the bit, and closer attention was paid to the rate of rotation, the weight on the bit, and the rate of mud circulation. At present most wells that are carefully drilled deviate less than 2 or 3 degrees from the vertical, and most drilling contracts specify a maximum allowable deflection of probably not more than 5 degrees. When serious drift of the bit does occur, the hole is plugged back, in present

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[12] R. R. Brandenthaler, W. S. Morris, and C. R. Bopp, *Engineering Study of the Seminole Area, Seminole and Pottawatomie Counties, Oklahoma* (U. S. Dept. Com., Bur. Mines, Report of Investigations 2997, mimeo., May 1930), pp. 27-40.

[13] A slender glass bottle, which, when partly filled with a solution of hydrofluoric acid, lowered into the well, and allowed to stand at rest, receives an etched ring at the level surface of the liquid. The angle between the plane of this ring and the longitudinal side of the bottle, when measured, determines the amount, but not the direction, of the declination.

practice, to the point where deflection started, and it is redrilled at that point. A long deflecting tool, called a "whipstock", is available to deflect the bit from its old course. The hole first is surveyed to determine the angle and direction of deflection; then the whipstock is attached to the end of the drill stem and oriented in the hole in a position that will cause the drill to be deflected toward the vertical. These operations necessarily slow drilling and increase labor requirements. Drilling crews are compelled to pay more attention to the factors that make for straighter drilling, and extra time and labor are required to survey the holes and to keep them vertical.

The experience acquired in solving the crooked-hole problem has led to the development within the last few years of a new drilling technique called controlled directional drilling,[14] wherein the hole is purposely so deflected from the vertical as to reach an objective point not directly beneath the derrick. A common procedure involves drilling a vertical hole to a predetermined depth, at which point deflection of the bit in the desired direction is effected by an oriented whipstock, and drilling is resumed in the new direction. Frequent well surveys are needed, several whipstock tools may be required, and lengthy plugging-back operations often are necessary before the objective point is attained. These and attending operations all require more labor than is needed in conventional drilling.

Controlled directional drilling has proved advantageous for the development of off-shore fields, such as those on the California coast, where the derricks are on the shore and the oil reservoirs underlie beach resorts or deep water, and of certain types of Gulf Coast salt domes, where stratigraphic conditions are complex. It is also employed where the building of derricks directly over the oil body is impractical because of swampy surface terrain. In some fields, where well locations fall beyond the outside edge of the field, holes are deflected toward the productive portion of the sand, for were such holes drilled vertically they would penetrate water instead of oil. For the same reason, holes are directed across

[14] J. D. Hughes, "Controlled Directional Well-Drilling and Surveying Practice," *The Petroleum Engineer*, Vol. VI, No. XI (July 1935) and subsequent issues through Vol. VII, No. V (Feb. 1936).

underground faults. A spectacular illustration of the use of directional drilling is offered by the drilling of "relief" wells - wells drilled expressly for the purpose of controlling wild or cratered wells. In the drilling of this type of well the derrick, through necessity, must be at a safe distance from the original well and the hole must be so directed as to penetrate the producing sand at or near the bottom of the offending well, which may then be brought under control by pumping mud or water down the relief well. There are records where several wells have been drilled in different directions from one location; this practice, although limited in application, tends to reduce the labor and time required to move the derrick and rig equipment from one site to another. Directional drilling also is used in drilling around lost tools or other hard objects in the path of the bit. Not infrequently, "windows" are milled in the side of steel casing through which drilling is guided by the use of deflection tools. Besides the whipstock, other special tools have been developed for use in controlled directional drilling, such as the knuckle joint and spudding shoe.

Controlled directional drilling, as well as better vertical direction of drilling, requires the constant vigilance of the drilling crew and of the supervising engineers. More time and labor generally are needed to complete wells, moreover, than when these techniques are not employed. Part of the increased labor is represented by a greater amount of employment for the regular drilling crew, and part is due to employment provided by the service agencies specializing in oil-well surveying and directional drilling. Not all of the increased time and employment is a net increase, however, for the care and attention given to drilling for controlled direction or verticality - although increasing the over-all time of drilling - often eliminate serious delays due to twist-offs of the drill pipe, difficult fishing operations, plugging back and redrilling, depreciation of drilling equipment, and other difficulties that may result from crooked or accidentally deflected holes.

Larger Derricks

As previously stated, wooden derricks, typical of the oil fields of a few decades ago, have been replaced to a great

extent by larger, heavier all-steel structures. The height of the rotary derrick has been increased to 122 feet, and where the drilling is extremely deep, to 136 and even 178 feet to provide ample headroom for the heavier drilling equipment needed and to accommodate the longer stands of drill pipe.[15] Moreover, the newer derricks usually are mounted on heavy concrete foundations. A steel substructure, which raises the derrick floor 7 to 8 feet or more above the ground, has come into general use where the drilling is deep or where high pressure is anticipated, as it provides more room for placing pressure-control equipment. For heavy equipment, supports under the derrick that uphold the rotary table, formerly set 6 feet apart, are now set on 10-foot centers, giving more clearance and working space around the well-head connection and blow-out preventers.[16] In the Gulf Coast, where the low, swampy terrain makes excavation difficult, the derrick substructure may serve in place of a cellar.

The standard cable-tool derrick is 86 feet high, although it may range from 64 to 122 feet, depending upon local conditions. Most cable-tool derricks, with the belt and engine houses, now are built of steel.

In the days when the wood derrick was dominant, lumber was sawed to the desired lengths at the well location. Today the steel derrick parts are prefabricated at the mill, and a rig-building crew of five men assembles the various pieces and bolts them together at the drilling site. Two to three days are required to erect a tall rotary derrick. About the same amount of labor is employed for erecting a steel or a wooden derrick, but the steel derrick, besides being stronger and more durable, has other advantages not possessed by the wooden structure. One advantage, for example, is that the steel derrick can be taken apart and reassembled numerous times without impairing its construction, whereas this is not possible with the wooden derrick. Many operators prefer to maintain the large steel derrick for drilling purposes only, moving it from one drilling location to another and erecting

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[15] The taller rotary derrick has a base that measures 32 feet square instead of the customary 24 feet, thus providing a larger floor space for racking in the derrick the greater number of "stands" of drill pipe used in deeper drilling. See W. A. Sawdon, "Drilling and Casing Deep Wells in California," *The Petroleum Engineer*, Vol. X, No. 2 (Nov. 1938), p. 67.

[16] C. E. Reistle, Jr., and S. T. Sikes, Jr., "Drilling Equipment Improvements and Changes," *Proceedings of the Natural Gas Department of the American Gas Association* (Annual meeting, Kansas City, Mo., May 10-14, 1937), pp. 129-40.

a smaller derrick - usually steel, but sometimes wood - over the completed wells.

If the terrain is flat and favorable and the distance between drilling sites is short, the drilling derrick sometimes is skidded from one location to another, thus saving the cost of tearing it down and reerecting it on the new location. In certain comparatively level Gulf Coast fields, for example, derricks are skidded successfully more than 3 miles and at a rate of about 1 mile per hour. The complete operation of moving the derrick from one site to another - including the short time it is actually in motion - requires about 2 days, whereas under the old dismantling program the time required to tear down and rebuild a derrick of the type and size used in this region was about 3 days.[17] Another advantage of the steel derrick is that it offers much less wind resistance during severe windstorms and requires less guying.

An extended-leg derrick has been developed for use in fields where the derrick is left standing for production purposes after the well is completed. The legs of the derrick, resting upon permanent foundations, are independent of the steel substructure, which can be removed to a new drilling location. The moving and reinstallation of this type of substructure require additional labor but represent an economy over the construction of an entirely new substructure.

During the past year considerable interest has been shown in a growing use of portable steel derricks of a special type. These derricks, about 84 feet high, can be erected in a few hours and are serviceable for drilling to 6,000 feet.[18]

Improved Circulating Systems

Successful rotary drilling depends in a large measure upon proper functioning of a circulating fluid, and some of the important achievements of modern deep drilling are due in part to recent improvements in circulating methods.

The circulating medium most commonly used is clay- or mud-laden fluid, to which are frequently added certain ingredients or chemicals that give it weight or thickness, as the occasion

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[17] B. Mills, "Derrick Skidding Now Highly Skilled Art," *The Oil Weekly*, Vol. 9, No. 11 (Aug. 22, 1938), p. 22.

[18] R. H. King, "Portable Derrick Facilitates Drilling of Wildcat Wells," *The Petroleum Engineer*, Vol. IX, No. 12 (Aug. 1938), pp. 25-6.

demands. In addition to providing a medium for carrying drill cuttings from the hole and keeping the bit cool, mud fluid deposits a coating of clay on the walls of the hole, the clay acting as a lubricant for the drill stem. The mud sheath so deposited also strengthens the walls of the hole and prevents them from caving. Moreover, it prevents loss of fluid in certain types of formations (both low-pressure and porous) and seals off high-pressure gas or water sands, thus preventing disastrous "blow-outs."[19]

A relatively recent process, developed and used successfully in low-pressure productive sands in California, involves the addition of finely powdered limestone to the circulating mud.[20] Thus, instead of the usual mud sheath lining the hole through the productive formation, a sheath of mud and limestone is formed which is disintegrated with acid after the well has been completed to the bottom of the producing formation.

During the earlier days of rotary drilling preparation of suitable drilling fluids was left largely to the judgment of the driller. The materials used were those found on the site. Now, through greater knowledge of the physical and chemical properties of mud fluids, advanced technique is employed in the preparation of native and synthetic drilling muds and in the development of mud-conditioning and reconditioning processes. The careful supervision necessary for maintaining the proper condition of mud fluid is generally in the hands of competent engineers who frequently test samples of the mud to determine its weight and viscosity. For this purpose special mud-testing instruments for field use have been devised, and field laboratories - often at the well site - are provided.

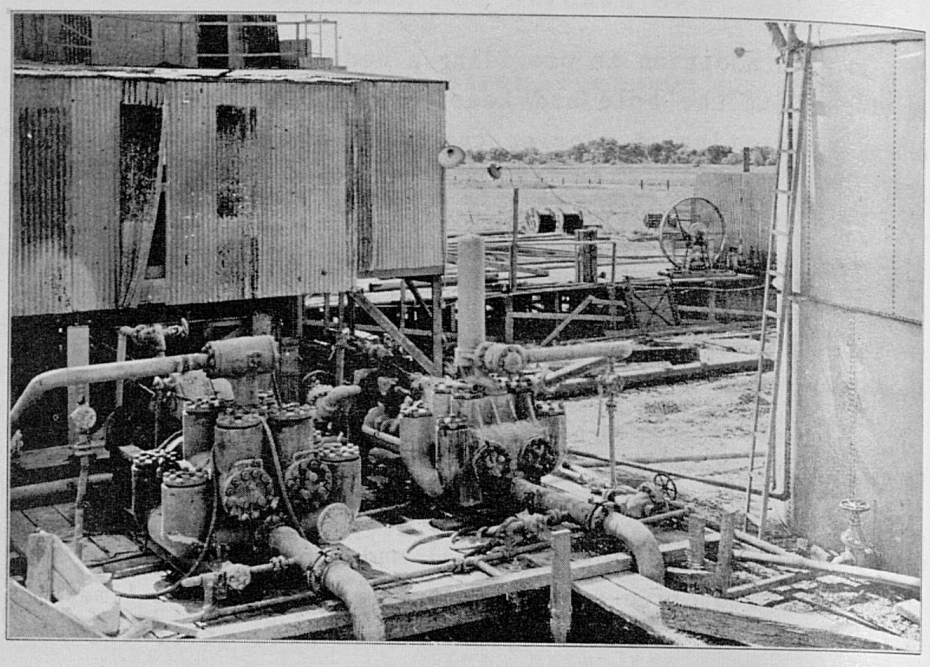
The efficiency of circulating systems has been increased by the development of mechanical vibrating mud-screens[21] that facilitate the removal of drill cuttings and the liberation of occluded gas bubbles from the returning mud stream, thus eliminating, to a certain extent, the necessity of providing long circulating ditches and large settling pits. Centrifugal

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[19] C. B. Carpenter, *Some Causes of Blow-outs During Drilling and Means of Prevention, With Special Reference to the Gulf Coast Region* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 6938, mimeo., Mar. 1937), 27 pp.

[20] H. C. Miller and G. B. Shea, *Chemical Method for Removing Mud Sheaths in Oil Wells* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3249, mimeo., June 1934), 19 pp.

[21] B. Mills, "Vibrating Screen Cleans Mud - Makes Big Saving," *The Oil Weekly*, Vol. 59, No. 5 (Oct. 17, 1930), pp. 25-6.



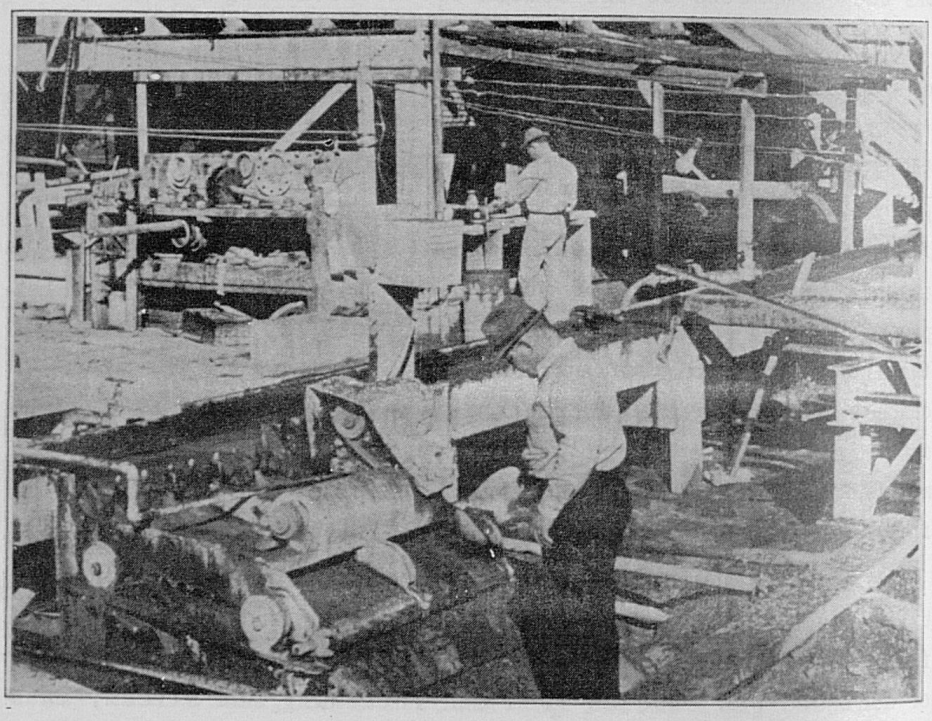


ILLUSTRATION 12.- MUD CONTROL IS AN IMPORTANT FACTOR IN ROTARY DRILLING

Heavy-duty mud pumps used in circulating mud in wells drilled to over 10,000 feet in depth are shown in the upper view. The lower view shows a vibrating screen which removes the sand, shale cuttings, and other large particles from the circulating mud fluid as it comes from the well before the mud is returned to the pit and used again after being reconditioned.

As the drill turns at the end of the drill pipe, the stream of mud-laden fluid is driven by the pumps through the hollow drill pipe; this fluid escapes through vents in the bit and circulates back to the surface between the drill pipe and walls of the hole. This mud cools the bit, carries off cuttings, seals water in penetrated formations, and plasters the walls of the hole. Where there are high gas pressures, special materials are used as admixtures to increase the weight of the fluid column in the well and to change the physical characteristics of the fluid to meet the underground conditions. Proper control of drilling mud requires careful technical direction.

separators are used for eliminating sand and gritty material from the circulating substance and for recovering large percentages of the weighting material from the mud fluid that has become unfit for further use. In some closely drilled fields in California and the Gulf Coast, large, centrally located mud-reclamation plants[22] have proved successful for conditioning drilling muds and for recovering weighting materials from waste mud. These plants are particularly advantageous in thickly congested areas, where the disposal of waste mud is a serious problem, where the cost of supplying drilling mud to wells is high, and, in regions of rugged topography, where the cost of constructing individual mud pits would be excessive. The number of these plants is small, however, and their labor requirements are not large.

Because of the unusually high formation pressure in many deep wells and the high cost of furnishing weighting material for the control of such pressures while drilling, a closed circulating system is sometimes used wherein the drill pipe rotates in a blow-out preventer or pressure-control head placed in the top of the casing, and the rising column of mud fluid is under pressure by reason of the enclosed surface equipment of the system. Under this arrangement a smaller quantity of weighting material is needed in the mud fluid for controlling a given formation pressure; another advantage is that the lighter-weight mud fluid may be delivered under pressure to the circulating pump and less power may be required of the pumping equipment, reducing the wear of pump valves. Controlled-pressure drilling, however, requires a larger force of workers than the conventional practice.

The well driller draws upon other industries for a variety of materials and ingredients that possess certain desirable characteristics and are added to drilling mud.[23] Often thousands of sacks of weighting material alone are used in drilling a single deep well; mining, grinding, sacking, and transporting of this material provide employment for many men beyond the

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[22] W. A. Sawdon, "Central Mud Reconditioning Plant Is Reclaiming Weight Material and Aiding Mud Control," *The Oil Weekly*, Vol. 76, No. 13 (Mar. 11, 1935), p. 28.

[23] Among these important ingredients are bentonite, a compound having the peculiar property of absorbing water, used for increasing the viscosity of mud; and barite, a heavy mineral substance having a weight over four times that of water, which is added to give weight to the circulating mud column, a matter of vital importance in the control of high pressures. A number of chemicals are also used in thickening, thinning, weighting, and improving the colloidal properties of drilling muds.

boundaries of the oil and gas industry. In some areas, such as the Gulf Coast, the agencies that supply these materials also furnish mud-conditioning services; they maintain engineering staffs and laboratory personnel as well as field workers specially trained in mud techniques.

Coring Formations

The successful development and exploitation of oil properties depend largely upon accurate and reliable records of the underground conditions, as determined by drilling. Such pertinent information as depth, thickness, character, and fluid content of underground formations, therefore, is essential for the conduct of future development work and for applying improved drilling methods, making appraisals, planning well repairs, and performing other engineering tasks. With the introduction of improved engineering practices and the employment of trained geologists and engineers, more attention was paid to the preparation of better well logs and to the development of better tools for collecting drill-hole samples.

In cable-tool drilling the logging of formations generally is not a difficult problem because the drill cuttings brought to the surface in the bailer, though usually pulverized and often contaminated by foreign material, are fairly representative of the formation in which the bit is working. Since the hole is drilled "dry" (that is, without a fluid column) the presence of water, oil, or gas in a formation generally can be detected easily.

The absence of a satisfactory method for obtaining formation samples and for ascertaining the character and content of the formations penetrated in drilling was, until the development of mechanical core-cutting tools, the principal objection to rotary drilling. The earlier rotary well logs, for example, were compiled by the driller, who based his data upon his observation and interpretation of the drill cuttings recovered from the mud in the circulating ditch, the behavior of the tools, the condition of the bit when it was removed from the well, and the rate or footage the bit drilled. Logs of rotary-drilled wells based upon such data bore many indefinite - and frequently meaningless - terms and in general were poor and of little value for interpreting underground conditions.

Frequently, moreover, oil sands were mudded and passed through unnoticed, owing to the weight of the circulating mud column. For the lack of a better method of sampling, an early practice involved "spudding" the rotary bit into the formation and "breaking down" or unscrewing the drill-pipe joints by hand, so that any sample of the formation that might be clinging to the bit would not be washed off by rotation of the drill pipe when it was being broken down by the customary method. This primitive method was slow, the results obtained were exceedingly uncertain, and it entailed considerable labor.

A forerunner of modern core-cutting tools was an improvised device called the "saw-toothed" core basket,[24] which appeared in the rotary-drilled fields about 18 years ago. Through the use of this tool a few inches of formation could be obtained from the bottom of the hole; but, because of the difficulties often involved, the time consumed, and the extra labor required to obtain so small a sample, its use was confined mainly to procuring small samples of prospective oil sands. Since no provision was made for cooling the tool, the heat generated during rotation often was intense enough to fuse the sample, destroying its value; moreover, samples from very soft formations often were lost from the basket while the drill pipe was being pulled, and repeated attempts frequently were necessary before an adequate sample was obtained. Although not entirely satisfactory, this device was an improvement over former methods and led to the development of several types of more substantial, efficient core-cutting tools. Obviously, the early attempts at coring delayed the speed of drilling and increased the over-all amount of labor needed for completion of the well.

Efficient coring tools are now available for rotary drilling in hard or soft formations; these tools are provided with stationary or nonrotating barrels and are cooled by circulating fluid. Those designed for coring soft formations have hard, chisel-like edged bits, resembling in shape the fins of the ordinary fishtail bit; those used for hard formations are equipped with roller-type or cone-shaped bits similar in design

[24] This core basket consisted of a short piece of pipe, in one end of which were cut a number of sharp teeth, bent slightly inward. When run into the hole on the end of drill pipe (in place of the regular bit) and rotated, this tool cored several inches of sand or soft formation; weight was then applied to buckle the teeth inward, catching the sample.

to the cutters on rotary, hard-rock bits. The cutter head or bit is detachable. Through improvements in design and quality of the cutters, coring bits have become highly efficient tools, capable of cutting 10-foot cores in any formation found in routine drilling. The use of longer core barrels and better core catchers has permitted longer cores to be taken and has reduced the number of times the coring tools must be inserted in the drill hole and removed per foot of drill core recovered. In fact, coring now can be accomplished almost as rapidly as drilling with a solid type of bit. The greater expense of coring is due mainly to the time lost while the drill pipe is run in and out of the hole each time the core barrel is withdrawn and the core removed. The use of longer core barrels materially reduced the amount of labor and time required for raising and lowering core barrels.

To eliminate frequent pulling of the drill pipe, wire-line coring methods have been developed and are being used extensively in the deeper drilling areas, particularly in the Gulf Coast region and in California. The advantage of this method lies in the fact that the core barrel is brought out of the hole through the inside of the drill stem on a wire line, and removal of the drill pipe for recovering the core is unnecessary. Full-hole drill pipe is necessary for wire-line core drilling. Considerable time and labor are saved in wire-line coring at deep wells, for at greater depths the importance of coring increases, but its cost increases as well. Users of wire-line coring methods report that the wire-line cutter shoe is kept in the hole longer than the conventional core bit and drills up to 150 feet per bit. Round trips of drill pipe are not made any faster than usual, but fewer trips are necessary. Since the drill pipe is removed only when the coring bit is removed or renewed, the time consumed in making round trips represents only one-eighth to one-half of the drilling time usually required for pulling and running pipe when coring with the conventional types of barrels.[25]

Coring is practiced so widely today that it has become part of the customary procedure of all rotary operations. In wildcat drilling and in deeper drilling and exploratory drilling in older producing fields, the underground formations

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[25] W. A. Clark, "Use of Wire-Line Core Barrels in California," *The Petroleum Engineer*, Vol. VIII, No. 8 (May 1937), p. 74.

often are cored continuously for thousands of feet. The cores brought to the surface are regarded as representative samples of the formations penetrated, and lithologic tests may be made upon them to determine the characteristics of the material. Another recent development is a side-wall sampler used to procure samples from formations previously drilled. Extensive coring has been practiced largely in rotary drilling, for although cable-tool coring drills have been developed they are not used widely, except in certain areas. Since more adequate cores have become available, more thorough study of the underground formations has been possible, and employment opportunities have increased for a large number of trained specialists, such as micropaleontologists and geologists, and for other persons engaged in collecting, assembling, and examining core samples. Fresh core samples usually are placed immediately in tin containers, hermetically sealed, and sent to the laboratory. Many operators maintain their own laboratories for core analysis and study.

Within the last few years an electrical method of logging, known as "electrical coring",[26] has been used extensively in many oil fields. By this method the electrical resistivity of rock strata penetrated by a well is determined; second, the electromotive force set up by infiltration of the drilling mud into porous strata is measured, providing information as to the permeability of the beds. When correlated with a graphic log of known formations, the measurements derived by electrical methods give a complete record of formations throughout the full depth of the new hole. Although the measurements usually are made in an uncased hole filled with mud fluid - a feature that makes electrical coring especially applicable to rotary-drilled wells - efforts are being made to extend the applicability of the method to cased wells. Electrical coring gives a fairly accurate estimate of the porosity and degree of saturation of a formation; under favorable circumstances it becomes a complete substitute for mechanical coring. Electrical coring operations are performed by specialized service agencies that maintain their own service equipment and trained crews. Owing to the greater speed with which a well can be electrically logged - often in 6 hours'

[26] C. Schlumberger, "Electrical Coring," *The Science of Petroleum* (London: Oxford University Press, 1938), I, 351-63.



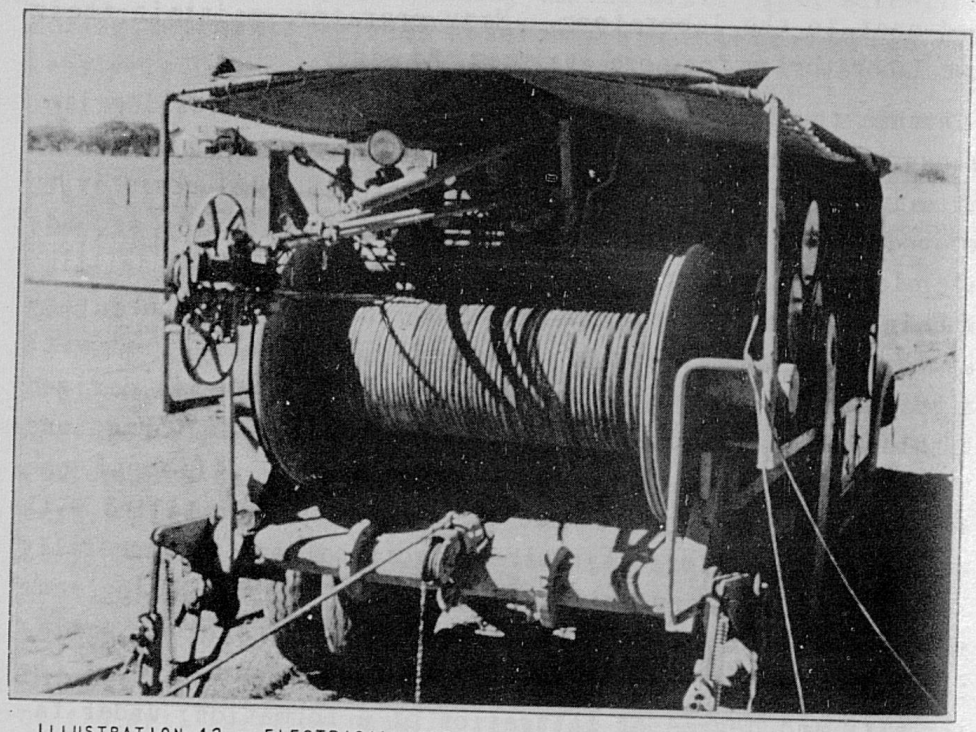


ILLUSTRATION 13.- ELECTRICAL LOGGING HAS BEEN USED EXTENSIVELY IN MANY OIL FIELDS AS A METHOD FOR OBTAINING INFORMATION REGARDING THE CHARACTERISTICS OF UNDERLYING FORMATIONS

Stated simply, electrical logging is based upon the principle of the varying resistance of different rocks to electrical current. This resistivity is measured by recording mechanisms connected to an electrical circuit, one terminal of which is an electrode that is run into the borehole; the other terminal consists of suitably placed grounding rods at the surface. The top view shows a workman holding the electrode preparatory to its insertion in the borehole. The bottom view shows the insulated electrical cable that performs the double function of transmitting electric current and serving as the hoisting cable for the electrode; the recording instruments, in the front part of the truck, are not visible. Electrical logging operations usually are performed by specialized service agencies that maintain their own equipment and trained crews.

time - this method reduces tremendously the amount of labor required as compared with conventional coring methods.

Formation Testing

The development of drill-stem testers has made possible the testing of formations suspected of containing oil or gas without the necessity of the costly operation of setting casing and lowering the column of drilling fluid by bailing or other means of fluid removal.[27] In testing the probable productiveness of new sands, large flows and high pressures are often found. Under these conditions it is sometimes necessary for the drill stem and tester to be left in the well.

A variety of other devices and instruments has been developed for acquiring greater knowledge of underground conditions. These include instruments for supplying data on bottom-hole pressures that are important for the proper weighting of drilling muds in high-pressure fields, for measuring formation energy within the reservoir that aids the determination of the most efficient oil-withdrawal rates, for taking underground temperatures (a factor of vital importance in deep-well cementing practices), and for determining well declivity (that becomes more important as wells are drilled deeper). Most of these instruments are run into the well on a single-strand steel measuring line through a special stuffing box; where considerable pressure is encountered at depth, a "lubricator" is required in addition. The reel now used for hoisting the smaller instruments is mounted either on an automobile or on a small trailer and is operated by mechanical power; it formerly was cranked by hand. The use of mechanical power enables one man to run these instruments in and out of a deep well many times faster than was done previously by a crew of men taking turns at a hand crank.

Improved Power Plants

The lighter and more inefficient power plants that characterized oil fields a decade ago are being replaced rapidly

[27] The drill-stem tester is essentially a conical formation packer containing a back-pressure valve, so arranged that it may be lowered into the well on the end of the drill stem, in place of the bit, with the drilling fluid excluded from the drill stem. When the tester is seated on the bottom and a shut-off is effected between the drill pipe and the walls of the hole by the weight of the drill stem, the valve is opened by application of additional weight. Fluid in the sand, if any, then has free access to the empty drill pipe. The valve is closed by lifting the drill stem, and any fluid trapped in the drill pipe is brought to the surface when the pipe is withdrawn.

by heavier, more efficient, better-balanced units.[28] An outstanding feature of this change is the trend toward the unitization of power equipment used in drilling operations. By this is meant the arrangement of all power equipment or important segments thereof into compact units, and the movement of these units rather than the individual machines and devices has been a large factor in saving labor as compared with the former methods of rigging up, tearing down, and moving drilling equipment.

Steam still is the predominant source of power in oil-well drilling, although within the last few years Diesel-electric power plants have replaced steam plants in areas where fuel costs are high and water for boiler use is obtained with difficulty. Electric power, obtained as alternating current from nearby transmission lines and either used in alternating-current motors or in direct-current motor generators, also is frequently used for drilling purposes. Internal-combustion engines are particularly adaptable to portable and mobile drilling units for both shallow and moderately deep drilling. These are quickly rigged up and require little labor compared with the standard drilling rigs.

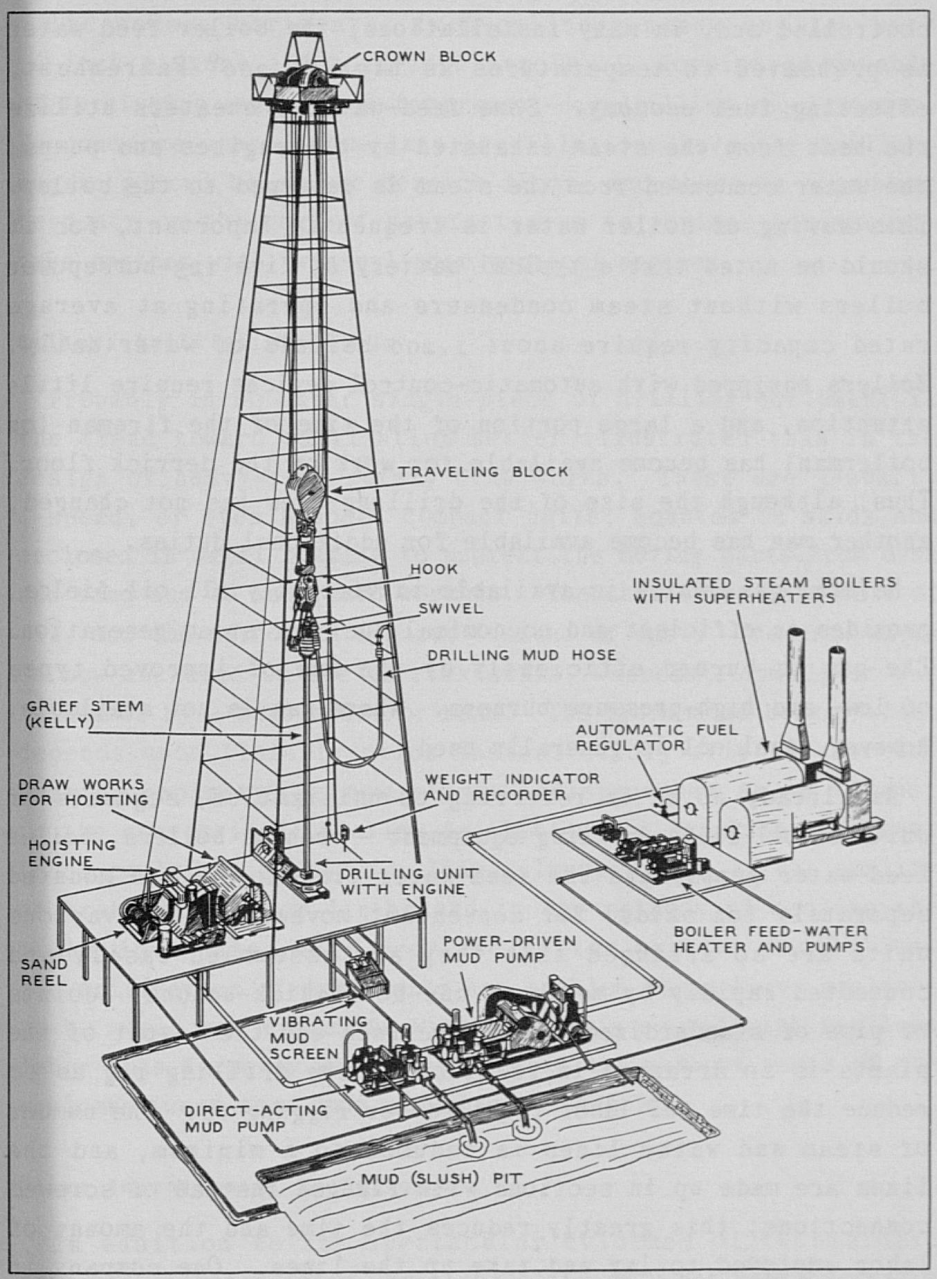
The trend toward increased power and higher efficiencies has brought about radical changes in oil-field steam plants. The typical 125-horsepower boiler of modern design generates steam at pressures of 300 to 350 pounds per square inch, compared with 125 to 175 pounds for older types of boilers. Superheaters raise the steam to a temperature as high as 500° Fahrenheit, increasing the boiler capacity 20 to 30 percent. A boiler of late design (see figure 19), with neither rivets nor the customary steam dome, is equipped with a superheater built in the stack end of the boiler and utilizes the heat normally lost in the flue gases; the entire boiler is insulated to reduce heat losses by radiation.

The development of automatic steam-plant control devices has reduced to a minimum the labor required for operating the boilers. Modern boiler plants are provided with automatic fuel-control devices, and some have automatic-damper and forced-draft controls. Boiler feed-water pumps are automatically

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[28] "Modern Trends in Surface Drilling Equipment," *World Petroleum*, Vol. IX, No. 5 (May 1938), pp. 64-71, 81.

Figure 19.- IMPORTANT FEATURES OF A MODERN ROTARY-DRILLING RIG AND ACCOMPANYING SURFACE EQUIPMENT



ROSS AND KIESSLING
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WPA-NATIONAL RESEARCH PROJECT E-126

The trend toward increased power and higher efficiencies has brought about many radical changes in the design, construction, and arrangement of oil-well drilling machinery. Boilers, pumps, engines, and other pieces of surface equipment used in modern drilling are grouped in compact units and are mounted on skids to facilitate moving and rigging up. The above illustration shows a late type of steam-driven rotary rig. Other arrangements and types of equipment than those shown are also used. For example, alternative equipment might include an auxiliary hoist and the rotary table might be driven by the engine for this hoist; also the table might be driven from the main draw works, which is the common practice today. The source of power might be horizontal steam engines, internal-combustion engines (including Diesel engines), or electric motors. This illustration has been simplified to emphasize the most important aspects of equipment, and the experienced eye will note that braces for the derrick and other items of equipment have been omitted for the purpose of the presentation.

controlled and, in many installations, the boiler feed water is preheated to temperatures as high as 200° Fahrenheit, effecting fuel economy. Some feed-water preheaters utilize the heat from the steam exhausted by the engines and pumps; the water condensed from the steam is returned to the boiler. This saving of boiler water is frequently important, for it should be noted that a typical battery of five 125-horsepower boilers without steam condensers and operating at average rated capacity require about 1,200 barrels of water daily. Boilers equipped with automatic-control devices require little attention, and a large portion of the time of the fireman (or boilerman) has become available for work on the derrick floor. Thus, although the size of the drilling crew has not changed, another man has become available for additional duties.

Natural gas, which is available in virtually all oil fields, provides an efficient and economical fuel for steam generation. The gas is burned efficiently by the use of improved types of low- and high-pressure burners. Where gas is not available, however, fuel oil is generally used.

As already noted in referring to unitization, segments or units of oil-field drilling equipment - such as boilers, boiler feed-water pumps, and the feed-water preheater - are mounted separately (on skids) for convenient movement. The various units are so arranged that they are assembled easily and connected rapidly by means of one-bolt quick-unions. Joints of pipe of standardized length are used and the layout of the plants is so arranged in relation to the drilling rig as to reduce the time and labor required for rigging up. The number of steam and water lines is reduced to a minimum, and the lines are made up in sections with flanged instead of screwed connections; this greatly reduces the time and the amount of labor employed to lay and take up the lines. One company in the Gulf Coast area has developed a standard layout for its rigs that requires little rearrangement in moving from one site to another. The movement of the rig and equipment, moreover, is handled by a regular-size crew on its usual shift, whereas formerly all three crews (required for continuous drilling) were drafted for work on the same shift.[29]

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[29] J. U. Teague, "Increased Drilling Speed in the Gulf Coast," *The Oil and Gas Journal*, Vol. 35, No. 48 (Apr. 15, 1937), p. 85.

The modern horizontal twin-cylinder steam engine, with 14-inch pistons and a 14-inch stroke, is considered capable of furnishing ample power for present-day drilling requirements. To conserve space, some late installations have the drilling engine placed below the derrick floor, and there is a growing tendency on the part of manufacturers to replace horizontal-type engines with twin-cylinder vertical engines.

Unitary Drilling Machinery

Probably in no other single piece of drilling equipment is the trend toward unitization better illustrated than in the design of heavy-duty rotary draw works. These are 3-shaft, 4-speed, or even 8-speed compact units, mounted on skids and enclosed in metal housing to protect the moving parts from dust and sand and to safeguard workmen. The chains run in a bath of oil, and the sprockets are cut instead of cast. The draw works is now anchored to the derrick sills, whereas formerly it was held down by a head board or beam. The hydromatic brake, which depends upon fluid friction instead of dry friction for its braking capacity, is now almost indispensable as an adjunct to the conventional braking facilities for handling the heavy loads employed in deep drilling. Improvements in the quality of brake lagging or lining and in the methods of cooling the brake drums also have provided better braking facilities. The unitization of draw works has enabled these heavy machines to be moved and rigged up with greater ease and with far less labor than formerly was possible when the various parts of the equipment were torn down and then reassembled.

Other Improvements in Equipment

In addition to the spectacular evidence of technologic progress, already noted, drilling efficiency has been increased by a large number of improvements made in auxiliary equipment. In some instances, such changes had a significant effect in themselves; in others, the combined effect of a number of minor changes was important. The effective control of drilling operations, for example, is aided by instruments and gauges. These indicate the weight of the drill stem on the bit, the load on the derrick, the pressure of the mud pumps, the torque in the drill pipe, and the speed of the rotary table. These

gauges often are supplemented by recording instruments that provide a continuous record of the drilling performance. The information provided by gauges and recording instruments makes possible a high degree of technical efficiency in drilling and represents data needed for the development of improved methods and equipment.

Several types of automatic controls have been developed for feeding the bit into the hole as drilling progresses. These methods of control, although not yet widely used, depend upon either the torque in the drill pipe or the weight of the drill pipe on the bit. The use of automatic feed control not only lightens the driller's duties but permits more uniform drilling performance; it also results in drilling a straighter hole, with a greater footage per bit, and reduces the physical wear and strain on the drilling equipment.

There is a growing tendency to drive the rotary table with an auxiliary engine that is smaller than the horizontal drilling engine usually employed. This is done for reasons of economy, because less power is required to drive the rotary table than is needed for some other tasks; thus the larger engine is retained, but its use is limited to heavy work. The smaller engine driving the rotary table sometimes is a separate vertical twin-cylinder engine and sometimes a small engine that is also used to drive a stand-by hoist. Rigs are equipped with stand-by hoists in areas where the drilling is deep and likely to be difficult and where such hoists may be needed for raising the drill pipe in an emergency. These stand-by hoists should not be confused with the lighter power-driven sand reels which are becoming standard equipment on deep-drilling rigs and are used for running wire-line core barrels and retractable drilling bits and for other purposes requiring a sand line.

The kelly or "grief" joint, drill pipe, drill collar, and bit constitute the drill stem, a slender shaft subjected to hard usage. The first drill pipe employed was ordinary tubing or line pipe, capable of drilling to a depth of 2,000 feet. It was unsuitable for deeper drilling, however, and in time was replaced by stronger drill pipe made from special steel and provided with upset ends. In addition to constantly better steels, the wall thickness of the pipe was increased, and better threads were cut to conform with standardized

specifications; eventually there evolved the modern drill stem capable of meeting the difficult conditions and severe strains incident to deep drilling. Present-day drill-pipe joints are 30 feet long compared with the 20-foot lengths used previously, and they are heat-treated. The tool joints (special couplings used for connecting the joints of drill pipe in "stands") generally are made of chrome-nickel steel and given additional hardening by heat-treatment processes. This alloy embodies a desirable combination of hardness, toughness, strength, and resistance to fatigue. The tool joints are provided with truncated V-formed or square (or nearly square) two-step threads, have full-hole inside diameters, and are guarded from excessive external wear by rubber protectors placed near the end of the drill-pipe joint. Because of the larger opening they make possible, full-hole tool joints have materially reduced the pump pressures necessary for circulating the drilling mud.

As the length of pipe increased, the kelly joint also was lengthened so that the longer pipe joints could be handled efficiently; it is also protected from wear by the use of roller drive-bushings. The kelly joint is at the top of the heavy drill stem that is suspended from a large swivel in which roller bearings, riding in a bath of oil, have replaced bronze bearings. The hose through which mud is supplied to the drill stem is manufactured from better material, and improved clamping methods are used to provide greater service and safety; at some operations the conventional rubber hose has been replaced by one made entirely of steel.

The common rotary bits are the fishtail (including the drag or modified fishtail bit), disc, and roller or cone types, used for soft, medium to moderately hard, and hard formations, respectively. The fishtail bit was used in early drilling and is now faced with extremely hard alloy to insure longer life; a recent type is provided with "weld-in" fins. Increasing the wearing qualities of bits by the use of higher-quality steels and by better heat-treating methods has saved time and labor in drilling because it has reduced the number of times the drill pipe had to be withdrawn for replacement of bits and reinserted in the hole thereafter. Wire-line drilling methods also have been developed, as has been noted; these permit removal of a retractable bit without withdrawal of the drill

pipe. They are being improved continually and are particularly important in deep drilling in the Gulf Coast region.

Early types of circulating mud pumps seem small and weak compared with the powerful equipment used today. The first mud pumps were common water or line pumps of small size; modern equipment comprises large, heavy direct-acting or power-driven pumps with piston strokes as long as 18 to 20 inches and capable of delivering as much as 700 to 800 gallons per minute against working pressures of around 800 pounds per square inch. Under special conditions of high pressure, two or more such pumps are connected in series or "compounded" for pumping against pressures as high as 3,000 pounds per square inch. Single power-driven mud or "slush" pumps tested to 6,000 pounds per square inch are now available for a working pressure of 3,000 pounds. In comparison with earlier practice, the primary installation of a powerful pump of this kind reduces the labor and time required for changing from low- to high-pressure equipment when high pressures were found. In ordinary practice two heavy-duty, direct-acting steam pumps usually are employed, one serving as a stand-by for the other; however, because of the increased efficiency obtained from the use of power-driven pumps in connection with steam-expansion engines, the recent trend is toward the use of one pump of this type instead of one of the direct-acting pumps. In very deep drilling a third stand-by high-pressure pump is also frequently provided. Friction in the mud-discharge lines, which requires extra pumping effort and power consumption, is reduced by eliminating sharp angles and bends in the pipe. Each pumping unit, complete in itself, is mounted on skids for easier transportation and connected with the other units of the rig by means of quick-unions, thus reducing the time needed in rigging up.

Portable Drilling Rigs.- As drilling with standard equipment frequently is expensive and as there is much uncertainty in finding new oil fields of commercial importance, portable rotary-drilling machines, which for many years have been used in geological exploration, are finding new and greater uses in oil-well drilling. In addition to exploratory work, they are also used in the development of oil pools lying at moderate depths.

The drilling units of this type have undergone remarkable development within the last few years. The engines, pumps, draw works, rotary table, and derrick are all mounted on a single truck or trailer. The derrick, ranging from 28 to 50 feet in height, is attached to the rear of the truck and folds over the cab when in transit; a more recent type is equipped with a derrick 84 feet in height that folds over the crawler on which it is mounted. Capable of drilling a "slim" hole to a depth of 4,000 or 6,000 feet, at a cost greatly reduced in comparison with that of standard rotary drilling,[30] these light drilling machines are destined to occupy a prominent position in future drilling operations. The larger units are powered by Diesel engines, with additional power available from the truck engine. A crew of four or five men is employed on each shift - the same number used on the standard rotary rigs. The equipment is so unitized that drilling can be begun within a short time after the machine arrives at a drilling site.

Better Materials

Through technologic progress in the metallurgical industries better materials are now available for use in oil drilling. Modern oil-field equipment requires a wide variety of alloys and special metal products.[31] Special steel alloys, involving the use of nickel, copper, manganese, silicon, molybdenum, and other metals, have been developed for specific uses in the oil industry. These provide a higher degree of tensile strength, greater toughness and hardness, greater resistance to fatigue and to corrosion, and better properties for welding.

Rubber is an important material in the manufacture of oil-drilling equipment. The quality of rubber has been improved, and rubber or rubber compositions are now available that are exceedingly tough and resistant to the action of oil. Rubber or rubber products are used in the valves and pistons of mud

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[30] Reported costs of small-hole drilling vary widely, depending upon depths and location of drilling. For example, an indicated range of cost is from $1.00 per foot in the most favorable instances to about $2.50 in the less favorable districts, which is much less than for large-diameter holes drilled with a heavy, standard rotary rig. (See B. Mills and F. B. Taylor, "Small Hole Drilling Holds Wide Possibilities," *The Oil Weekly*, Vol. 90, No. 9 [Aug. 8, 1938], p. 22.) Drilling costs are even lower where depths are shallow (500 to 1,000 feet) and may be as low as $0.50 to $1.00 per foot.

[31] R. Seiden, "Metallurgical Progress in Drilling, Production and Pipe Line Equipment," *The Oil Weekly*, Vol. 87, No. 4 (Oct. 4, 1937), pp. 34-6.

pumps for reducing the rapid wear caused by the abrasive action of sand in the circulating fluid; in the rams of blow-out preventers for shutting off high pressures; in oil savers for preventing the flow of oil and gas while tools, wire line, or tubing is withdrawn from a flowing well; in packing, belting, rotary hose, and for many similar uses. Synthetic rubbers and compositions that have special oil-resisting properties are also available.

As drilling technique advanced, the disadvantages of a lack of standardization of equipment became apparent. There was great variation in the sizes, threads, weights, and other features of oil-field equipment. No serious progress was made toward standardization until 1919, when the American Petroleum Institute was formed; one of the first functions of this organization was to set up standards for casing, drill pipe, tool joints, rig irons, and other equipment. This program of standardization of drilling equipment has had a marked influence upon oil-well drilling practices and has resulted in enormous savings for the industry.

Improved Completion Practices

In the earlier days of cable-tool drilling, before such pressure-control equipment as drilling gates, control casing heads, and oil savers was introduced and before drillers had adopted the practice of loading the hole with water before drilling into the high-pressure sands, the "bringing in" of an oil well was more or less a spectacular event in which the drilling tools were sometimes blown into the air and the well went out of control. All this has been changed by modern drilling technique. Wells having enormous formation pressures are brought in today under complete control, attended by no greater confusion than that accompanying ordinary drilling.

Except when cable tools are used for special reasons, most rotary-drilled wells are completed in the producing formation with the same rotary tools with which the well was drilled. Good practice requires that suitable precautions be taken against a possible blow-out, and control equipment - consisting of drilling gates and blow-out preventers - is screwed to the top of the cemented casing, which usually extends downward to the top of the oil horizon; this control equipment is

anchored firmly by steel rods and clamps before the producing formations are entered. After the pay sand is drilled to the desired depth the blow-out-preventer equipment is removed, and surface-flow connections are installed while the hole is still loaded with drilling mud. If the pressures are high, tubing is lowered into the well and packed off at the surface, a "Christmas tree" or system of well-head connections is installed, and the well is "washed-in" (started flowing) by circulating oil, water, or some other fluid lighter than the heavy drilling mud. Sometimes gas under high pressure is circulated to start the well flowing. If pressure in the producing formation is too low to cause the well to flow under a fluid column the fluid is bailed or swabbed from the well until the pressure due to the fluid weight is reduced to a point that will permit natural flow. In some areas it is found more practicable to drill into the producing formation with cable tools after drilling with the rotary drill has been completed to the top of the pay sand. This practice requires more time and a larger outlay of labor than completion with the rotary drill.

The use of efficient blow-out preventers has enabled drilling operations to be carried on safely in areas where well pressures are exceedingly high. These devices are provided with rubber or rubber-faced steel rams that can be closed around the drill pipe in an emergency. Blow-out preventers are operated manually by means of long extension arms, hydraulically by water pressure obtained from an auxiliary pump, or even automatically by excessive pressure from the well itself. With reference to well-head connections for producing wells, many operators prefer to use shop-assembled Christmas trees because they are more compact, more tightly assembled, shop-tested for pressure, and quicker to install than those assembled on the well by the field crew. Most preassembled units are provided with flanged connections that reduce the time and labor required for installation.

In areas in which unconsolidated or loose sands tend to flow in and clog the well, various types of screens or perforated liners are placed opposite the oil horizon before the well is completed. A recent practice involves setting the well casing through the productive sands and, after the casing has been cemented, perforating it in the productive zone by means

of a gun perforator.[32] The latter is a device with a number of short gun barrels from which large steel bullets are shot through the casing wall and cement jacket, into the formation, by a firing arrangement controlled electrically from the surface. The holes so opened permit oil and gas to enter the well. Gun perforation usually is done by specialized service contractors who maintain mobile hoisting units and trained crews. Although the practice is comparatively new, during a period of a little over 2 years prior to 1937 more than 3,000 perforation jobs for 431 different customers were performed in the Gulf Coast area alone.[33]

Another relatively new well-completion practice is the controlled-pressure method[34] in which the circulating medium is oil or oil and gas instead of drilling mud. The advantages of this method are that the well is permitted to flow while drilling progresses, the productivity of each foot of sand drilled is determined in the course of drilling, and the capacity of porous, low-pressure sands to produce is unimpaired, for no mud comes in contact with the face of the sand. This method is, of course, particularly applicable to reservoirs with relatively low pressure. Another method used under roughly the same conditions is a variation of controlled-pressure drilling; it requires reversal of the circulating medium in which oil, pumped down the casing, is circulated to the surface through the inside of the drill pipe.[35] This procedure is particularly successful for completing wells in the East Texas and West Texas fields. In this instance, furthermore, equipment used is of the portable type rigged up at the well after the casing is cemented, releasing the heavier drilling equipment for the drilling of other wells. Although this arrangement speeds up drilling operations and increases the output of the regular drilling crews, it provides employment for additional crews specializing in controlled-pressure drilling operations.

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[32] E. R. Smith, "Casing Perforation by Gunfire and Its Application to Oil Production," *Mining and Metallurgy*, Vol. 17, No. 353 (May 1936), pp. 243-6.

[33] I. W. Alcorn and J. U. Teague, "Bottom-Hole Well-Completion Methods in the Gulf Coast," *Drilling and Production Practice, 1937* (New York: American Petroleum Institute, 1938), p. 30.

[34] J. S. Ross, "Review of Controlled-Pressure Drilling Method," *The Petroleum Engineer*, Vol. VII, No. XIII (Sept. 1936), pp. 116-21.

[35] F. G. Beckman, "Completing Wells by Reverse Circulation in East Texas," *The Oil and Gas Journal*, Vol. 36, No. 43 (Mar. 10, 1938), pp. 45-6.

Efficient Transportation of Machinery and Supplies

In contrast to the early horse-and-wagon transport, high-speed trucks, equipped with tandem dual wheels capable of supporting great loads and drawing trailers, are used today for transporting heavy rigs, equipment, and drilling supplies. Improved roads - sometimes paved - connect the drilling field with the city storehouse or machine shop, or link one field with another, permitting the rapid movement of drilling machinery and supplies. As a general rule, graded - and sometimes surfaced - field roads are built to facilitate movement of drilling rigs from one drilling location to another. In swampy areas it is often necessary to build miles of road entirely of wood.

Trucks are loaded largely by means of heavy, mobile cranes or cranes mounted on trucks, and heavy pieces of drilling machinery are manipulated into place either by powerful tractors or by winch lines operated from trucks.

Along the Gulf Coast, where drilling operations extend offshore, drilling equipment and materials are transported by barges and launches. Besides those engaged in the actual drilling operations, a large number of men are employed on dredges, piledrivers, and in performing other duties accessory to this type of drilling. Because of the unusual conditions under which such wells are drilled, special operating techniques have been developed that provide employment for men familiar with them.

The development of better transportation facilities, the unitization of drilling equipment, and the standardization of a carefully planned rig lay-out have reduced materially the labor and time needed for moving from one drilling site to another. Recently an instance was noted where deep drilling rigs were moved 5 miles in 9 hours.[36]

PROSPECTS OF FURTHER TECHNICAL PROGRESS IN DRILLING

Taking into consideration the rapid developments and achievements that have characterized oil-well drilling in the last 2 decades, and noting the present-day trend toward deeper drilling, the authors believe that technical progress in

[36] Teague, *loc. cit.*

drilling will continue. It seems probable, moreover, that future advances will be more in the nature of improvements of existing techniques or suggested by these techniques and that changes in the fundamental principles of drilling technology are unlikely.

Recent drilling operations have demonstrated that equipment available today can drill to a depth of 15,000 feet, a little over 2,000 feet deeper than the previous record depth (see figure 18). So little is yet known of the nature of the deep sands or of the quantity and character of the fluid they may contain under exceedingly high pressure and temperature conditions that any prophecy as to what may be expected in drilling very deep sands is hardly more than a conjecture. Nevertheless, it appears that whether or not the very deep sands can be exploited profitably under any prevailing proration system and price structure will depend in large measure upon improvements in existing drilling techniques and in the quality of the materials used in the manufacture of tubular goods, tools, and other drilling equipment; upon the character, content, and productive capacity of the deeply buried sands; and upon the continued development of efficient methods for recovering oil from great depths.

In spite of past technologic progress, drilling equipment still has inherent weaknesses and inefficiencies that are subject to further improvement.[37] Notable improvement may be anticipated, for example, in the manufacture of stronger, better alloy steels. Further metallurgical advances are expected to give steel tubular goods the greater tensile strength required to withstand the more severe strains imposed by deeper drilling. Moreover, in the not-too-distant future there will probably be available a special alloy-steel drill pipe and casing having a yield point nearly half again greater than that of the best-grade pipe now on the market. Stronger steels also would permit the design and manufacture of smaller, lighter drilling machinery and equipment.

Aided by technical improvements and more extensive use, automatic feed control of drilling is likely to replace the conventional method of manual control. Automatic feed control has the desirable results of providing a steadier pressure

[37] J. E. Brantly, "Many Improvements Required in Modern Rotary Drilling Equipment," *World Petroleum*, Vol. VIII, No. 2 (Feb. 1937), pp. 62-6.

on the bit and a more even rate of feed than are attained by manual control. Since these are important factors in drilling straight holes and obtaining high footage per bit, as they eliminate crooked-hole troubles and reduce the frequency of bit changes, automatic feed control promises to increase output per man in terms of footage drilled per unit of time. Its adoption will not entirely replace the driller, however, although he will have more time for attention to other work about the drill rig.

It is not improbable that in the future deep rotary drilling will be accomplished with bits driven by turbines or hydraulic motors attached to the lower end of the drill stem, deriving their power from the energy imparted to the drilling fluid by the mud pumps. Although turbo-drills,[38] as these are called, have been under development in the Soviet Union for many years, they are now attracting attention in this country. Only recently a well in southern California, using a newly perfected drill of this type, was sunk 4,000 feet in less than a month. This is the first well drilled by this method in America. It is reported that since the bit rotates much faster, greater drilling speeds are attainable than with the conventional rotary system in general use today. Another interesting feature is that loss of power and wear of drill pipe owing to friction are largely eliminated, since the drill stem does not rotate.

Most failures in the rotary drill stem occur at the point where the tool joint is connected to the drill pipe, and undoubtedly a better method of connection will be developed. Welding of the tool joint to the pipe has had considerable success, but in some instances this method has tended to impair the crystalline structure of the metal of the heat-treated drill-pipe joint at the point of the weld. Since twist-off or breakage of the drill pipe causes considerable delay in drilling, improvement of the drill stem through the use of better alloys and better methods of connecting tool joints would increase the output of the drilling crew by maintaining continuity of drilling.

Further progress in unitizing drilling equipment is also expected. The costs involved in rigging up, tearing down,

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[38] "Well Drilled With Power Unit on Bottom," *Petroleum World*, Vol. XXXV, No. 5 (May 1938), p. 63.

and moving heavy equipment from one well location to another are large and increase as equipment is made heavier and bigger. The rapid progress during the last few years in unitizing new drilling equipment, in standardizing rig lay-outs, and in developing better transportation facilities will continue. Where the drilling is not excessively deep, more and more portable drilling rigs will be used. These, being mounted on trucks, crawlers, trailers, or skids, and powered by internal-combustion engines, can be rigged up at a well with a minimum of labor.

The new drilling conditions at great depths will require the development and application of new technologic knowledge and improved techniques. For example, there will be the problem of providing drilling muds that will have enough weight to control not only normal hydrostatic pressure but also abnormally high pressures, and that will meet the conditions of increased earth temperature at these depths. Such muds must have proper viscosity and wall-building characteristics but must not be too viscous for suitable circulation. They must also have thixotropic or jellying properties that will permit retention of cuttings in suspension if circulation should be stopped. The industrial use of colloidal muds is a comparatively new science, and the importance of properly conditioned mud fluid in deep rotary-well drilling is such that it merits thorough study to determine its properties and behavior under high pressures and temperatures.

Where high hydrostatic pressures are combined with certain plastic conditions of some types of deeply buried shale formations, new difficulties lie in the path of very deep drilling. The so-called "heaving-shale" problem until recently has been unsurmountable in some regions, notably in the Gulf Coast and California. The tendency of very deep, compacted shales to slough or "squeeze" into the hole during drilling is being combatted by the use of specially prepared muds, chemicals, and controlled-pressure drilling methods. Through better understanding of "earth pressures" and the difficulties they involve, technologists undoubtedly will devise better methods for penetrating the deep formations.

Anticipated advancements in existing drilling techniques probably will not reduce over-all employment opportunities in the oil fields. There has been little change in the number

of men composing the drilling crew or in the number of men serving a drilling crew, and unless the fundamental principles of drilling are modified radically, approximately the same number of men will be required on the derrick floor in the future as is required today. Furthermore, although drilling speeds have been greatly increased and this trend probably will continue, the increased depth of future wells promises to offset such gains in technical efficiency. Most significant, however, is the fact that the demand for petroleum and natural gas has grown steadily and probably will continue to expand; this will require more wells and more labor to drill them. When other factors affecting labor requirements, mentioned in chapter XI, are considered, all indications point toward increased employment in drilling. It should be noted, however, that more intensive technical training will be required for a larger proportion of the labor force in the future. Progressive employers recognize the importance of such training for occupations in drilling and in other developmental activities as well as in various field and office departments. This tendency will continue to raise the quality and skill of labor in the oil fields but it will not help the older men who find it difficult to adapt themselves to methods with which they are unfamiliar.

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CHAPTER VI

TECHNOLOGIC ADVANCES IN PRODUCTION*

Improvements in recovery techniques have enabled constantly larger proportions of the gas and oil in the underground reservoir to be captured, once the driller has struck pay sand. The development of production engineering, throughout three-quarters of a century, represented a tendency toward greater efficiency and economy of operation and toward a larger proportionate recovery of the contents of the pool. As was true of drilling practice, however, early techniques in production were primitive and comparatively inefficient. This is illustrated by a few landmarks. For example, in the Bradford (Pennsylvania) field and other areas that were drilled and produced by early oil-recovery methods, only 10 to 20 percent of the oil originally in the sand was recovered when the fields reached the stage where no more oil could be recovered economically with the technologic practice then in use.[1] Today, by contrast, at least 40 and possibly more than 50 percent of the oil originally in place in the huge East Texas field will be recovered.[2] Even greater oil-recovery efficiencies are anticipated in some exceptionally well managed fields, such as Sugarland, Texas, where the oil-recovery expectancy is 70 percent[3] and the decline in pressure is low because as much as 85 percent of the gas produced with the oil has been returned to the reservoir.

It is difficult to differentiate the influence of more efficient production engineering from that of other important, closely related factors also tending to increase output per man. In chapter III, for example, it was noted that the westward movement of the industry was toward sands with a larger

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*By J. S. Ross; W. B. Berwald, Senior Petroleum Engineer, U. S. Bureau of Mines, Bartlesville, Oklahoma; O. E. Kiessling; and Andrew W. Rowley, Oil Editor, *Tulsa Tribune*, Tulsa, Oklahoma.

[1] J. O. Lewis, *Methods for Increasing the Recovery from Oil Sands* (1st ed.; U. S. Dept. Int., Bur. Mines, Bull. No. 148, Oct. 1917), p. 8; see also E. Steidle, "Some Basic Problems in the Conservation and Future Production of Pennsylvania Grade Crude Oil," *The Oil Weekly*, Vol. 74, No. 1 (June 18, 1934), p. 22.

[2] C. E. Reistle, Jr., "East Texas Production," *The Oil Weekly*, Vol. 72, No. 11 (Feb. 26, 1934), p. 15.

[3] H. C. Miller and B. E. Lindsly, "Report on Petroleum Development and Production," *Petroleum Investigation* (U. S. Congress, House of Representatives, Hearings on H. Res. 441, 73d Cong., Recess, 1934), part 2, p. 1221.

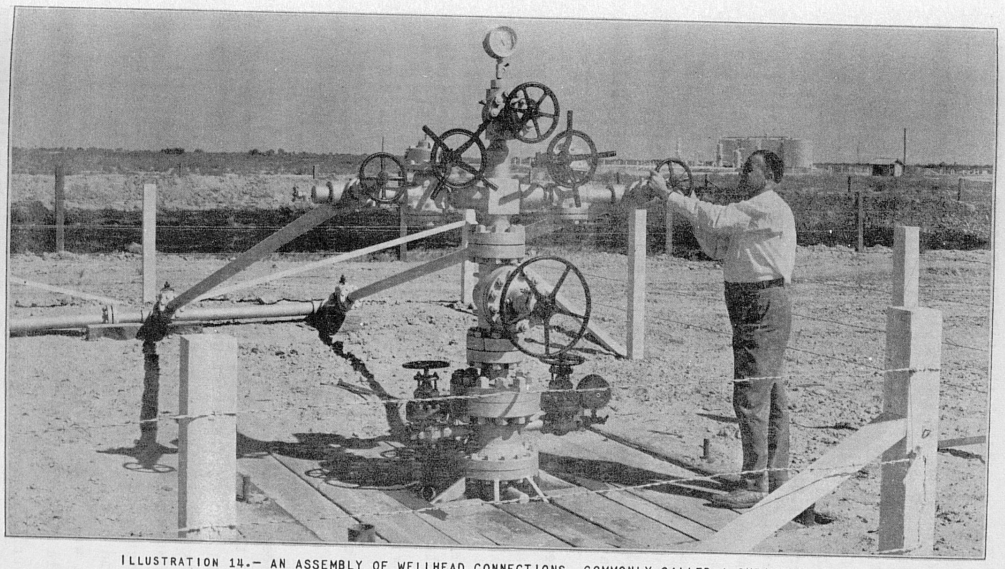


ILLUSTRATION 14.— AN ASSEMBLY OF WELLHEAD CONNECTIONS, COMMONLY CALLED A CHRISTMAS TREE, IS AN IMPORTANT ITEM OF OIL— OR GAS—WELL EQUIPMENT

This well is flowing as a result of high pressures in the producing formation. The derrick used while drilling has been moved to a new location and is being used to drill another well. Later, when the pressure in the underground reservoir is reduced and natural flow ceases, the oil will have to be lifted by artificial means, as by pumping.

potential productive capacity than the pools that were first drilled. Thus a part of the rising average output per man was due to the discovery of more abundant reserves. Another part, however, was due to the ability of the technologist to appropriate for the needs of man a greater share of what nature provided. Notable progress toward more efficient recovery practices increased the amount of oil recovered per unit of labor expended. Both factors contributed toward the lower average labor requirements per unit of product as noted in chapter II. Moreover, production technology - viewed in the narrow sense of operations performed between the striking of pay sand and the abandonment of the well - is also of interest because it represents a crucial stage in the processes of the industry. The ability of the latter to carry on extensive programs of exploration and drilling and to meet other heavy expenses of the business is largely dependent upon the success of the engineer in obtaining enough oil to meet these costs from wells that are productive.

EARLY PRODUCTION PRACTICES

The first wells were shallow and did not flow naturally, and the simple brine-pumping methods used in the salt industry were adopted for lifting the oil to the surface. The early equipment consisted of brass tubing containing wooden "sucker" rods, which transmitted a reciprocating motion to a traveling valve in a "working barrel" attached to the bottom of the tubing. The sucker rods were attached to the end of the walking beam, which, when driven by a steam engine and crank, imparted the necessary reciprocating motion to the sucker rods and pump; many of the first wells, however, were reported to have been pumped by manual power. From these primitive pumping devices were developed the common plunger-type pumps and the "beam" method of pumping oil wells. The oil was raised to the upper end of the tubing and then flowed into a large cup, from which a wooden trough led to a large rectangular wooden box buried in the ground near the derrick.

The buried tanks were made of matched planks, held together by clamps fastened with keys. They were built on the site from lumber cut near the well and ranged in capacity from 10 to 250 barrels. When sunk in the ground, only the upper 1 or

2 feet extended above the surface. The tops of the boxes or tanks were covered with planks overlain with earth or sod.

Simple pitcher pumps, then in common use for pumping shallow waterwells and cisterns, were used to pump the oil from these tanks into wooden barrels. These hand-operated pumps were installed so as to permit setting a barrel under the lip of the pump; all shipments of oil were made in wooden barrels or containers. Under the methods prevailing in the early days, the tasks of pumping, handling, and transporting crude oil required a great amount of manual labor, and large numbers of men sought and found employment in the oil fields.

By 1861 improvements in drilling practice and equipment permitted deeper drilling in the search for larger production. In May of that year the first flowing well was completed at Oil Creek, Pennsylvania,[4] and further advances were made in adapting the existing production technology to wells of this type.

As flowing wells produced larger quantities of oil than pumped wells, it soon was found that the older types of rectangular boxes did not provide adequate storage facilities. Furthermore, it was difficult to prevent the buried boxes from leaking, and loss of oil by seepage was appreciable. Thus the buried boxes were replaced by vertical wooden tanks with tapered staves and flat hoops constructed of native lumber - mostly pine - by a rapidly growing cooperage industry. Use of the vertical tanks required that the well tubing be continued up into the derrick to a point high enough to permit the oil to flow into the tops of the tanks. In addition, the valves or gates that were installed on the pipe, so that the well could be shut in when the tanks were filled, represented the first type of wellhead control on producing wells.

EARLY ADVANCES IN PRODUCTION METHODS

As the production of oil expanded, the technique of oil extraction improved. From the first days of the industry technologists have sought to operate wells more economically and to recover a larger proportion of the potentially available oil. An early development of this type was the practice of operating more than one pumping engine from a central boiler.

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[4] "Early Drilling and Production Methods Indicate Mechanical Genius," *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934), p. 28.

This was made possible as iron steam pipe with threaded ends and short couplings became available in adequate quantities and at prices that permitted their use. Explosives were also employed at an early date to increase the amount of oil recovered.

Oil-well "shooting" or blasting began in 1865 when the first torpedo was exploded in a well in Oil Creek, Pennsylvania.[5] It was so effective in shattering the hard, tight oil sands and in increasing production by permitting the fluid to flow into the drill hole that it became widespread in early production engineering.[6] Oil-well blasting was such standard practice that it was even done in routine fashion where the underlying oil-bearing sands were soft or unconsolidated; the subsequent development of engineering knowledge, however, indicated that blasting under such conditions was generally unsuccessful and also frequently impaired the potential productive capacity of the well.

A growing demand for high explosives and for capable oil-well shooters brought about the growth of a small auxiliary industry specializing in oil-well shooting. Because of the hazardous nature of his occupation, the well-shooter became a colorful figure in the oil fields. The nitroglycerin was manufactured and stored in isolated spots near the producing areas and was transported to the wells in specially built, cushioned carriages known as "soup wagons." At the well the explosive was poured into metal containers or "shells", which were lowered into the wellhole on a shooter's line. Detonation of the charge was accomplished by dropping a weight or "go-devil" on a firing device or by dropping from the surface a "squib shot" containing a fuse and detonation cap. A safer method of detonation, employing electrically operated detonators, was developed later and used extensively.

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[5] "How Roberts Smote the Rock," *The Derrick's Hand-Book of Petroleum: Petroleum Developments From 1859 to 1898* (Oil City, Pa.: Derrick Publishing Co., 1898), p. 1045; for detailed account of oil-well shooting see C. O. Rison, "Manufacture of Nitroglycerin and Use of High Explosives in Oil and Gas Wells," *Transactions of the American Institute of Mining and Metallurgical Engineers: Petroleum Development and Technology, 1928-29*, Vol. 82 (1929), pp. 240-312.

[6] The reasons for the ready acceptance of the oil-well torpedo in 1865-66 and a description of this device are given in S. F. Peckham, "Report on the Production, Technology, and Uses of Petroleum and Its Products," *Tenth Census of the United States: 1880*, Vol. X, "Special Reports on Petroleum, Coke and Building Stones" (U. S. Dept. Int., Census Office, 1884), pp. 84-5. For other early discussions of the oil-well torpedo see J. T. Henry, *The Early and Later History of Petroleum, With Authentic Facts in Regard to Its Development in Western Pennsylvania* (Philadelphia, Pa.: Jas. B. Rodgers Co., 1873), pp. 251-4; J. F. Carll, *The Geology of the Oil Regions of Warren, Venango, Clarion, and Butler Counties* (Harrisburg, Pa.: Board of Commissioners, Second Pennsylvania Geological Survey, 1880), pp. 325-9.

The principal improvements in shooting technique have been in the manner of placing and tamping the charge and in the methods of detonating the explosive.[7] Early detonating devices now have been replaced by the time bomb, which may be set to explode in ½ to 24 hours after the shot is placed. This development has lessened the danger of premature explosion, which was not uncommon under older methods. Because of the danger of accidental explosion in transporting and handling raw liquid nitroglycerin, particularly in populated areas, solidified forms of explosive have been used in many instances. Oil-well shooting today is used less extensively than formerly; in many fields where the oil is produced from formations that are predominantly limestone, moreover, it is either employed in conjunction with or has been replaced by acid-treating methods (see p. 152). In spite of technical progress in shooting technique, however, the most common disadvantages of oil-well shooting remain. These are the danger of bringing in water instead of oil with the blast, the difficulty of repairing shot holes when subsequent production troubles develop, and the possibility of damaging the well casing.

The use of vacuum for increasing the production of small wells in partly depleted fields also dates back to the early history of the industry; indeed, vacuum was applied to wells in the Oil Creek field as far back as 1869.[8] The practice spread to other early producing areas and eventually was used widely. Vacuum lines were laid to the casing heads of the pumping wells; the suction effect on the producing sand tended to "pull" the oil and gas into the well, whence it was produced in the ordinary manner. There has been much controversy over the precise effects of vacuum on the productive sands, particularly among those interested in adjoining properties. The use of vacuum in production today is negligible. It is employed, however, in a few old fields chiefly to increase the supply of fuel gas for other production operations and as a protection against drainage of oil to wells on adjoining properties to which vacuum is also being applied.

Better methods for pumping wells and improved pumping equipment represented an important aspect of technologic progress in

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[7] P. F. Lewis, "The How and Why of Oil Well Shooting," *The Oil Weekly*, Vol. 88, No. 13 (Mar. 7, 1938), p. 46.

[8] B. E. Lindsly and W. B. Berwald, *Effect of Vacuum on Oil Wells* (U. S. Dept. Com., Bur. Mines, Bull. No. 322, 1930), p. 4.

oil extraction. For example, the early wooden sucker pump-rods, hewn from ash or oak and fitted on the ends with iron straps that served the function of connecting pins and boxes, were replaced by steel rods with special up-set pins and boxes constructed as integral parts of the rods.[9] This improvement was important mainly because it made feasible pumping from greater depths. Another important change that made for greater efficiency and reduced the amount of labor required for oil-field pumping was the development and widespread use of "jack" pumping, whereby several wells were pumped simultaneously with a central source of power and control. By this method one man could operate as many as 40 pumping wells at one time. In early equipment a large, rotating, horizontal band wheel containing an eccentric imparted a horizontal reciprocating motion to steel or wooden rod lines, which in turn imparted an up-and-down motion to jacks or devices that actuated the sucker rods at the individual wells. The efficiency and size of such pumping arrangements were increased gradually, better methods of supporting the rod lines were devised, and losses of power due to friction and other causes were reduced. Special hooking devices on the rod or jack lines enabled one pumper to connect or disconnect the individual wells, and in many western fields rod lines were supplanted by steel cable lines.

The early dominance of the steam engine as the source of power for oil-well pumping was threatened by the internal-combustion engine that became available in the last decade of the nineteenth century. The first oil-field gas engines were reported on the market in 1894.[10] They gradually grew in favor and virtually replaced steam power for pumping. The gas engine materially reduced the amount of labor needed for pumping as compared with that formerly required to operate steam engines, and introduction of gas engines in the fields probably constituted one of the major factors that increased the output of oil-field labor. More recently many gas engines have been replaced by electric motors, tending further to increase labor productivity.

In addition to output obtained either by natural flow or pumping, oil sometimes is raised to the surface by other

[9] For illustrations of technical changes in pumping wells between 1861 and 1878, see Peckham, *op. cit.*, plate VI (opposite p. 82), figs. 1-3.

[10] "Transition From Wooden to Iron Equipment Started in Third Era," *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934), p. 97.

methods. The practice of lifting oil to the surface by a bailer attached to a cable, for example, has been used as a temporary measure but never was adopted in the United States as a general production practice. Also, the oil-well swab, which operates somewhat like a piston attached to a heavy drilling cable, has been used extensively, but largely as a temporary method of producing more oil than could be obtained by either bailing or pumping. The first swab was reported to have consisted of rope wrapped around a bailer and was used to wipe paraffin off the walls of casing. Rubber swabs, fitted with valves, were developed later. Swabbing sometimes has been used for establishing a higher potential production in a well than is possible by other means. The rapid wear of the rubber (which is frequently increased by the presence of sand), the large overhead operating expense, and the possibility of causing water to break into the producing sand and thus injure certain types of small wells have discouraged the use of swabbing in regular production. The higher overhead cost of either swabbing or bailing in comparison with pumping is due principally to the larger amount of labor required. Although one man can attend several pumping wells, as already noted, a crew of at least two and sometimes three men per shift is required for swabbing or bailing.

In addition to technologic advances in such immediately productive activities as pumping wells, there has been more effective handling of other tasks performed by oil-field labor. Part of this work, for example, is represented by the services required to some extent by nearly all wells to maintain reasonably productive conditions.[11] The amount of such service that wells require depends mainly upon the natural characteristics of the specific pool, upon whether the well is flowing naturally or is pumped, and upon the durability of equipment. For example, pumping wells require more service work than wells flowing naturally, and in some fields paraffin, sand, and water are more troublesome than in other fields. As equipment became more durable, moreover, there was less wear and breakage and hence less service work for purposes of

[11] A general description of some tasks performed by production workers in Texas, including some data on rates of pay, are given in National Youth Administration of Texas, J. C. Kellam, Director, *Employment Opportunities in the Oil Industry in Texas* (Austin, Tex.: Industrial Study No. 1, mimeo., Sept. 1, 1938), pp. 33-5.

replacement. In the early days, on the other hand, pulling the pump rods (and sometimes the tubing), replacing worn pump cups, and repairing broken sucker rods were necessary at brief intervals. Producing wells are also frequently cleaned out and repaired from time to time. This usually means the handling of heavy equipment. In most shallow fields, where the custom has been to remove the derricks after the wells were completed, the well-servicing crews have used portable masts and "well-pulling" machines that were moved from one well location to another as the equipment was needed. The tasks of pumping and servicing, performed by pumpers, gaugers, helpers, and roustabouts who comprised the rod, tubing, and clean-out crews, plus special services performed by contractors, represent the large bulk of the labor needed in oil fields after drilling has been completed and output established. Better knowledge of oil structures, better engineering techniques, and more durable equipment have reduced the amount of labor per unit of production needed in servicing wells.

Large Flowing Wells as a Special Problem

In the early part of the present century the industry did not have equipment or knowledge adequate for controlling and producing efficiently the enormously large flowing wells that were brought into production. When wells were drilled into the deeper-lying high-pressure formations, for example, they often became veritable geysers, ejecting oil and gas - and often sand and water - with tremendous force. Frequently the derricks were demolished and the equipment buried in the sand that was catapulted from the well. Often, upon becoming ignited, the gushers burned furiously until large batteries of boilers were massed near the well and the fire extinguished by snuffing with steam,[12] so that workmen might connect pumps to the casing head and "kill" the flow by pumping mud fluid into the well. Dikes and dams, hastily thrown up around the well and across streams, permitted recovery of part of the output, but invariably the dissipation of oil and gas into the air and soil was appreciable. The task of capping and controlling such wild gushers often was difficult, slow, and hazardous and entailed the employment of a sizable force of men. Various

[12] Today oil- and gas-well fires are extinguished successfully by the use of high explosives.

ingenious control and capping methods were devised, including tunneling under the surface of the ground and then tapping the casing below the mouth of the well, and rigging up special hoods, connections, and valves, which were then swung over the gusher and anchored to the well casing.

Despite some early successes in subduing gusher wells, many flowed uncontrolled until the pressure in the well was reduced to the extent that natural flow ceased, either because they became choked by sand or by caved formations or became flooded by water. The abrasive action of sand often destroyed the casing and the well became a crater; when this happened a well was generally beyond possible control. Most notable among the wild wells of this type was the famous Lakeview gusher in the old Sunset field, California. This well came into production in 1910 and ran wild for years, producing at its peak over 40,000 barrels of oil a day. The loss of oil and gas from other wild gushers was enormous.

After the Lakeview disaster the first blow-out preventer apparatus was developed in California. The use of this equipment, together with the expansion of rotary drilling - particularly in the areas of high-pressure sands in the Gulf Coast and in California - that permitted the use of a column of mud-laden fluid for controlling high pressures, resulted in fewer premature blow-outs and wild wells. Heavier and stronger well-control equipment was the result of gradual improvement; standard cast-iron valves were replaced by high-pressure valves of cast steel and finally by valves fabricated from steel forgings. In spite of advanced technique and improved well-control equipment,[13] wells occasionally get out of control and catch fire today.

Perhaps even more serious than the loss of oil from wild wells was the widespread dissipation of natural gas - a most important ally of the technologist in achieving efficient extraction. For example, for years most wells flowed into open earthen pits, boxes, open tanks or tanks rigged with vent stacks, so that the natural gas accompanying the oil escaped into the atmosphere. Such practices resulted in enormous waste

[13] M. T. Works, "The Development of Mechanical Control Equipment Used to Prevent Blowouts," *Drilling and Production Practice, 1937* (New York: American Petroleum Institute, 1938), pp. 48-62; C. B. Carpenter, *Some Causes of Blow-outs During Drilling and Means of Prevention, With Special Reference to the Gulf Coast Region* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 6838, mimeo., Mar. 1937), pp. 16-27.

of natural gas and in evaporation of the lighter, more volatile constituents of petroleum. As late as 1924 large gas reservoirs were exhausted into the air to obtain comparatively small productions of oil, as the dissipation of gas and reservoir pressure caused the wells to "blow into oil",[14] a practice that greatly reduced the quantity of oil which it was technically possible to produce from the pool. The custom of producing wells at high rates of flow or at full well capacities, moreover, generally proved detrimental to the productive life of the wells, for fields produced under open-flow conditions usually were short-lived, due to the rapid decline of reservoir pressures that hastened the day of artificial lifting or mechanical pumping and to the encroachment of water from the edge of the field. Most wells today, however, are produced under restricted rates of flow; moreover, in many fields the operators produce oil and gas with a full realization of the value of conserving and utilizing the total available reservoir energy. These changes are a result of advancing production techniques and of man's relative success in reconciling the economic and legal arrangements of exploitation with the physical characteristics of an oil or gas pool. A growing market for natural gas also has encouraged the development of conservation practices.

Increased Importance of Production Engineering

Although many methods and processes now commonly used in producing oil and gas were known to the older operators, the conditions under which oil was found and produced in the early days of the industry did not require the application of complicated engineering principles. In fact, most of the work was in charge of practical men who had only an elementary educational background, and as long as they continued to be successful there was no great need for more thoroughly trained personnel. As certain production problems became more difficult, however, the industry turned increasingly to the trained engineer for aid. Operators in California particularly were among the first to adapt engineering technique to oil-field conditions. In that State in 1908, and even earlier, engineers were employed to make studies of underground conditions with

[14] J. S. Ross, *Engineering Report of Cotton Valley Field, Webster Parish, La.* (U. S. Dept. Com., Bur. Mines, Tech. Paper No. 504, 1931), p. 61.

a view to improving production technology. How to protect the oil-bearing sands from water intrusion was a problem that required special and immediate attention. Progress in production engineering was especially rapid after 1910, in which year the U. S. Bureau of Mines was organized and began the work of disseminating information pertaining to improved technology.

Progress toward more widespread use of engineering knowledge was accelerated by official developments in California and by continued demonstration of the utility of engineering techniques. In 1915 the Department of Petroleum and Gas of the California State Mining Bureau was formed. This agency was given statutory powers to regulate and supervise drilling activities in the State, primarily for the protection of the producing sands. It employed capable geologists and engineers to make detailed studies of underground conditions in cooperation with the other field engineers. There was begun, for example, the practice of graphically plotting well logs and other engineering data, and the arranging of such information in the form of subsurface oil-field cross sections for the purpose of visualizing more clearly the geological and other underground physical conditions. The data collected were also used for the construction of peg models that depicted the producing formations as they actually existed underground. To aid in determining the source of extraneous waters, chemical analyses of waters from known water sands were made. Such investigations threw new light upon many pressing underground production problems. Upon the recommendation of engineers, considerable remedial work was also undertaken, including the redrilling, recementing, and the abandoning and plugging of old wells.

The demonstration in California of the role engineering could play in oil production was convincing, and the use of advanced engineering practices gradually spread to other oil-producing regions. This development was aided by the large amount of experimental work and research conducted both in the field and in the laboratory by private, State, and Federal agencies. Through a better knowledge of the occurrence of petroleum and the efficient extraction of oil, higher proportionate recoveries have been achieved. Especially significant has been recognition of the importance of natural gas in obtaining maximum recovery from the reservoir, and greater attention has

been given to the conservation and utilization of the energy contained in the gas.[15] The development of other advanced practices that fostered both better recovery and conservation has also been significant.

As employment opportunities in oil-field engineering expanded, many universities of accredited standing established curricula in petroleum engineering. Besides the regular fundamentals of engineering, instruction was provided in exploration, exploitation, refining, and crude-oil transportation, with special emphasis on techniques of drilling and production. In some schools practical field experience has been made a prerequisite for graduation, and the engineering students find employment in the oil fields during the summer vacation months where they work as roustabouts, pumpers, gaugers, and so on. Some graduate engineers enter special training courses maintained by the major oil companies before being employed as members of the regular engineering staffs of those companies. The rapid gain in the number of technically trained men[16] and the increasingly complicated art of oil production have narrowed the field of employment for those without considerable education or technical training. In executive and supervisory positions, experienced production engineers gradually are replacing the older men whose background has been principally practical experience.

PRESENT PRODUCTION PRACTICES

There seems to be no end to technical advances in oil production, for progress has continued to the present as new and improved methods were developed and as oil-producing operations became highly specialized. Today, upon completion of drilling in most fields, an efficient production organization takes over the well and employs methods that are carefully adapted to local field conditions.

Most flowing wells are brought into production and produced through tubing, and they are controlled at the wellhead by

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[15] H. C. Miller, *Function of Natural Gas in the Production of Oil* (New York: U. S. Dept. Com., Bur. Mines, in cooperation with the American Petroleum Institute, 1929), pp. 44-7.

[16] In the school year 1936-37, for example, 2,466 students in accredited engineering schools were studying to become petroleum or natural-gas engineers, compared with 372 students in the school year 1927-28. See T. T. Read, *Careers in the Mineral Industries* (New York: American Institute of Mining and Metallurgical Engineers, Seeley W. Mudd Memorial Fund, 1939), p. 25.

a system of valves and other fittings comprising the "Christmas tree", mentioned in chapter V (see p. 117). The flow is regulated by a choke or "bean", usually adjustable. The oil and gas are carried in flow lines to an oil and gas separator, from which oil is delivered to receiving tanks and the gas to a gas-gathering system (or vented into the atmosphere where it has no other utility). To minimize the abrasive action of sand, the flow bean sometimes is made of a heavy steel plug through which is bored a hole of small diameter. In contrast to the elaborate arrangement of wellhead fittings and connections that were typical in high-pressure fields a few years ago, modern Christmas trees are simple, compact units, equipped with fewer but better valves.

Tubing Wells for Production

From the standpoint of efficient recovery and the conservation of reservoir energy, the use of tubing in flowing wells - particularly where natural gas is the chief propulsive agent - is probably one of the most important recent technical practices. Such tubing, usually 2 or 3 inches in diameter, is placed inside the casing (which is usually about 6 or 7 inches in diameter) and extends from the surface to the producing sand. When wells are produced at considerably less than open-flow rates, as under proration schedules, higher efficiencies of flow are attained through the smaller-diameter tubing than would be obtained through large-size casing, and less of the available gas energy is dissipated. Furthermore, at wells where pressures are high, tubing permits more flexible production control and affords a means of bringing the well under control if troublesome conditions are imminent. Recognizing these advantages, some State oil and gas regulatory bodies require that the oil be produced through tubing. Whereas 10 years ago the tubing of flowing wells was limited principally to oil-field practice in California (except as an emergency measure in other fields to improve the flow of wells that had begun to surge or "head", or to revive the flow of wells that had ceased to produce naturally through casing), within recent years there has been general adoption of this improved practice.

The development of a method for installing tubing in wells under flowing or high-pressure conditions has been an important

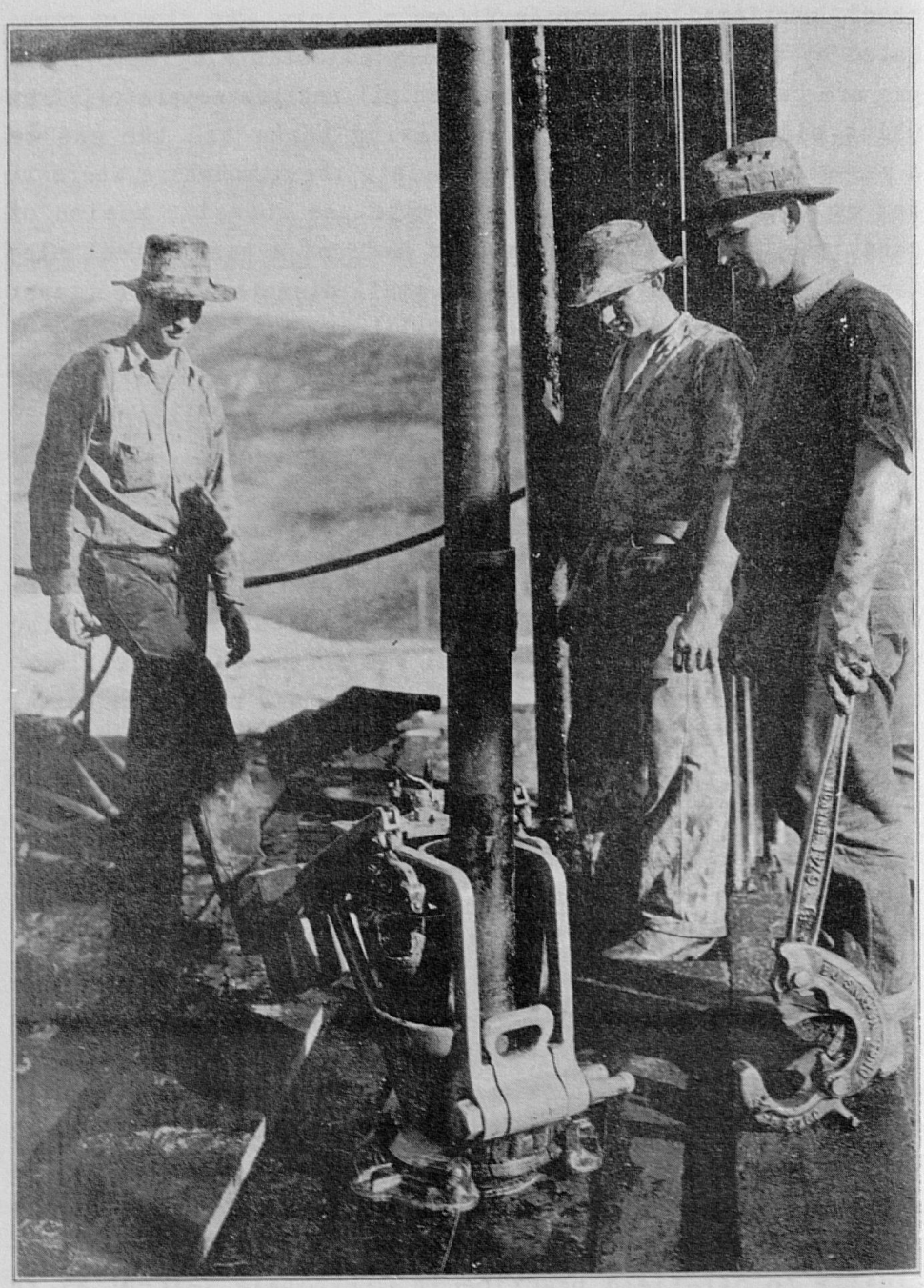


ILLUSTRATION 15.- PULLING TUBING FROM A PRODUCING WELL

Most pumping wells must be serviced at relatively frequent intervals. This usually requires that the rods or tubing be withdrawn. In the above illustration the "well-pulling gang" is using a special type of "tubing spider" to support the tubing while making or breaking joints. Specially designed tongs are used to grip the tubing. Such equipment has improved worker productivity in the production division of the industry.

contribution of modern technology. This practice had its inception in 1928 in the gas fields of northern Louisiana, where small-diameter water siphons were snubbed through rubber blow-out preventers against gas pressure. Subsequently the method was improved through the development of better equipment and technique, and it is not uncommon at present for tubing to be snubbed into oil and gas wells against pressures as high as 2,000 pounds per square inch. Tubing generally has been inserted against very high pressures by special crews equipped with winches mounted on trucks. But with the introduction of improved control equipment, a large amount of tubing work has been done at moderate pressures or under flowing conditions by regular tubing crews that worked with standard portable well-pulling machines. Such tubing crews consist of 4 or 5 men, the number of men depending upon the condition of the well and the size of tubing to be installed.

Although the use of tubing improved oil recovery and conserved natural gas, it required a temporary increase in the gross labor outlay for production early in the life of the well. The long-time benefits of the practice, of course, more than offset the temporary increase in labor cost. Moreover, because of continued improvement in technique, the time and labor required for tubing a flowing or producing well have been greatly reduced. Former methods, for example, entailed considerable time and expense, since it was necessary to set boilers, pumps, and other equipment to mix mud fluid with which to kill the well and to clean the hole of mud or other material and place the well in producing condition again after the tubing was installed. Furthermore, mudding of the well or even loading the hole with "dead" oil often had a detrimental effect on production, Consequently, methods were welcomed that did not interrupt or impair the well production. Under ordinary conditions today, moreover, wells are tubed under pressure in 2 to 5 days, depending upon the depth and well pressure, whereas with former methods the tubing operation would have consumed a week or more.

Improvements in the quality and design of tubing have also been significant. Better metallurgical and manufacturing processes have produced a higher-quality product that is now available in longer seamless joints (30 feet instead of 20, as formerly) with external up-set ends to strengthen the

threads. The longer joints were important because they reduced the time and labor involved in tubing operations. The quality and design of tubing heads and other equipment used for supporting and packing off the tubing string at the wellhead have also been improved. For example, tubing catchers - designed to prevent tubing from falling if the tubing string should break accidentally - are used extensively, particularly for wells that are being pumped. The use of such tubing catchers and of stronger tubing joints has reduced appreciably the amount of well-repair work required, such as fishing for parted tubing strings and replacement of damaged pumps.

Oil and Gas Separators

Modern oil and gas separators, operating under pressure, effect efficient separation of fluids and allow virtually complete recovery of the gas accompanying the oil. These devices have been developed and improved over a long period. An early form of gas trap used in 1865, for example, consisted of a barrel placed on top of an oil tank; the gas escaped through an opening in the top of the barrel, and the oil flowed out the bottom through a U-tube which provided an oil seal and prevented the escape of gas into the oil-storage tank. The principle illustrated by this early device was incorporated in all later equipment.[17] Various types of horizontal traps followed the barrel trap, and as the demand for natural gas increased, the first of the upright cylindrical-shaped traps was developed.[18] From the latter evolved the present pressure-type oil and gas separators, now commonly found in the oil fields, that represents a marked improvement over older equipment.

A typical modern separator is a tall, cylindrical, tight tank, made of heavy steel plate and capable of withstanding working pressures as high as 2,000 or 3,000 pounds per square inch. The inflow of oil and gas either impinges on many baffles, which assist in directing the flow downward and knocking out the gas, or circulates around the inner side of the shell of the tank, creating the same effect. Valves, actuated by floats inside the separator, operate automatically to

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[17] W. R. Hamilton, *Traps for Saving Gas at Oil Wells* (1st ed.; U. S. Dept. Int., Bur. Mines, Tech. Paper No. 209, Feb. 1919), p. 9.

[18] The tall flow tanks, which were used widely for many years, served only as receptacles for the separation of gas and oil and were not designed to trap and recover the gas, which was permitted to escape into the air through vents and manhole openings.

discharge the oil to receiving tanks, while the gas discharges at the top, at fairly uniform pressure, into a gas-gathering system or into a vent pipe. Most separator installations permit measurement of the gas production, which usually is accomplished by a Pitot tube or an orifice-type meter.

There has been a tendency to increase the working pressures of oil and gas separators in the last few years, and in some fields - where special operating techniques are practiced - high-pressure separators are used in series with low-pressure separators. Multiple-stage separation[19] is found particularly desirable where large quantities of gas are produced with the oil under high-pressure conditions. It is now recognized generally that better separation of the oil and gas is effected under higher pressures than at atmospheric pressure.

Under moderate rates of production, modern oil and gas separators ordinarily require comparatively little attention. One operator, usually the oil switcher or lease man, usually attends to the separators at a number of flowing wells. Use of this equipment does, of course, represent some additional capital outlay, but the higher recoveries of gas and oil more than counterbalance the extra labor costs for construction, installation, and maintenance.

Advanced Lifting Techniques

More effective technical procedures both for lifting and pumping oil have increased the total amount recovered and were a factor in the long-time upward trend of output per man noted in chapter II. Nowadays, after natural flow from a well ceases, the gas lift is widely used as a transitional method of raising oil. This delays advantageously the early installation of mechanical pumping equipment. Owing both to technical advances in lifting equipment and technique and to more effective pumps and pumping arrangements, discussed later in this chapter, oil today is lifted from depths which a few years ago were regarded as too deep to be reached economically by prevailing methods.

Although the gas or air lift was first applied to oil production fairly early in the industry's history (to some extent

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[19] W. F. Cloud, *Petroleum Production* (Norman, Okla.: University of Oklahoma Press, 1937), p. 194.

in California and Gulf Coast fields early in the present century), it was not extensively developed until after its application in Oklahoma in 1925.[20] In this method of producing oil, compressed gas - introduced into the casing head of the well - enters an eductor tube with the oil in the bottom of the well; as the gas expands upward in the tubing it lightens the column of fluid and moves with the oil to the surface. Ordinarily the gas used in lifting the oil, together with the gas associated naturally with the oil, is recovered in an oil and gas separator, recompressed, and recycled in the well to lift more oil. Spaced at intervals in the eductor tubing are "kick-off" collars or small gas jets, which facilitate the starting of the gas lift, eliminating the necessity of providing high "kick-off" pressures.

The operation of the lift generally requires very little attention. Some wells produce month after month without interruption and without other attention than a daily visit from the pumper. It has been reported that one company in southern California employed only nine men, three each for a tour of 8 hours, to look after 80 gas-lift wells.[21] These men cover such a wide territory that they are furnished automobiles in which to make their rounds.

In many fields, notably in California, manual operation of gas-lift wells has been replaced by automatic volume control, reducing supervision to a minimum. For example, at one installation where over 20 wells were flowing from a common header, one man per shift maintained efficient flowing conditions in the wells, some of which were a mile from the header house.[22]

Engineers have also devised methods for flowing the wells intermittently when production began to decline under the ordinary or straight gas-lift methods. This is achieved by the intermittent injection of gas, which is controlled automatically by electrical, mechanical, or pressure-operated timing devices.

Efforts to continue the use of the gas lift after wells had declined to the point where direct gas injection was no longer

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[20] *Ibid.*, p. 238.

[21] H. C. Miller, *Gas-Lift Method of Flowing Oil Wells (California Practice)* (U. S. Dept. Com., Bur. Mines, Bull. No. 323, 1930), p. 54.

[22] *Ibid.*, p. 61.

practical led to the development of special techniques. These require the use of tubing packers, tubing footpieces containing valves, and intermitters, and have made possible the lifting of oil from wells having low reservoir pressures and low fluid levels. In one method oil is lifted to the surface in stages, hence is known as the "stage lift"; in another, known as the "plunger lift", oil is raised to the surface by a close-fitting cylinder or plunger, containing valves, which moves up and down the entire length of the eductor tubing. Surface equipment has been designed and arranged to reduce back pressure and friction by elevating oil and gas separators to permit the flow of oil by gravity to the tanks, shortening flow lines, and replacing sharp-angle bends in pipe by long, sweeping curves.

Thus, owing to a series of technical refinements, oil operators have been able to extend the usefulness of their existing gas-lift installations and to continue the production of oil economically with comparatively few employees at wells long after they have reached the stage at which mechanical pumping formerly was necessary. Furthermore, although the construction and installation of gas-lift equipment, such as compressor plants, gas lines, and separators, and additional work for tubing crews, gas engineers, and a limited number of plant operators meant an increase in gross employment, labor requirements per unit of product declined, because the gas lift enabled oil operators to produce large volumes of oil for a relatively long period with virtually the same number of men employed as when wells were flowed naturally. In many fields, in fact, a much greater production has been obtained by artificial flowing methods than by either natural flow or mechanical pumping.

Mechanical Pumping Systems

Recent progress in pumping technology is well illustrated by a specific example. In 1928 5,000 feet was regarded as the maximum depth from which oil could be lifted by plunger pumps. By 1934, however, sucker rods and pumping units had been so much improved that it was practicable to lift oil commercially from depths of 7,000 or 8,000 feet.[23] Although the old reciprocating plunger-type pump is still the most common in the old

[23] B. Mills, "Improved Methods and Equipment Meet Conditions Encountered in Deep Pumping," *The Oil Weekly*, Vol. 74, No. 12 (Sept. 3, 1934), p. 20.

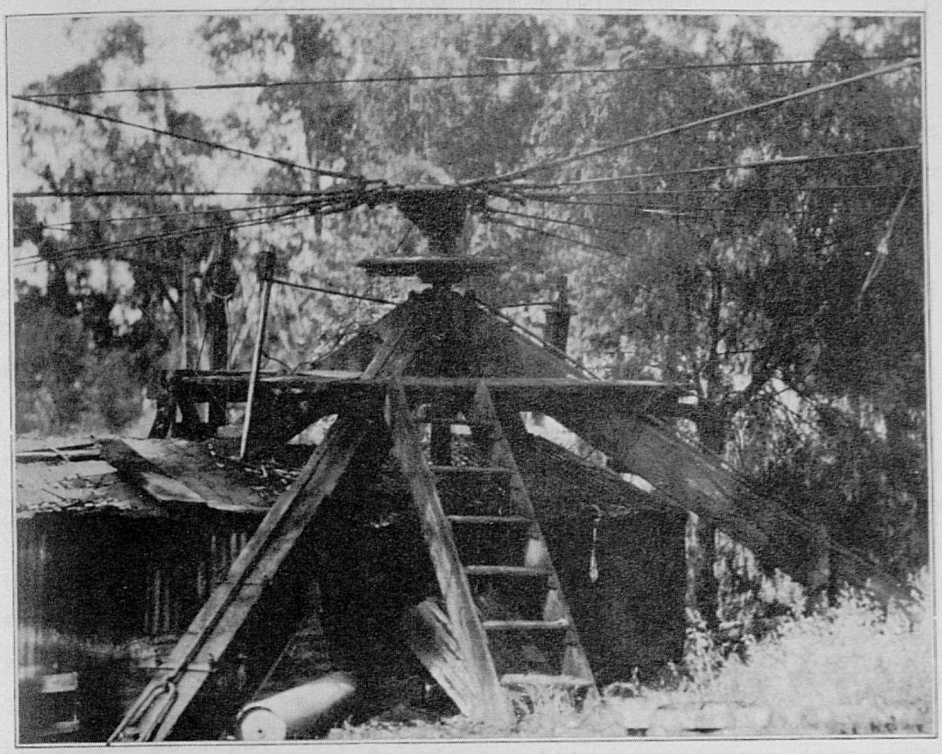
fields, it has been cleverly adapted to meet a wide variety of operating conditions. Beam pumping units, moreover, have been improved materially during the past few years.

Much attention is now paid to the efficiency of oil-well pumping. The "weighing" of pumping wells by the use of the dynamometer, an instrument which - attached to the "polish rod" or top sucker rod - has enabled engineers to determine the operating characteristics of pumping units. This permits elimination of many of the common difficulties of pumping operations as technical details (the type of prime mover, amount of counterbalancing, length of stroke, rate of piston travel, etc.) are properly adjusted. Thus the life of pumping equipment is lengthened, rod breakage is reduced, and the frequency of shut-downs for well repairs is decreased.

The standard rig equipment for pumping wells on the beam is being replaced rapidly by individual all-steel reduction-geared units, and the modern pumping units present a marked contrast to the old gas-engine, belt-driven band wheel of earlier days. Prime movers are either an electric motor or a single-cylinder or multicylinder internal-combustion gas engine, connected to the geared unit either by a silent chain or V-belts or by direct shaft and reversible clutch. Crank-arm and rotary-type counterbalances are replacing beam counterbalances.

To overcome certain disadvantages of beam and central-power pumping, such as limited length of stroke and sudden, uneven stresses on the sucker rods, the pneumatic pumping cylinder is sometimes used. This mechanism is mounted in the derrick directly over the well, and the sucker rods are coupled to the piston of the pump cylinder. The pumping cylinder is operated automatically by an air compressor.

The development of electrically driven, subsurface centrifugal pumps and deep-well, hydraulically operated rodless pumps has progressed rapidly in the last few years. The use of such equipment is gaining favor in many fields, particularly where oil is pumped from great depths. Subsurface centrifugal pumps are operated by motors which are supplied with electric power through armored cables extending from the surface. Sometimes these pumps are used in conjunction with the gas lift, the pump raising the oil to a point part way up the well, whence gas lifts it to the surface. Hydraulic pumps



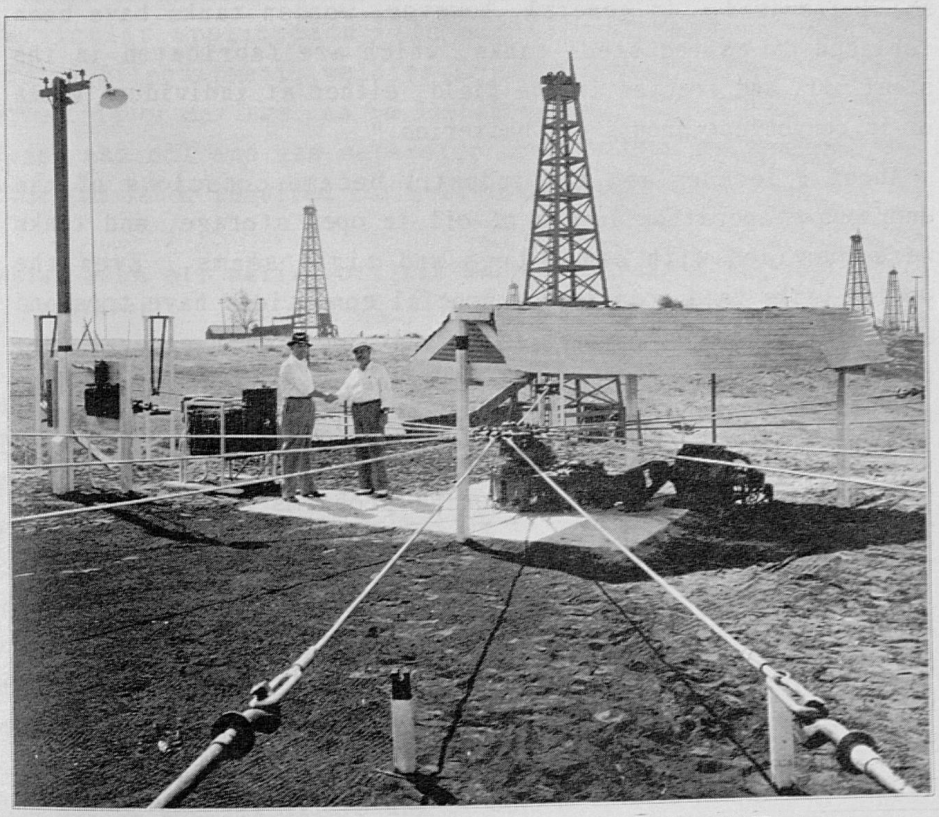


ILLUSTRATION 16.- PUMPING WELLS BY CENTRAL POWER

Pumping wells with rod lines or cables extending from a central source of power is nearly as old as the industry, but recent improvements in equipment have brought about savings in maintenance and operation expenses. The top view shows an old-type central-power or jack plant in contrast with the unit shown below.

are actuated by filtered oil pumped under pressure from the surface. The absence of sucker rods makes this type of pump especially adaptable to deep-well pumping, particularly if the wells are crooked.

Better Handling and Temporary Storage Facilities at Wells

Facilities for extracting gas, water, and sand and methods of treating and handling oil before shipment have been improved greatly. In addition to the pressure-type oil and gas separator that has been already noted, vapor-tight steel gauge tanks, efficient oil pumps, recording gas meters, and oil meters comprise some of the modern equipment situated near the wells.

The wooden tanks that were typical of early operations in all fields virtually have disappeared, except in those special areas where high-sulphur and other compounds produced with the oil and gas cause excessive corrosion of metal equipment. Under such conditions, wooden tanks of improved construction still are used. In general, however, wooden tanks have been replaced by bolted steel tanks, which are fabricated in the steel mill and erected in the field, either at individual wells or in convenient groups or "batteries."

About 2 decades ago the industry became conscious of the enormous evaporation losses of oil in open storage, and tanks were provided with steel tops and tight seams. Even the wooden tanks used today under special conditions have tops and are vaportight. It is such tanks that are now in general use; most types can withstand 2 to 4 ounces of pressure or vacuum and are provided with special breather vents. Heavier types of steel tanks may withstand as much as a pound of pressure. (For further discussion of storage problems and evaporation losses see pp. 246-9.)

The tank-gauging method of measuring oil production has been in use ever since the beginning of the industry, but within recent years dependable oil meters have been developed and introduced.[24] The adoption of oil meters in some oil-producing States, notably California, Texas, and Louisiana, has eliminated the necessity for providing individual well or lease

[24] *Proceedings of the Petroleum Fluid Metering Conference* (Petroleum Division, American Society of Mechanical Engineers and College of Engineering, University of Oklahoma, Norman, Okla., Apr. 7, 8, 1938), 78 pp.

storage tankage. The metering of the flow from wells under high pressures has become common practice in some fields, as the operators of such wells depend chiefly upon individual well meters for oil measurements.[25] Although oil meters probably will not entirely replace lease storage tanks and some forms of gauging oil, even their limited adoption tends to reduce the work of building and servicing individual well storage tanks and of gauging.

A factor that has contributed to better construction and equipment in the vicinity of wells has been the development of welding practices. Although the great importance of welding in pipe-line construction is discussed in a later chapter (see pp. 229-31), it was also important in the construction of metal equipment used in direct production. Supplied with an assortment of steel tubes and plates, a skilled welder today can fabricate, at the well site, almost any type of simple equipment desired. Both the electric-arc and the oxyacetylene methods of welding are used extensively, and each has its own particular application. In addition to more durable and efficient equipment, welding in some instances has achieved direct labor savings, as in instances when the welding of flow lines and oil and gas separator connections has reduced the time and labor required for well-connection work.

Water From Oil Wells, Oil and Water Emulsions, and Paraffin Formation

Water associated with oil reservoirs has caused production difficulties ever since the beginning of the petroleum industry. The water encroaches upon the pay sand as oil is withdrawn from the reservoir; eventually it invades the wellhole and is produced with the oil, increasing in amount as the field grows older. Lifting the water to the surface becomes a costly item of operation. In some fields, moreover, the waters are extremely corrosive and cause rapid deterioration of the pumping equipment so that frequent replacement and repair of tubing, pumps, casing, and tanks are necessary. Corrosion and wear of equipment under such conditions, however, have been reduced by the use of special alloys and of corrosion-resisting metals.

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[25] B. Mills, "Progress in Engineering," *The Oil Weekly*, Vol. 88, No. 9 (Feb. 7, 1938), pp. 44-6.

In many oil-producing areas, especially in farming communities, stock ranges, and congested districts, the disposal of salt water produced with the oil becomes a serious problem. Often there are legal barriers to discharging salt water into fresh-water streams and into sewage systems. Where the problem of water disposal is serious in major producing fields, methods are provided for disposal in large evaporation pits, underground porous formations,[26] streams, or the sea if the areas lie near the coast. Such arrangements are provided and maintained by cooperative, nonprofit organizations in which the oil-producing companies participate. Likewise, the disposal of petroleum wastes other than brines from oil fields causes operating difficulties.[27]

When oil and water are produced in emulsion, additional technical processes are required to separate the water from the oil before the latter can be marketed. These processes are adapted to local conditions and may be relatively simple or complicated arrangements. In recent years, however, the prevention of emulsions has been the subject of extensive research and experimental work. The results of this work provided new knowledge of the physical character of emulsions and of the conditions under which they are formed. Thus chemists and engineers have been able to devise better methods for preventing the formation of emulsions. It was found, for example, that faulty operation was the principal cause of oil-water emulsions at many wells and that the formation of emulsions frequently could be prevented. As a result, some operators have effected much greater economies by adopting techniques that prevent emulsions than by improving dehydration methods.[28] Where the latter still are necessary, however, the old, established practice of heat treatment has been improved and, in many operations, replaced by electrical, chemical, or centrifugal processes for breaking down the emulsions. The new processes are continuous in operation and require less

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[26]For a discussion of some social aspects of disposal of oil-field brines and for conclusions of recent investigations of conditioning brines for subsurface injection see S. S. Taylor, C. J. Wilhelm, and W. C. Holliman, *Typical Oil-Field Brine-Conditioning Systems: Preparing Brine for Subsurface Injection* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3434, mimeo., Jan. 1939), pp. 6-9, 69-71.

[27]L. Schmidt and C. J. Wilhelm, *Disposal of Petroleum Wastes on Oil-Producing Properties* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3394, mimeo., Mar. 1938), pp. 1-21.

[28]J. S. Surfluh, "Prevention of Oil-Field Emulsions," *Drilling and Production Practice, 1937* (New York: American Petroleum Institute, 1938), pp. 229, 237.

attention than former batch-treatment methods, in which "cut" oil was heated by steam coils placed in the bottom of settling tanks or passed through fire-tube boilers.

The formation of paraffin in tubing and on the walls of the casing also causes production problems in many fields. The older practice was to clean out accumulated paraffin by mechanical methods, using paraffin scrapers, an operation that has provided considerable employment for oil-field workers. In recent years, however, this practice has been replaced to some extent by the use of solvents and of heat- and chemical-treating methods that require very little labor.[29]

Squeeze Cementing

"Squeeze" cementing is used extensively and with a high degree of success for shutting off gas or water, and sometimes both, without shutting off oil. It is a process wherein cement slurry is forced by pressure into or against permeable formations or through perforations in casing and well liners. A feature of this technique is that the cement slurry, when introduced into a well under pressure, enters and seals gas- or water-saturated portions of the productive zones but apparently does not enter or damage the oil-producing sand. During 1937 several thousand squeeze-cementing jobs were completed, with squeeze pressures up to 5,600 pounds per square inch and an average of around 3,000 pounds, without shutting off oil.[30]

The development of the gun perforator and of selective perforating technique has made possible certain special types of squeeze cementing. In many fields, for example, it is common practice to force cement through selectively placed perforations in blank well liners at points opposite water or gas strata or unproductive zones and to perforate opposite the pay zones.[31] In some fields the casing is cemented throughout the productive zones and later perforated at selective points for oil production. The gun perforator used for this purpose is sometimes also employed to puncture the walls of tight producing sands to increase oil production and to perforate

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[29] C. E. Reistle, Jr., *Paraffin and Congealing-Oil Problems* (U. S. Dept. Com., Bur. Mines, Bull. No. 348, 1932), pp. 60-97.

[30] C. P. Parsons, "Squeeze Cementing," *The Oil Weekly*, Vol. 88, No. 12 (Feb. 28, 1938), p. 38.

[31] In an older method, perforated pipes or screens were placed in the well below the casing in order to hold back loose and unconsolidated sands.

casing and the cement jacket behind the casing so that oil or gas excluded by them may flow into the well bore.

Squeeze cementing usually requires the use of tubing and of high-pressure pumping and cement-mixing equipment, as well as large quantities of cement. Before the cement is introduced, wells are conditioned by washing with water and forcing water - and sometimes acid - into the formation. Usually the work is performed by regular oil-well cementing companies with specialized apparatus and trained personnel. Some cementing jobs require a crew of 20 to 30 men. Perforating operations also are usually conducted by field crews of special service organizations owning and operating their own equipment.

Acid Treatment

The treatment of producing formations with acid when those formations are limestone is another method employed for increasing output from oil and gas reservoirs.[32] In practice, hydrochloric acid is pumped through tubing to the bottom of the well and forced by pressure into the permeable portions of the producing formation. The action of the acid on the limestone enlarges the openings, cracks, and pores in the calcareous reservoir rocks surrounding the well, thus increasing the permeability of the producing formation in the immediate vicinity of the hole and increasing the flow of oil into the well.

Although acid was used before 1900 to stimulate production, the process and technique of well treating now commonly used are developments of the past decade. The growth of the practice has been phenomenal, and at present about 10,000 wells are treated annually, approximately 25 million gallons of acid being required for this purpose. The acid is applied in most instances by specially trained crews of contract service agencies that also have acid tank trucks, acid pumps, and other needed auxiliary equipment. The recent rapid development of acid treating has been due mainly to improved methods for

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[32] Although the producing formation is frequently called "oil sand", this does not imply that it is always sandstone. The use of the term "oil sand" is a heritage from the early days of the industry when the sandstones of the Pennsylvania producing formations were pulverized by the drill bit and hoisted to the surface and appeared as oil-yielding sand. In addition to sandstones, however, it should be noted that petroleum in commercial quantities is produced from certain other types of rock. For a more detailed description of rocks found in productive formations see Cloud, *op. cit.*, pp. 26-43.

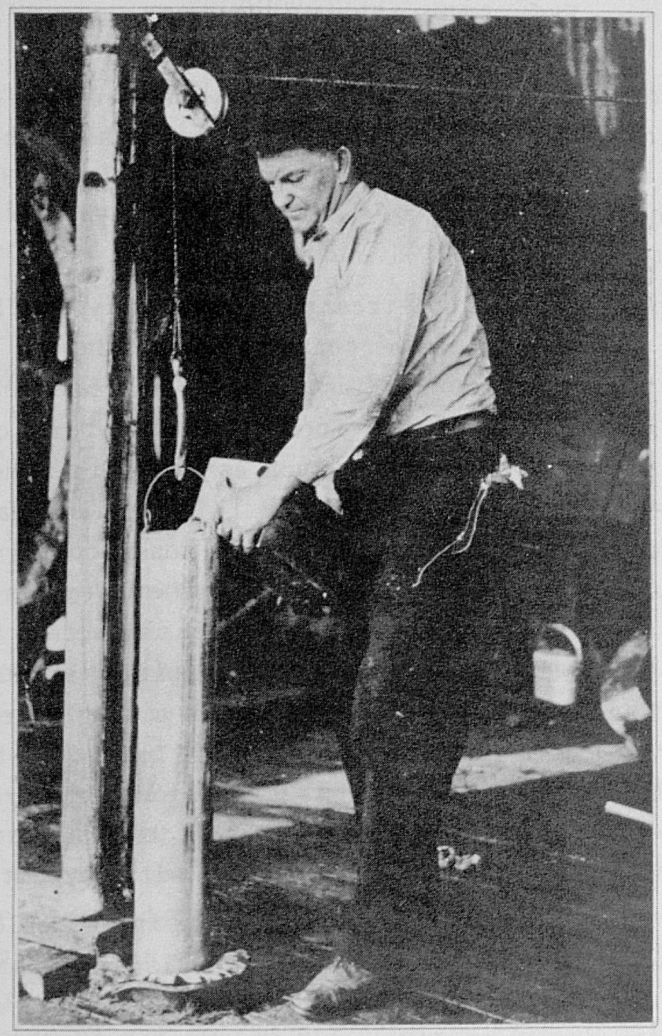




ILLUSTRATION 17.- EXPLOSIVES AND CHEMICALS ARE USED TO STIMULATE PRODUCTION UNDER CERTAIN CONDITIONS

The upper view shows a shooter pouring nitroglycerin into a container that is to be lowered into a well in the Bradford (Pennsylvania) field. The lower view shows trucks used for the transportation of acid and other chemicals used in certain stimulative recovery practices.

applying the acid, to the development of inhibitors or methods that tend to control and to minimize the corrosive action of hydrochloric acid on the well and on metal equipment, and to unusually good results that have accompanied the use of the new acid-treating technique.

A feature of modern acid-treatment technique is that the application of the acid can be controlled and adapted to meet special well conditions. For instance, it has been observed that the production of water from exposed water zones is stimulated by acid treatment as much as - and in some cases more than - the production of oil. This problem has been met in large measure by "blanketing" the zones contiguous to water levels with acid-resistant gelatinous substances before introducing the acid; moreover, extreme care is used in placing the acid in the well. The amount of acid applied is determined by detailed knowledge of well conditions and a single treatment may vary from 200 to as many as 30,000 gallons. An average treatment, however, is about 2,500 gallons. In some areas the mixing of reagents with the acid to retard chemical action so as to permit greater penetration is meeting with success.[33]

Acid treatment has been used successfully in the calcareous and dolomitic reservoirs of Michigan, Louisiana, Kentucky, Kansas, Ohio, north-central Texas, and the Seminole area of Oklahoma. In some areas it is at least a partial substitute for well-shooting, although a combination of the two methods sometimes is used to advantage in the denser productive limestone formations. In fact, many new pools in limestone areas are made commercially productive today entirely by the use of acid.

Acid treatment is particularly important in rejuvenating many small or stripper wells in some older fields that have almost reached the point of exhaustion by ordinary methods of production. Heithecker, for example, has reported that in the Zwolle field of Louisiana "at least a dozen wells . . . . have been . . . . placed upon production following the acid treatment that otherwise probably would have been abandoned as noncommercial wells."[34] In the Fairport field of Kansas

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[33] J. G. Staudt and W. W. Love, "Sustained Action Acid May Solve Mid-Continent Problem," *World Petroleum*, Vol. IX, No. 5 (May 1938), pp. 78-80.

[34] R. E. Heithecker, *Engineering Studies and Results of Acid Treatment of Wells, Zwolle Oil Field, Sabine Parish, La.* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3251, mimeo., Oct. 1934), p. 35.

(situated in Russell and Ellis Counties) the average daily production per well, having declined to about 10 barrels, was increased to over 30 barrels by the use of acid.[35] Such reconditioning has prolonged the life of semidepleted fields and provided additional employment for pumpers, lease men, and well-servicing crews that otherwise would not have been available. Moreover, the stripper class of wells generally is in poor mechanical condition and a reasonable increase in output made possible by acid treatment frequently enables the operators to recondition or replace obsolete pumping equipment.

Natural Forces Harnessed and Controlled for Greater Recovery

Wider acceptance of the concept that oil can be produced in accord with engineering standards of high efficiency has been one of the major victories of petroleum technology and one of the principal reasons why oil recoveries have improved. This development was due partly to a rapidly growing body of technical knowledge and to production-control arrangements that permitted slower production of wells and enabled engineers to apply methods that were impracticable under the older practice of unrestricted competitive production. Much attention has been given, for example, to controlling water incursion, to conserving and utilizing reservoir pressure, to reducing the ratio of gas to the oil produced, and to other practices that emanated from the technologist's view of an oil pool as a single gigantic engine. Under this view, the maximum technical efficiency is obtained by harnessing and controlling the underground forces - such as gas pressure and hydrostatic pressure - to obtain the largest recovery of oil over the longest period. The net effect of new engineering concepts and knowledge and advanced technical procedures based upon them has been to extend the productive life of many oil fields many years into the future and to increase the gross output of oil that will ultimately be extracted from those fields.

Why an efficient recovery technique must take detailed account of underground conditions is suggested by the occurrence of oil, gas, and water in petroleum reservoirs and by the factors determining the movement of these fluids through

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[35] R. E. Heithecker, *Effect of Acid Treatment Upon the Ultimate Recovery of Oil From Some Limestone Fields of Kansas* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3445, mimeo., Apr. 1939), p. 4.

sands and their flow up to the well. It is known, for example, that oil-bearing sands are rarely uniform in texture and that coarse-textured sand layers are relatively permeable. When wells are produced at open-flow or excessive rates, the rapid drop of reservoir pressure in the vicinity of the well often causes water to channel to the well through these coarse-textured sand layers, thereby trapping much oil in the finer-textured layers of sand. Oil thus trapped usually becomes unrecoverable by known methods. For the same reason, water in the bottom of the sand cones upward and into the well, shutting off the oil. The tremendous underground losses of oil sustained by the petroleum industry in the past are attributed principally to the rapid depletion of reservoir pressure that permitted premature flooding or encroachment of water, which trapped oil in the less accessible parts of the sand.

Successful operation in many fields today is related directly to pressure maintenance, which is accomplished by returning natural gas produced with the oil back into the sand under pressure and by controlling the production of oil so that the encroaching water will tend to keep the pressure in the oil reservoir at or near its original pressure. Control of water in the producing horizon is effected by producing the well at a slow, efficient rate so that full advantage is taken of the energy (hydrostatic pressure) exerted by the encroaching water.[36] Gas is conserved for productive use by reducing the ratio of gas to the oil by producing the latter through small-diameter tubing, tapered tubing, and surface and bottom-hole chokes and by applying varying degrees of back pressure at different rates of flow. Commonly the pressure on the gas and oil confined above the encroaching water in a reservoir is equal to the hydrostatic head of water. In reservoirs where the amount of gas or the gas pressure does not suffice to produce most of the oil originally present, the pressure of the water (frequently called "water drive"), if properly controlled, can often be utilized to wash from the pore spaces and lift to the surface most of the oil in the reservoir. If water advances unevenly, however, due to lack of adequate control over reservoir pressures, much oil is sealed off and lost.

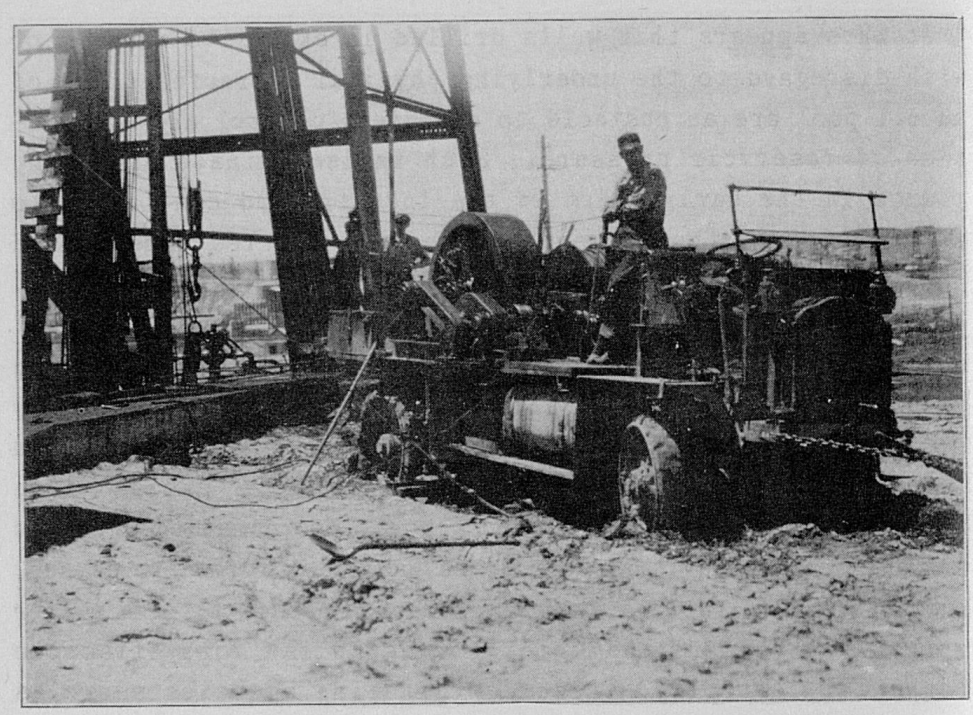
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[36] F. G. Miller and H. C. Miller, *Résumé of Problems Relating to Edgewater Encroachment in Oil Sands* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3392, mimeo., Mar. 1938), p. 2.

It thus appears that wells drilled in excessive numbers or with disregard to the underlying physical characteristics of an oil pool are an obstacle to efficient control and utilization of reservoir pressure. Such indiscriminate drilling, common in the early years of the industry and continuing to some extent to the present, has been corrected somewhat in recent years by controlled drilling and wider spacing of wells. Although engineering views differ on the question of well spacing, apparently wider spacing of wells than that found in many fields would have resulted in at least an equal recovery of oil, in more efficient use of reservoir energy, and in lower costs of production.[37] In many larger fields where management is progressive, furthermore, coordinating agencies and engineering advisory committees have been formed to gather, exchange, and disseminate the information needed for the proper control of pressures in order to establish more effective technical controls. These coordinating agencies serve as clearinghouses for data on bottom-hole pressures, taken periodically at certain key wells, either by their own crews or by company crews, and for data on water levels and other engineering information that is useful in the endeavor to extract the maximum quantity of oil from the reservoirs.

Evidence that the conservation of gas and proper utilization of reservoir energy is economically desirable and a technical necessity if the greatest ultimate recovery is to be obtained is represented by recent accomplishments in pressure maintenance. For example, with the production methods usually employed, the normal expectancy from one 11-year-old field in north-central Texas was 7,500,000 barrels, or about 20 percent of the oil in place. Due to a program of repressuring and pressure maintenance that was instituted early in the life of the pool, however, about 13,600,000 barrels of crude oil have already been recovered from this field. From present indications, moreover, it appears that some 21,000,000 barrels will be the ultimate recovery. The technical validity of this pressure-maintenance project is measured by an ultimate

[37] ". . . . if permeability of the sand and other elements of fluid-energy relations are taken into account, a spacing of wells wider than that in many fields apparently would have given at least equal recovery during the present 'proration period' and would have resulted in more efficient use of reservoir energy and lower costs of production." (R. A. Cattell and H. C. Fowler, "Fluid-Energy Relations in Production of Petroleum and Natural Gas," *Minerals Yearbook, 1934* [U. S. Dept. Int., Bur. Mines, 1934], pp. 715-6.)



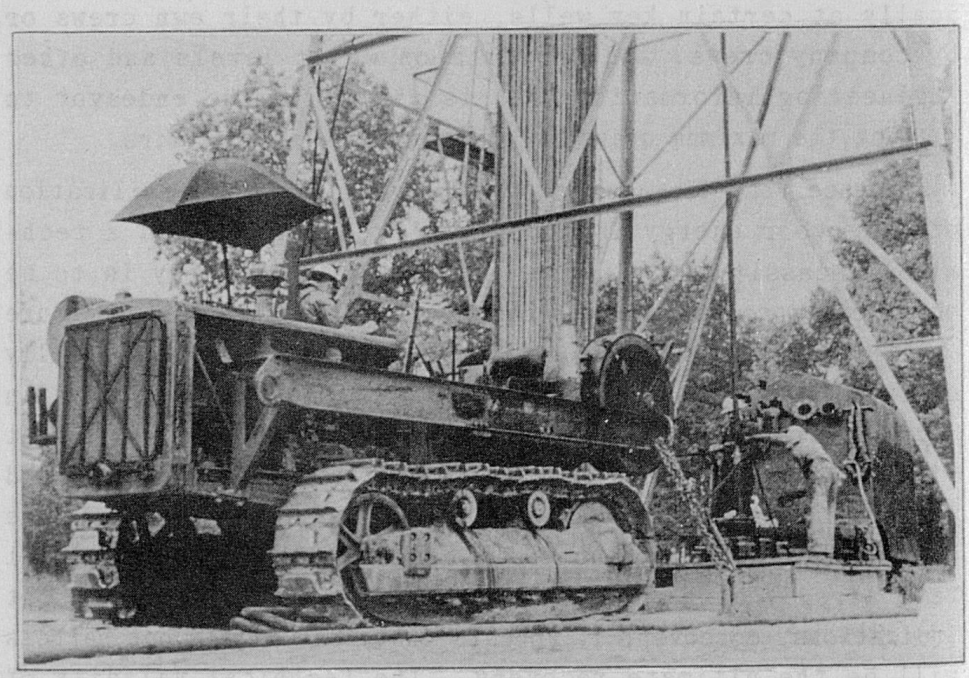


ILLUSTRATION 18.— PORTABLE HOISTS FREQUENTLY ARE USED FOR HEAVY WORK AT PRODUCING WELLS

The pulling of rods and tubing at producing wells, as well as other heavy work, is usually done with the aid of portable hoists. The upper view shows such a truck-mounted hoist in use in Wyoming in 1927; the lower view shows a hoist equipped with caterpillar traction in use in Louisiana and Texas in 1938.

recovery about 300 percent greater than that normally produced from similar fields.[38]

Other significant examples of successful pressure maintenance and control are found today in some of the more recently developed deep fields of the Gulf Coast area. In these, as in other deep fields, gas-bearing sands or reservoirs apparently prevail with high ratios of gas to oil. Under the high pressure and temperature conditions that exist at great depths, for example, it is believed that most, if not all, petroleum hydrocarbons are in a gaseous phase at those depths. By applying advanced techniques it is possible to prevent premature condensation of the reservoir material until it reaches the well bore and thus achieve greater recovery. In this process, the dry gas is returned to the reservoir for pressure maintenance after the wet fractions are extracted. In one flush field of this type, pressures as high as 3,640 pounds per square inch are maintained in the reservoir; the natural gas has been returned to the reservoir to hold the pressure on the sand.[39] After the oil-producing potentialities of the pool have terminated, the gas will still remain available either for sale or for further repressuring in another field. In adopting advanced oil-recovery methods of this type, operators are looking ahead many years with a view to obtaining high proportionate recoveries from deep sands.

Unit Operation the Technical Ideal.- The need for conserving and harnessing the powerful natural forces in an oil or gas reservoir if maximum recovery is to be obtained suggests the desirability of exploiting that reservoir as a single gigantic engineering project. The primary object of such technical control is to obtain the maximum recovery of oil at the lowest possible cost. Production with these objectives is most frequently identified in the industry by "unit operation", a term that is loosely used to describe both adequate technical control over an entire reservoir and legal or economic arrangements whereby the interests of different property owners are reconciled to permit unified technical control. Such operation is the antithesis of production under the "rule of capture"

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[38] E. O. Bennett, *Pressure Maintenance* (preprint; paper for presentation at Eighth Midyear Meeting, American Petroleum Institute, Wichita, Kans., May 24, 1938), pp. 13-4.

[39] *Ibid.*, p. 6.

whereby each operator or landowner endeavors to procure all the oil possible from wells on his property without any regard as to how much of the pool's potential productivity may be lost because of destructive individualistic productive practices; it also is potentially more efficient than production under the usual proration programs.[40] Sponsorship of unit operation as a technical ideal is not new,[41] but there have been serious barriers to its more widespread adoption.

Unified technical direction, or unit operation, is largely practicable today only in those instances where the development of a single pool is in the hands of a few producers. The possibility for unitization lessens as the number of individuals with property rights in the pool increases; unitized production in such a pool is possible only when all persons holding equities have voluntarily agreed upon what shares they will accept of the oil emanating from the common source of supply. It should be noted, moreover, that unified technical direction, whether obtained by reconciling many or a few property interests, offers the potentiality for maximum efficient recovery but does not guarantee it. The full possibilities are realized only when unified technical control is combined with advanced engineering. It is possible, for example, to have unified control of a pool and to subordinate efficient recovery to current business requirements of the individual operators, as might be represented by a more rapid withdrawal of oil than efficient extraction warranted.

Practical difficulties have been a serious handicap to any broad extension of unitized operation and only a few fields are actually operated in this manner. In some instances interests representing a segment of a pool have combined to form a unitized block. In addition to those fields where private interests have cooperated to secure the advantages of unitization, the Federal Government has adopted the policy of requiring unitized operation of oil properties in areas where it holds prospective oil-bearing sands. ". . . . Congress passed an act approved August 21, 1935 (49 Stat. 674), ... amending the Mineral Leasing Act and continuing provisions

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[40] For a brief, simplified description of unit operation see O. E. Kiessling, *Cooperative Development of Oil Pools* (American Institute of Mining and Metallurgical Engineers, Tech. Pub. No. 28, Nov. 1927), pp. 8-11.

[41] L. M. Logan, Jr., *The Stabilization of the Petroleum Industry* (1st ed.; Okla. Geol. Survey, Bull. No. 54, Oct. 15, 1930), p. 142.

for unitization of public lands. As of March 1, 1936, a total of 14 unit plans, involving 162,700 acres, had been approved by the Department. . . . . More than 700 additional plans, involving approximately 10,000,000 acres of public land, are now under consideration."[42]

Ample explanation of the advantages of unit operation of oil and gas pools is available in the technical press. For the purposes of this discussion it is sufficient to note that only by unified technical control can the reservoir energy be harnessed to produce the maximum. Moreover, the cost of exploitation is lessened greatly as the drilling of unnecessary wells is eliminated. Any scheme of production that restricts the engineer in controlling reservoir energy or that requires a larger expenditure of capital than the amount needed to obtain efficient recovery falls short of the technologic ideal in oil and gas production.

Technical Aspects of Production Regulations

Although very efficient recovery is technically possible under unit operation, most of the country's production of oil and gas is achieved under less effective arrangements; the engineer has to consider other factors besides high technical efficiency in developing and applying production techniques. Powerful influences determining the kind of technology applied and the intensity of the applications, for example, have been the business and legal controls exerted over production. Of particular importance has been the system of proration whereby the manner in which oil is taken from the ground is regulated by law or by agreement. When coupled with other regulations, such as those governing well spacing, gas-oil ratios, and other production practices, the area of optional technological endeavor in production engineering is seen to have been greatly delimited.

Originally conceived practically for the sole purpose of curtailing the supply of oil and to uphold prices,[43] proration has grown to represent a variety of production controls and

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[42] U. S. Bureau of Mines, Petroleum and Natural-Gas Division and Petroleum-Economics Division, "Conservation of Petroleum and of Natural Gas," *Transactions of the Third World Power Conference* (1936), Vol. VI (Washington, D. C.: 1938), Sec. IV, Paper No. 12 (U. S. A.), p. 789.

[43] E. G. Nourse and H. B. Drury, *Industrial Price Policies and Economic Progress* (Washington, D. C.: The Brookings Institution, 1938), p. 193, ftn. 8 (continued from p. 192).

instrumentalities. A well-known observer of the industry has reported recently that although "proration literally means the allocation of demand among competing producers on a pro rata basis, ... the term now carries a much broader significance for it is employed to describe the entire process by which the production of crude oil in the United States is regulated. . . . . The procedure is administered by State regulatory bodies through use of the police power of the States under authority of State conservation laws; the practice is supported by a considerable degree of voluntary conformance on the part of operators; and the Federal Government has accorded its cooperation by providing advisory quotas, circumscribing imports, checking movements of hot oil in interstate commerce, and ratifying an Interstate Oil Compact. In the course of the past 12 years, this regulatory system has become an institution with a framework of laws, court decisions, administrative bodies, committees, trade practices, and traditions."[44]

The authority of the States to restrict and prorate production and to define and enforce conservation measures appears to be on sound legal ground.[45] State legislation for these purposes falls into two groups: (1) legislation to prevent physical waste and to promote increased recoveries and (2) legislation for the proration of production among the pools or fields within a State or among wells and leases within a pool. In a State such as Texas, which produced nearly 40 percent of the total crude petroleum in 1938, State authority, for example, has extended to each of 528 producing oil fields that now operate under distinct separate orders applicable to local conditions. It is estimated that at least one-half of the oil fields of the United States now produce under orders from State authorities or in accordance with plans approved under Federal laws. There is no uniformity, however, in the proration formulas followed and in the conservation measures enforced by the various States; the efficiency of recovery and the extent to which production is controlled vary widely among the major producing areas, but the general result of production regulations has been a slower and more efficient withdrawal

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[44] J. E. Pogue, *A Design for More Effective Proration* (preprint for New York Meeting, Feb. 1939, American Institute of Mining and Metallurgical Engineers, Tech. Pub. No. 1028), pp. 1-2.

[45] For an informative discussion of the legal background of production control in the petroleum and gas industry, see N. Ely, "The Conservation of Oil," *Harvard Law Review*, Vol. LI, No. 7 (May 1938), pp. 1209-44.

of oil with less physical waste than would have occurred under unrestricted competitive drilling.

Present proration arrangements, nevertheless, leave room for much additional progress when viewed from the standpoint of potentially attainable technical efficiency. There are also numerous problems related to production allocation that have never been solved conclusively. For example, no wholly satisfactory formula for prorating production has been found. No one of the three factors generally recognized - per-well allowances, potential capacity, and acreage - has been sufficient by itself, and probably an adequate formula must take additional factors into account. The potential capacity of an oil well to produce, for example, has usually been determined in such a way as to obtain an exaggerated idea of a well's potentialities over any extended period; for this and other reasons there has been a growing tendency to look upon open-flow potentials as an inadequate measure of a well's capacity to produce.[46] Other methods, however, based on per-acre allowances or upon a combination of several factors, also produce major difficulties. Engineers are now attempting to develop another basis for proration, termed a "productivity index."[47]

In addition to the difficulty of deriving a satisfactory formula for allocating production, certain aspects of practical proration practice suggest outstanding technical inefficiencies. Where the basic unit is the individual well, for example, the drilling of unnecessary wells is encouraged. "In East Texas alone, 13,000 of the 24,000 wells are said to be unnecessary from an engineering standpoint."[48] "In the Oklahoma City Pool, where 300 wells would have been adequate . . . . nearly 700 were in fact drilled . . . . ."[49] Aside from the waste of capital, such excessive drilling results in the depletion of reservoir energy, both through improper location of wells and through a reduction of the allowable production per well and a consequent slower rate of production, which in the larger wells (where gas-driven) might result in the gas by-passing

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[46]H. C. Fowler and R. A. Cattell, "Influences of Petroleum Technology Upon Composite Interest in Oil," *Minerals Yearbook, 1935* (U. S. Dept. Int., Bur. Mines, 1935), p. 785.

[47]M. L. Haider, "The Productivity Index," *Transactions of the American Institute of Mining and Metallurgical Engineers: Petroleum Development and Technology, 1937* Vol. 123 (1937), pp. 112-8; see also Ely, *op. cit.*, p. 1228.

[48]Ely, *op. cit.*, p. 1233.

[49]*Ibid.*

the oil without lifting it to the surface. Attempts to meet this problem by providing spacing regulations, moreover, have been extremely ineffective due to numerous exceptions that are granted. For example, in the East Texas field a regulation requires a spacing pattern of one well to 10 acres, yet more than 17,000 of the 24,269 wells drilled in that field prior to January 1, 1938, were drilled under exceptions allowed by the Railroad Commission.[50] When proration is applied with the results just noted, it is essentially a device that arrests efficiency and technical progress at a certain level.

That there is room for considerable improvement in present production regulations is suggested by *A Design for More Effective Proration*, offered by Joseph E. Pogue.[51] Pogue suggests the five following points for consideration to make proration "into a perfected conservation measure, carrying with it a high degree of derived economic stabilization at the expense of minimum interference with competitive processes . . . .":[52] (1) "The development of the optimum rate concept as a yardstick for restricting the individual oil pool", (2) "the standardization of the application of bottom-hole pressure readings for the effectuation of ratable takings", (3) "the harmonizing of drilling incentives with the requirements of delayed production", (4) "the employment of market-demand quotas to reconcile the interim differences between optimum rates and market requirements", and (5) "the preservation of flexible markets to proportionate capital flow to economic requirements and prevent the development of intra-industry pressures." Alternative suggestions on how to meet the technical and economic problems raised by proration doubtless will be offered by other qualified observers, and it can be expected that the regulations controlling production will probably continue to be modified to harmonize more closely with standards of reasonable technical efficiency.

A byproduct of proration has been the reduction of stocks of crude oil stored above ground. Prior to some arrangement for production control it was not possible to determine with any degree of accuracy how long a pool would continue to produce

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[50] *Ibid.*, p. 1230. "These were granted because the size of the tracts, or the density of offset drilling, were supposed to require such exceptions in order to prevent inter-lease drainage."

[51] Pogue, *loc. cit.*

[52] *Ibid.*, p. 5.

or how large its ultimate output might be. Rapid dissipation of reservoir energy often caused abrupt declines in output. With slower withdrawals and some degree of output stabilization possible under proration, it becomes less necessary to have large stocks of crude oil above ground. For example, stocks of domestic crude oil on January 1, 1930, were about 425 million barrels. By January 1, 1938, the total was approximately 303 million barrels; by January 1939 it was approximately 272 million barrels. This decline becomes moresignificant when it is noted that the consumption of crude oil has increased enormously since 1930.

Insofar as proration operates to stabilize production and to prevent the tremendous flush yields - with accompanying waste - that prevail under unrestricted exploitation, its immediate effect is to curtail output[53] and hence to reduce production per man temporarily. The long-time effect of production regulation, however, has been to prolong the life of producing fields and to increase greatly the quantity of oil obtained from them. The long-time trend of output per man, therefore, will be higher than it would have been without production control. Moreover, by holding in leash the flood of oil from flush fields, proration has had a stabilizing effect on employment. Were the East Texas field allowed to produce without restriction, for example, it could for a time supply the country's need for petroleum. Such a development would shut down hundreds of other pools, particularly those that embrace wells of the stripper class, and would create widespread unemployment. Cessation of production from such wells, moreover, would probably effectively destroy most of them for future production.

Secondary, or Stimulative, Recovery Methods

Regardless of whether an oil field is developed under a unit plan, proration orders, or unrestricted competitive drilling, there eventually comes a day when the field can no longer produce by the usual methods of flowing and pumping. The wells then must be abandoned unless it is possible to apply additional doses of technology to increase the proportionate recovery. Such techniques, identified here as secondary

[53] Nourse and Drury, *op. cit.*, p. 194.

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[53] Nourse and Drury, *op. cit.*, p. 194.

or stimulative methods,[54] have shown much progress and have obtained from wells once abandoned oil that might have been lost forever. At the present time two methods are practiced on a commercial basis - water-flooding and repressuring with air or gas.

Water-Flooding.- The use of artificial water-flooding, whereby an artificial water drive (as distinguished from the natural water drive of many fields) is employed to achieve production, has been confined largely to the Bradford field in Pennsylvania and New York. Flooding in the Pennsylvania fields began accidentally prior to 1880, but regular and intentional use of this method had its inception about 1900, although it was not until about 1915 that the technique received favor and attention.[55] The present method consists of injecting water into the oil-bearing sands through input wells, carefully selected in regard to their location in the pool, so as to drive the oil toward outlet wells by water pressure. Development of an effective water drive requires careful planning and close attention to operating details, as the character of the water used, the rate of injection, and the movement of water in the oil-bearing formation must be carefully controlled. Although the producing sand of the Bradford field is peculiarly adapted to this method, water-flooding has recently been applied with success in a few other old fields where conditions are similar to those in the Bradford field.

Areas are known that would not have produced 1,000 barrels of oil per acre over a long period of time, as indicated by production-decline curves, and that already have produced to date over 4,000 barrels per acre under properly planned water-flooding methods. Two observers have noted that an operation approaching its economic limit under present conditions may be made to produce further by one of three methods, with the following results: Pumping for 25 years with a yield of 1,500 barrels per acre, repressuring for 10 years with a yield

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[54]Strictly speaking, much of the production technology already discussed - the application of vacuum, explosives, acid treatment, etc. - is stimulative in the sense that it increases well recovery above what would have been obtained simply by flowing and pumping. It is difficult, in fact, to draw a sharp line between initial and secondary recovery methods. Here the term "secondary" is used to describe the techniques used to obtain additional recoveries after wells either were abandoned or were in danger of abandonment under the usual production practices. For both water-flooding and air or gas repressuring, broad engineering controls are needed over at least a segment of a field.

[55]J. O. Lewis, *op. cit.*, p. 109.

of 2,000 barrels per acre, and water-flooding for 2 years with a yield of 3,000 barrels per acre.[56] Since it would be economically impractical either to pump 25 years or to repressure 10 years to obtain the total recoveries indicated, the importance of water-flooding in attaining greater proportionate recovery from the reservoir is apparent.

In addition to increasing recovery, water-flooding has interesting aspects for employment and reserves. Before it was applied in the Bradford field, for example, the area had almost been abandoned, and only a small amount of labor was used in pumping and servicing old wells for a gradually vanishing production. By contrast, the Bradford field today is one of the most productive and active east of the Mississippi River. Moreover, probably more men are employed in production activities in Bradford than in any other field except East Texas, and the output of these areas is approximately 50,000 and 450,000 barrels per day, respectively. Thus a short-time effect of such secondary recovery methods as water-flooding has been to increase the industry's labor requirements.

Although no new major producing fields have been discovered in Pennsylvania for many years, the State is credited with a greater crude-oil reserve today than 13 years ago. In 1925, for example, the reserve was estimated at 86 million barrels. Recently the State has been credited with 300 million barrels, and virtually all of this increase has been due to advancing production technology, and particularly water-flooding.[57]

Repressuring With Air or Gas.- Capable of wider application in secondary recovery than water-flooding is the use of the air- or gas-pressure drive, called repressuring. This consists of the injection of gas or air under pressure into the oil-bearing sand from which the original pressure has been depleted. The purpose is to provide energy in the petroleum reservoir to move additional oil through the sand to the well bore. Apparently the first successful application of repressuring of an oil sand was made in 1911 near Chesterhill, Ohio.[58] By 1916 the process was in use in some measure at

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[56]G. H. Fancher and K. B. Barnes, "Water-flooding in the Mid-Continent," *Transactions of the American Institute of Mining and Metallurgical Engineers: Petroleum Development and Technology, 1936*, Vol. 118 (1936), p. 140.

[57]W. L. Baker, "U. S. Reserves," *The Oil Weekly*, Vol. 88, No. 8 (Jan. 31, 1938), p. 35.

[58]J. O. Lewis, *op. cit.*, p. 38.

approximately 4,000 wells in southeastern Ohio and northwestern West Virginia. Since then the practice has spread rapidly to other partly exhausted oil pools and has produced good results in almost every producing State.

It has been the custom in the older fields to use existing wells as "key wells", through which compressed gas or air is injected into the oil sand, but in the larger and more extensive projects new wells are often drilled expressly for gas-injection purposes. Within recent years the technique of gas injection and repressuring operations has improved materially. Natural gas, being a better medium for repressuring than air, is now used in most areas for injection when cost permits. Injection pressures range from 25 to 500 pounds per square inch, the average being about 200 pounds.

Shallow fields of low initial reservoir pressure are usually well-adapted and respond readily to repressuring. In such pools the original pressure was rather low; as a result, the percentage of recovery of the oil from the sand was low, because the energy in the reservoir was enough to move only a small percentage of the oil to the well bore. The proportion of oil left in the sand in such pools is larger than in pools of higher original reservoir pressure. For example, engineers estimated the original content of crude oil in a producing sand in a shallow field in northeastern Oklahoma at 40,000 barrels to the acre.[59] After 2,000 barrels an acre had been produced from this property, the output was so low it was not economical to continue further ordinary pumping operations. Three separate areas in this section were repressured with natural gas, and the production of oil increased 169, 300, and 408 percent, respectively. Records of even greater proportionate gains in recovery have been reported in some of the older fields in Pennsylvania.

In addition to water-flooding and repressuring, oil is now being mined in France and Germany[60] by running tunnels from a central shaft. Although there are vast quantities of unrecovered oil in the United States at depths that can be reached by shafts, oil mining has not been used commercially in this country. A horizontal oil well has been completed recently

[59] A. M. Rowley, *Oil Royalties Worth Much More Under New Methods* (pamphlet published by author; Tulsa, Okla.: 1937), p. 18.

[60] G. S. Rice, *Mining Petroleum by Underground Methods* (U. S. Dept. Com., Bur. Mines, Bull. No. 351, 1932), pp. 4-70.

near McConnelsville, Ohio,[61] and it has been suggested that horizontal drilling could be undertaken from mine shafts sunk to the pay sand as well as from outcrops. If horizontal oil wells prove successful they would doubtless be used in secondary recovery.

In citing the success of water-flooding and repressuring, it should be noted that these practices are now applied to fields in which as much as 80 to 90 percent of the original oil in the reservoir was not recovered by the early production methods. "If early production practices had been in accord with present-day methods, based on increased understanding of fluid-energy relations in reservoir sands, it is likely that secondary recovery methods such as are used today would be far less profitable."[62] In fact, the total percentage of oil that will be recovered from the older pools by initial and secondary methods will just about equal the percentage recovery achieved in newer fields where modern standards of engineering practice are followed.[63] Under efficient production methods available at present, for example, the estimated recovery for most fields ranges from 30 to 50 percent or more.[64] Thus, in the newer fields the proportion of the reservoir content remaining for secondary recovery at some future date has become much smaller. It should also be noted that the amount of engineering effort that can be made in the way of complicated secondary extraction methods is largely determined by the revenue available to defray the cost. Hence, if oil prices should rise notably at any time in the future, greater intensity of effort for secondary recovery appears possible.

IMPROVEMENT IN PRODUCTION TECHNOLOGY TO CONTINUE

Advances in technology may be expected to continue to increase engineering efficiency in petroleum production. The Director of the U. S. Bureau of Mines indicated the character of this progress when he reported that ". . . . petroleum technologists are giving more attention to reservoir conditions, movement of fluids through porous rocks, characteristics of the

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[61] L. Ranney, "The First Horizontal Oil Well," *The Petroleum Engineer*, Vol. X, No. 9 (June 1939), pp. 25-30; L. Ranney, "Horizontal Drilling Through Outcrop Brings Results," *The Oil and Gas Journal*, Vol. 37, No. 49 (Apr. 20, 1939), pp. 68-9.

[62] U. S. Bureau of Mines, Petroleum and Natural-Gas Division and Petroleum-Economics Division, *op. cit.*, p. 770.

[63] *Ibid.*

[64] Miller and Lindsly, *op. cit.*, p. 1193.

rocks themselves, and the composition of natural hydrocarbon mixtures. With increased knowledge of these and related factors, the producer will . . . . obtain increased ultimate recovery."[65]

Although the development and application of improved apparatus and techniques may be expected, it should be noted that use of the technologic knowledge already available will result in efficient extraction. This is proved in those fields where production processes are determined by engineering standards unhampered by legal and economic restrictions. For reasons indicated in chapter VIII, however, the full potentialities of the existing technology cannot be utilized at present in most producing areas. Nevertheless, judging from past changes in the industry, it may be expected that there will be continued progress toward the increased use of superior available techniques. It should be noted that much of this development - when it occurs - will have the appearance of the creation of new techniques, whereas what is really happening is that the environment has become favorable to the application of practice that is already known to engineers. The effect of the change on employment and output per man will be the same, however, regardless of whether known techniques are spread or new techniques are evolved.

The net result of progress toward more efficient oil and gas production on employment is not easy to determine. Such an appraisal requires consideration of what appear to be conflicting products of short- and long-time forces. An immediate effect on employment of wider spacing and fewer wells, for example, was a smaller number of jobs in drilling and oil-field development, whereas a long-time effect was more continuous employment for a longer period in individual fields than would otherwise have been possible. Moreover, a concomitant of technologic progress has been an increase in the labor required for precise engineering processes and for operating controls at the wellhead; this increase in labor, however, has been small compared with the increased production that the improved techniques made possible. Finally, the demand for petroleum has continued to expand so rapidly that

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[65] J. W. Finch, *Mineral Productivity and Scientific Progress* (paper delivered before the American Association for the Advancement of Science, Indianapolis, Ind., mimeo., Dec. 28, 1937), p. 11.

the total number of jobs continued to increase irrespective of any labor saving that the technologist was able to achieve in the individual tasks required for production. Although data are not adequate to differentiate the precise influence of conflicting as well as of closely interrelated causes, from a statistical viewpoint technologic progress in production does not appear to have reduced the total number of jobs in the industry. In addition, important byproducts of technical progress have been greater long-time stability of employment,[66] higher output per man, and lower production costs than would otherwise have been possible.

[66] "Stability" is used here in a relative sense in contrast to the short-time fluctuations that usually characterized employment through most of the industry's history. Under the older methods of unrestricted production from a large number of wells in each field, the peak employment was reached during the early drilling campaigns (similar to gold-rush phenomena), and a rapid slump in employment and migration of workers took place thereafter. Although this exists today over large segments of the industry, it is not so pronounced as in the early period, and in some areas employment has been stabilized as much as efficient production permits.

CHAPTER VII

TECHNOLOGIC PROGRESS IN NATURAL-GAS AND NATURAL-GASOLINE RECOVERY*

An earlier section has shown that in the primary production branch of the petroleum and natural-gas industry (including natural gasoline) output per man-hour increased more than 850 percent during the past half-century.[1] Immediately preceding chapters have been devoted to analysis of the factors affecting principally the drilling and extraction techniques in petroleum production that were partly responsible for this remarkable increase. Another unit of the industry remains to be considered before the discussion of technical advances in primary production is complete. What has technologic progress in natural-gas and natural-gasoline recovery contributed to the over-all increase in unit output?

This question is easy to pose but difficult to answer. The difficulty arises primarily from the fact that some of the segments that converge to form the complex and interlocking structure that is the petroleum and natural-gas industry are fitted together much too tightly to be detached for separate statistical analysis. Even operators are sometimes unable to state with certainty where crude-petroleum production leaves off and the production of natural gas begins, and the production of natural gasoline is not infrequently a joint product. With none of the segments mutually exclusive, the clear-cut division of labor that characterizes many other branches of economic activity is lacking at certain points in the petroleum and natural-gas industry.

Although certain aspects of the natural-gas and natural-gasoline divisions of the industry are somewhat beyond precise quantitative appraisal, persuasive evidence is at hand to indicate that both of them have contributed heavily to the over-all increase in productivity. The magnitude of the contribution is suggested, first of all, by the fact that both divisions have as their basis products that formerly were largely wasted in the production of crude petroleum. One has to go back no more than a single

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*By M. A. Schellhardt, Natural Gas Engineer, U. S. Bureau of Mines, Bartlesville, Oklahoma; J. S. Ross; G. R. Hopkins; and O. E. Kiessling.

[1] See p. 26.

generation to the time when natural gasoline was not even a name; 5 decades ago our grandparents were burning natural gas with spectacular abandon in great open torches[2] simply because they had no means for utilizing it for other purposes. Today, by contrast, the oil- and gas-well operators realize 125 million dollars annually from the sale of natural gas, and the plant value of the natural gasoline produced exceeds 70 million dollars a year.

In domesticating the great mass of energy represented by 2 trillion cubic feet of natural gas and 2 billion gallons of natural gasoline - the approximate output for recent years - to the needs of society, moreover, the labor requirements have been remarkably small. Between 1902 and 1935 a fourfold increase is shown in the output of "dry"-gas wells alone,[3] while employment increased by slightly more than one-half.[4] Similarly, production of natural gasoline has quadrupled since the war, but the number of wage earners employed at the natural-gasoline extraction plants has little more than doubled.[5]

Although this discussion is confined largely to advancing techniques employed in natural-gas and natural-gasoline recovery, the great importance of some related factors is recognized. Closely allied to more efficient production processes, for example, were the development and expansion of pipe-line transportation. Improvement in the art of transporting gas (treated in chapter IX) represented an important aspect of engineering progress because a successful specialized form of transportation was prerequisite to any extensive use of gas and as long-distance pipe lines bridged the gap between the gas field and the distant consuming center. Since the extending pipe-line network made possible the use of much energy that probably would have been wasted, as well as the use of constantly greater quantities of natural gas[6] and

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[2] National Resources Board, *A Report on National Planning and Public Works in Relation to Natural Resources and Including Land Use and Water Resources, With Findings and Recommendations* (Dec. 1. 1934), p. 392.

[3] The corrected production of natural gas in 1902 was 281 billion cubic feet (see table A-10) as compared with 1,150 billion cubic feet produced from "dry" wells in 1935 as determined from the records of the U. S. Bureau of Mines. It is assumed that all of the gas credited to 1902 was from "dry" wells.

[4] Compare *Special Reports of the Census Office*, "Mines and Quarries: 1902" (U. S. Dept. Com. and Labor, Bur. Census, 1905), p. 787, with *Minerals Yearbook, 1937* (U. S. Dept. Int., Bur. Mines, 1937), p. 1058.

[5] According to the U. S. Bureau of the Census, 3,391 wage earners were employed in 1919 by extraction plants representing somewhat less than two-thirds of the industry (as determined by the value of the gasoline produced by these plants compared with the total value of all natural gasoline produced). In 1935, however, the total number of wage earners employed by natural-gasoline plants was 7,997. (See *Minerals Yearbook, 1937*, p. 1094.)

[6] Among large cities the gradual shift from manufactured gas to natural gas has continued to the present. See L. Stotz and A. Jamison, *History of the Gas Industry* (New York: Stettiner Bros., 1938), pp. 299-302.

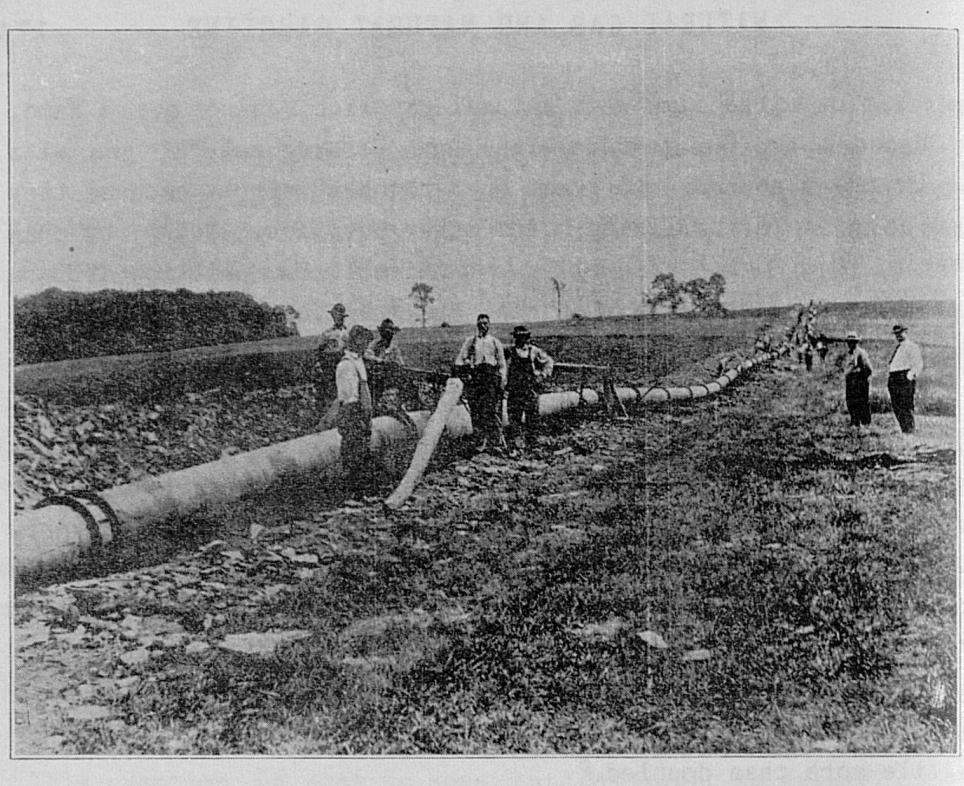




ILLUSTRATION 19.- THE RAPID EVOLUTION OF A TECHNOLOGY FOR BUILDING EFFICIENT HIGH-PRESSURE GAS PIPE LINES HAS BEEN CLOSELY ALLIED TO THE INCREASING ECONOMIC IMPORTANCE OF NATURAL GAS

The upper view shows a natural-gas transmission line under construction in 1922, with a special type of coupling that was used for joining the sections of pipe. The lower view shows a pipe line under construction in 1930 in which the joints were oxyacetylene-welded. More recently, electrical welding has been used widely in pipe-line construction.

derivative products, it played an important part in the continuously growing volume of B. t. u. credited to the entire industry in chapter II. This and other related developments that increased or retarded output per man, however, are treated in other portions of the report for convenience in presentation.

TECHNOLOGIC DEVELOPMENTS IN NATURAL-GAS PRODUCTION

Many of the factors that were influential in increasing the output per man in crude-oil production also played a prominent role in natural-gas production. First, natural gas shared with petroleum the enormous gains that have been made in exploration and discovery techniques. Similarly, the natural-gas division of the industry profited greatly from improvements in the art of drilling. The advances in discovery and drilling technology, in turn, enabled natural-gas production to keep abreast of petroleum production in the march across the country to the richer fields of the West.

Improved methods in well operation, regulation, and metering of gas production have also contributed heavily to the rising output per worker employed. Within recent years the growing interest in conservation and increasing opportunities to market gas and to put it to greater use in many fields have helped to improve operating technique to reduce waste.

Of particular significance to the natural-gas industry have been the conservation and increased production of natural gas in association with petroleum. Where once the marketed natural gas was produced almost wholly from "dry"-gas wells, today more than 40 percent of the total volume of natural gas produced and consumed in the United States comes to the surface of the ground in association with oil. Increasingly larger volumes of natural gas have been made available through the development of high-pressure gas-oil separators, the improvement of other surface recovery equipment, and conditions created by restricted rates of oil recovery.

Improvements in Discovery and Drilling Techniques

In natural-gas recovery, technology made its greatest contribution in the field of discovery and drilling. Since the geology of natural-gas and oil reservoirs is similar, the arts of geological and geophysical exploration that were developed

and applied in the search for oil, already noted (chapter IV), are equally applicable to the search for natural gas. Indeed, most natural-gas reservoirs, whether they contained gas only or gas in association with oil, have been discovered and their limits defined as a result of oil exploration.

For the same reason, there is little difference between the drilling equipment and technique used in developing oil fields and that used in developing natural-gas fields. Consequently natural-gas recovery benefited as did oil recovery from technologic advancements in drilling and well completion, as well as in exploration.

In the early development of the petroleum industry the finding of natural gas was considered a dangerous and unwelcome discovery. Often gas was found in sands overlying the oil horizons or in the higher portion of sands containing oil, and it was allowed to flow into the atmosphere and to be wasted until the pressure was reduced enough to permit drilling to proceed. The most courageous drillers attempted to work the drilling tools against the flowing gas, and often succeeded. Later, however, an ingenious method was devised for controlling the flow of gas by filling the hole with water. Adoption of this method of control made it possible either to install casing after a gas-bearing stratum was penetrated or to drill through and case off gas-bearing strata penetrated in the course of developing reservoirs at greater depths. Under these adverse conditions drilling operations were laborious because the lightweight cable tools worked more slowly in a "wet" hole. The absence of suitable wellhead pressure-control equipment, moreover, made the drilling of gas-bearing formations a hazardous undertaking. Furthermore, gas and water rarely were confined to their respective horizons because cementing technique was unknown in the early days of the industry. Until recent decades oil and gas development was characterized by drilling operations that were wasteful of natural gas.

A long stride in the direction of the conservation of natural gas was the development and intelligent use of mud-laden fluids for the control of well pressures and the gradual shift from cable- to rotary-drilling equipment which began early in the century. The protective coating of mud administered to the walls of the rotary-drilled wells, together with the pressure exerted by the drilling fluid, confined natural gas, water, and oil to

their native zones during drilling as well as after casing was installed. Not only were gas wells kept under control during drilling and until production-control equipment was safely installed on the wellhead, but the speed with which gas wells were drilled and completed was also greatly accelerated, particularly in the development of deeper reservoirs in areas characterized by relatively soft rock.

These improvements have been developed along with advanced casing and well-cementing techniques that provide for the exclusion of water and the elimination of losses caused by the migration of gas from important reservoirs to other porous strata penetrated by the well, or to the atmosphere. A large part of the success of recent accomplishments in deep drilling is due to the use of efficient cement mixers and powerful equipment for pumping generous quantities of cement behind lengthy strings of casing. Chemicals are also employed to accelerate or retard the setting time of cements, depending upon the conditions encountered in drilling. Despite high earth temperatures and gas pressures at great depths, the proportion of cementing failures is strikingly small in contrast with a decade ago.

The practice of coring formations during drilling and the electrical logging of the formations after they have been penetrated by the drill, with but little interruption of routine drilling operations, have permitted the discovery of numerous gas reservoirs that otherwise would have been passed in the course of drilling and cased off without recognition. Determination of the presence of gas or oil in subsurface formations by the electrical method has reduced the labor that would have been required to obtain the information by other means. Electric logs also have provided information for the study of reservoir conditions so that casing could be cemented at the most advantageous points. Discoveries of gas reservoirs that have been made through the use of electric logging devices have contributed materially to the large increase in the natural-gas reserves developed within the last few years. Progress in research has provided methods for studying the porosity, permeability, and saturation of core samples, and such determinations have facilitated the estimation of natural-gas reserves and an appraisal of their availability.

Natural-gas wells, like oil wells, have benefited by the progress made in well-completion practices. Great strides also have

been made in the manufacture and installation of steel casing and of efficient wellhead fittings that comprise the Christmas tree.[7] Today, in contrast with former years, Christmas trees are installed on high-pressure gas wells before instead of after they are brought into production. This insures complete control of the well. The use of improved screen or perforated liners for excluding sand and other wall material which might clog the borehole, or which, because of their abrasive character, might damage the well equipment, has improved the operation of wells completed in friable gas strata. On the other hand, where the productive strata are extremely hard, blasting or "shooting" of the gas-bearing formation has increased the flow of gas into the well bore.

Within the last few years the perforating of well casing by means of a gun perforator, at points opposite known productive gas horizons, has become common procedure for developing additional productive capacity. Used often as a means for testing the productivity of prospective gas-bearing zones that had been cased off during drilling operations, this method has resulted in a reduction of drilling labor that otherwise might have been expended for equipping wells with additional strings of casing or for drilling additional wells.

Improvements in Gas-Well Operations

The technique of gas-well operations improved rapidly once producers began paying more attention to protecting the sources of natural-gas supply upon which the well depended. Before the advent of gas meters, for example, gas wells, drilled in the course of oil exploration, were connected to pipe lines, and the gas was sold on a flat-rate basis, with little knowledge of the actual volumes produced. The revenue derived from the sale of gas in this manner frequently was less than the development costs of the wells. There was also little scientific knowledge regarding the producing characteristics or the delivery capacities of gas wells; the geological logs obtained from the wells had little value for determining the true underground conditions in the gas fields. The general belief was held that natural gas was inexhaustible, and this fostered wasteful methods of production and consumption. Towns piped for natural gas changed from gas

[7]For explanation see pp. 117, 136-7.

to coal and back to gas, time and again, as old gas fields were depleted and new discoveries made. As capital investment in marketing facilities of the gas industry increased, however, more attention was given to the application of engineering principles and to increasing the efficiency of gas production.

One of the most important tenets of efficient natural-gas production - namely, that restricted rates of production were conducive to increased ultimate recoveries from almost all gas wells - was recognized early in the industry. Thus an important technologic advance was the development of equipment for measuring the production of gas from individual wells. The orifice meter[8] which evolved from the Pitot tube, long used for measuring the open-flow capacity of gas wells, was accepted quickly by the industry, and by 1922 measurement of gas production from individual wells or from groups of wells was established as common practice in many areas.

Measurement of natural-gas production tended to reduce waste of gas by directing the attention of operators to the discrepancies between volumes of gas produced and volumes sold. Such differences were not apparent when the gas produced from individual wells was not metered. Metering also provided a means for correlating gas production and well pressure for studies of reserves and reservoir conditions; such studies indicated the need for better technical control to improve the performance of gas wells. Although gas-well operations were benefited, the measurement of gas deliveries from individual wells increased employment materially in natural-gas production. The installation and maintenance of the large number of meters and the handling and reading of many meter charts daily required a large technical and clerical force. Although this development contributed indirectly to increased long-time production from many wells, recoveries apparently were not increased over the short run in proportion to the gain in labor requirements.

The regulation of deliveries from gas wells was improved by the substitution of orifice disks or choke nipples for gate valves that generally were used for this purpose.[9] However, as well pressures increased with corresponding increases in the ratios

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[8] H. P. Westcott, *Measurement of Gas and Liquids by Orifice Meter* (2d ed.; Erie, Pa.: Metric Metal Works, 1922), p. 11.

[9] E. O. Bennett and H. R. Pierce, "New Methods for the Control and Operation of Gas Wells," *Proceedings of the Natural Gas Association of America*, Vol. XVII (annual meeting, Atlantic City, N. J., May 18-21, 1925), pp. 76-83.

of wellhead working pressures to pressures on gathering systems, the freezing of moisture or the formation of hydrates in all types of pressure-reducing equipment installed downstream from wellheads required the operation of heating equipment to insure uninterrupted gas deliveries. The use of such equipment required additional labor for installation and operation; however, had not this equipment been installed, the wells would have "frozen",[10] and a relatively large amount of labor would have been required to get them back into production.

Before 1925 few gas wells that were not troubled by liquid entry were tubed. As well pressures increased with deeper drilling, however, the practice of installing tubing in gas wells as completed became common. This practice facilitated the regulation of deliveries of gas for the reason that gas, in flowing through the small-diameter pipe, was subjected to considerable pressure reduction. Within the past few years various devices have been developed that increased materially the range of subsurface control of gas deliveries from high-pressure wells. Among these were removable chokes[11] that could be installed at any desired depth in the tubing strings and bottom-hole chokes that were adjustable from the surface. These, with other devices that have appeared from time to time, represent an important stride toward solving the problem of regulating gas deliveries from high-pressure wells. The use of subsurface chokes for regulating deliveries from high-pressure wells in some instances reduced materially the labor entailed for such work in comparison with regulating gas deliveries from the wells by means of surface control equipment.

Water associated with natural-gas reservoirs has long been a source of production difficulties. Many an early gas well was amazingly short-lived because of the untimely incursion of extraneous water which flowed into the well through faulty casing seats or encroached upon the well from within the sand reservoir itself. Improved casing techniques and regulated rates of production from gas wells have accomplished much in removing the danger of premature flooding. Yet, despite modern well-completion practices, varying amounts of water are produced with the gas in most gas wells. Some of it is moisture condensed from the gas,

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[10] The flow line, tubing, or pipe connections of a gas well sometimes become completely plugged by the formation of ice or hydrates.

[11] H. C. Otis, "The Operation of High-Pressure Gas Wells by Means of Bottom-Hole Chokes," *Proceedings of the Natural Gas Department of the American Gas Association* (annual meeting, Memphis, Tenn., May 6-9, 1935), pp. 174-8.

but generally it is water that is displacing the gas as the gas is withdrawn from the reservoir.

The rates of water entry in many instances have been reduced by control of pressures[12] and by remedial measures or repair work on the wells Efficient operation of gas wells in some fields has been improved by the installation of properly designed siphons[13] and in others by locating tubing packers so that only relatively small quantities of water could accumulate in the annular space in the well bores above the lower ends of the strings of tubing. Drip traps, placed in the delivery line from the wellhead, provided a means for collecting condensate (water, gasoline, or both) from the gas.

In gas fields where the reservoir rocks are predominantly limestone, acid treating[14] of wells increased the production of gas and possibly the volumes of gas ultimately recoverable from them. The technique used differed only slightly from that developed for the acid treating of oil wells.[15] Formerly the acid was pumped down the siphon pipe and then forced into the lime formation by means of gas pressure, but in recent practice water is used to force the acid into the formation.[16] The remarkable results obtained in some north Louisiana gas fields have given special impetus to acid treating of gas wells. An indication of the possible effect of acid treating of gas wells on the output of men engaged in drilling and production operations is illustrated strikingly by the results obtained in the Monroe gas field. Tests by an operator on 95 acid-treated gas wells showed that their total open-flow delivery capacity was increased from 588,000,000 to 1,207,000,000 cubic feet per 24 hours, or about 105 percent. Thus the acid treatment, which probably cost $300 or $400 per well for labor and materials, increased the availability of gas from the reserve[17] by about the same amount that would have been

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[12] J. R. Hatfield, "Control of Gas Wells," *Proceedings of the Natural Gas Department of the American Gas Association* (annual meeting, Memphis, Tenn., May 6-9, 1935), pp. 180-5.

[13] I. B. Williams, R. R. Brandenthaler, and Morgan Walker, *Design and Operation of Gas-Well Siphons* (U. S. Dept. Com., Bur. Mines, Tech. Paper No. 460, 1929), 45 pp.

[14] E. L. Rawlins and M. A. Schellhardt, *Back-Pressure Data on Natural-Gas Wells and Their Application to Production Practices* (U. S. Dept. Int., Bur. Mines, Monograph 7, 1935), pp. 89-93.

[15] See pp. 150-3.

[16] M. E. Chapman, "Acid Treating of Gas Wells to Increase Production," *American Gas Journal*, Vol. 148, No. 6 (June 1938), p. 24.

[17] The reservoir rock in the Monroe field probably contained more acid-soluble material than many limestone reservoirs. Equally favorable results could not be expected if the treated formations contained a greater proportion of sand or insoluble material. Water conditions in some reservoirs make acid treatment inadvisable.

obtained by drilling and operating 100 additional wells having an average delivery capacity equal to that of the wells that were treated.

Storage of gas in underground reservoirs[18] in several experimental projects is being studied as a means of conserving gas produced in excess of current utility requirements that otherwise would be vented to the atmosphere and as a means of meeting peak-load demands on long pipe-line systems. Preliminary studies of developed reservoirs considered for gas storage were facilitated by the development of a method for evaluating the intake capacities of "dry"-gas wells from data determined from their output characteristics.[19]

Treatment of "sour" gas for the removal of hydrogen sulphide, though not essentially a production operation, represents technologic progress in gas conservation which provides a larger volume of marketable gas than would otherwise be available. At present a large proportion of the sour gas produced is used for the manufacture of carbon black. Treatment of sour gas for distribution to fuel markets is not practiced extensively at present because adequate supplies of sulphur-free (or sweet) natural gas are available, and the cost of removing hydrogen sulphide by commonly applied processes is relatively high. If a scarcity of sweet gas should develop so that it would be economically feasible to treat large volumes of sour gas - either under existing or reduced processing costs - for distribution for fuel, the labor needed to provide gas acceptable for transportation would be increased materially.

ADVANCING TECHNIQUE IN NATURAL-GASOLINE PRODUCTION

Accompanying the rise of other branches of the industry, the natural-gasoline division has rapidly grown to become an important segment of the petroleum industry. Within a quarter of a century the annual production of natural gasoline has climbed from about 7 million to more than 2 billion gallons, and the total cumulative recovery of about 86 million gallons before 1915 was increased to about 21 billion gallons by 1934. Today over 87 percent of the

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[18] J. H. Dunn, "Natural Gas Storage," *Proceedings of the Natural Gas Department of the American Gas Association* (annual meeting, Memphis, Tenn., May 6-9, 1935), pp. 191-8.

[19] M. A. Schellhardt and E. L. Rawlins, *Comparison of Output and Intake Characteristics of Natural-Gas Wells in Texas Panhandle Field* (U. S. Dept. Int., Bur. Mines. Report of Investigations 3303, mimeo., May 1936), 25 pp.

total production of natural gas produced and sold in the country is passed through natural-gasoline plants. Equally striking is the growth in the number of such operations. In 1936 there were in operation 700 plants that provided employment for 9,036 wage earners,[20] exclusive of salaried employees, whereas 3 decades earlier no commercial plants were in existence.

Long before the process of extracting gasoline from natural gas was commercialized, accumulations of gasoline were observed in drips of natural-gas pipe lines and in lines used for gathering the gas available at the casing heads of pumped oil wells. The condensate that was thus commonly obtained became known as casing-head gasoline. This gasoline, then regarded as a waste product, often interfered with the operation of the wells or retarded the flow of gas in pipe lines and was disposed of as waste or collected from the drips and used locally for fuel. Early in the century, when the automobile increased the demand for motor fuel, casing-head gasoline was collected and blended with straight-run naphtha to raise the quality of the refinery product. It was recognized that raw casing-head gasoline, because of its high volatility, was unsuitable for use in ordinary motor car engines.

Aside from the influences of such fundamental factors as rising demand for motor fuel attending the growth of the automotive industry, increased consumption of marketable natural gas, and regional migration of the oil and gas industry, the increased productivity at natural-gasoline plants may be ascribed to technologic advancements. In the evolution of the natural-gasoline industry, extraction processes underwent extensive development and modification, the size of plants and the yields of gasoline increased greatly, and the quality of the product improved. It is not surprising, therefore, that modern plants are extracting gasoline economically from natural gas that is considerably leaner or "drier" than the tail gas of the early-type plants. The bulk of the natural-gasoline production - over 2 billion gallons in 1937 - is used for blending with refinery naphtha in the production of motor fuel.

Early Production Processes

In the normal process of pipe-line transportation, natural gas, rich in gasoline vapors, was found to yield a large quantity

[20] G. R. Hopkins, "Natural Gasoline," *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), pp. 948, 951.

of natural gasoline upon being compressed and subsequently cooled. This led to the increased use of gas compressors and eventually to the development of the compression process of natural-gasoline extraction. Thus the first plants were based upon the principle of condensation of the gasoline by compression and subsequent cooling of the gas. The early equipment consisted essentially of a compressor for compressing the gas, a prime mover for driving the compressor, cooling coils, and a tank for collecting the condensate. As refinements in plant construction and operation developed, the compression process gained rapid headway, and by 1912, 250 such plants were in operation, the number increasing to 863 in 1921.[21]

Various methods were developed for cooling the compressed gas, for operating the plants at lower pressure, and for increasing the efficiency and the gasoline recovery. But despite the advances in equipment and technique, the product from the compression process was "wild" and required weathering or stabilization before it could be blended with naphtha or shipped. Furthermore, the process did not work well on lean or so-called "dry" natural gas.

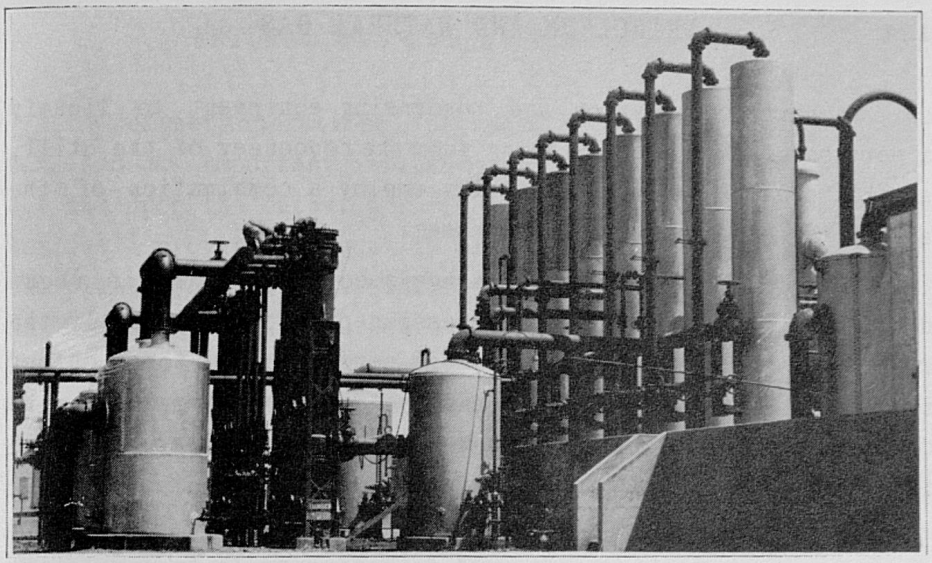
RISE OF THE ABSORPTION PROCESS

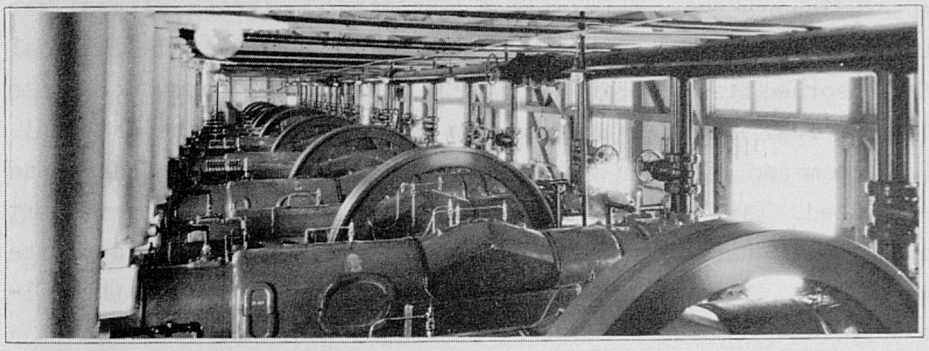
The compression method of extracting gasoline from natural gas was in commercial practice but a few years when the absorption process was developed. This process extracted gasoline from lean or dry natural gas more efficiently than the compression process. It consisted in bringing natural gas into contact with an oil heavier than gasoline, causing the oil to absorb the heaviest hydrocarbon fractions in the gas. The absorbed gasoline vapors then were recovered by distillation from the absorption oil in the form of gasoline, and the denuded absorption oil was pumped back to the absorbers to receive another charge of gasoline.

At first the oil-absorption process was reserved for extracting gasoline from high-pressure dry gas, but as operating technique developed it was adapted for use with casing-head gas. The low pressure at which this gas was available made this change desirable. Eventually most new plants operating on casing-head gas were of the absorption type.

Various modifications of the oil-absorption process have appeared from time to time, and today the process embraces as one

[21] G. A. Burrell, *The Recovery of Gasoline From Natural Gas* (New York: The Chemical Catalog Co., Inc., 1925), p. 35.





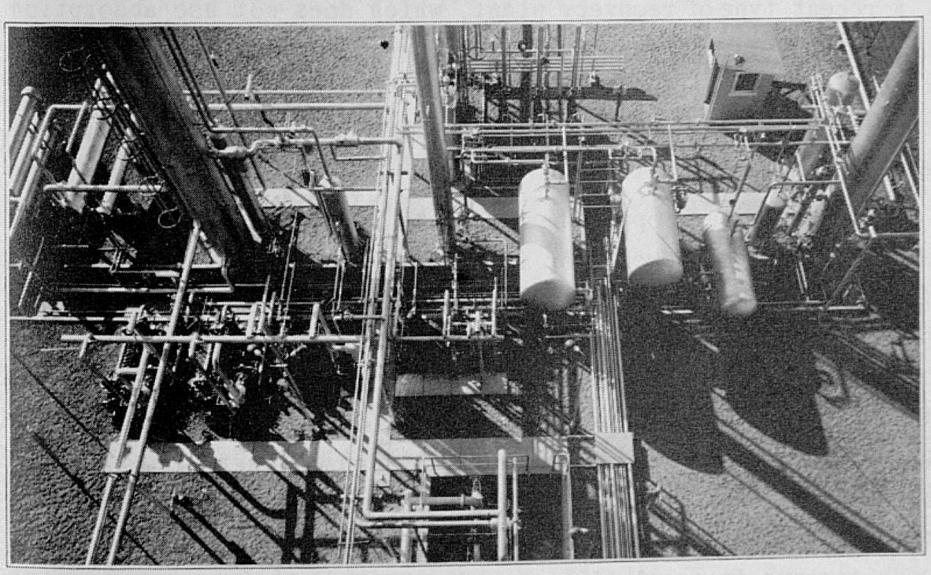


ILLUSTRATION 20.— NATURAL-GASOLINE EXTRACTION HAS INCREASED IN IMPORTANCE AS OTHER SEGMENTS OF THE OIL AND GAS INDUSTRY HAVE EXPANDED

Natural-gasoline extraction has gradually grown to be an industrial activity of considerable importance and employs a technology of its own. Absorption towers and compressors used in the extraction of natural gasoline are shown in the two upper views. The lower picture shows a portion of a modern natural-gasoline plant as viewed from the top of one of its several high fractionating towers or columns.

of its parts compression and condensing equipment to liquefy a portion of the gases escaping from the condenser of the still, so that present-day plants usually employ a combination of the absorption and compression processes.

Labor productivity in the average absorption plant is about double that of the average compression plant; consequently the rise in absorption production from 26 percent of the total output in 1919 to 88 percent in 1936 and the corresponding decline in compression production have been closely related to the gain in over-all productivity.

Another process that received considerable notice a decade ago and was put into limited commercial practice was the charcoal-absorption process. This process consisted in passing natural gas into absorbers containing activated charcoal. After the charcoal had absorbed its quota of gasoline, live steam was introduced into the absorber and the gasoline was distilled from the charcoal. The steam and gasoline vapors were liquefied in condensers and separated. This process - never widely used - was an intermittent one, three absorbers being required for the operation of the extraction cycle; it has been generally replaced by the oil-absorption process.

A recent type of recovery plant, which does not use absorption but employs a combination of refrigeration and dehydration of the gases, is attracting attention. It depends upon cooling the incoming feed gas to a temperature low enough to liquefy all desirable constituents.

An important development has been the use of elaborate fractionating columns or towers for removing the more volatile fractions from the natural gasoline, thereby making marketable a larger portion of the plant product than is otherwise possible. The operation of the towers or stabilizers is governed by the products to be recovered. The gasoline fraction is recovered from the bottom of the tower and is usually blended with refinery-gasoline stock. If other products such as butane and propane are to be recovered, they are taken off either overhead and rerun, or as side streams from stabilizers and run to pressure-storage tanks. The remaining incondensable gases from the stabilizer, such as methane and ethane, are used for fuel or carbon-black manufacture. This development, in about 1923, explained a sharp increase in production in this segment of the industry.

As in refinery operations, instrumentation and automatic control have had an important influence upon the quality of the product and upon the output per man in natural-gasoline operations. Besides improving the quality of the gasoline and safeguarding the plant equipment, automatic recorders and regulators, as well as remote controls, have reduced manual operations substantially. The field of application for automatic control devices is being extended even in the operation of gas-gathering systems supplying gasoline plants with natural gas. In one major oil field, for example, automatic control devices, attached to the compressors of the booster stations, have reduced by more than two-thirds the number of plant operators formerly employed.

The last decade has witnessed a phenomenal growth of a minor industry that has sprung from natural-gasoline production. This is the recovery and marketing of liquefied gases - propane and butane and, to a lesser extent, pentane - which formerly were wasted or burned in flares or under boilers. Compressed and distributed in steel cylinders or in pressure tanks, these products are used for domestic fuel in some areas where natural or manufactured gas is not available and for the manufacture of artificial gas distributed to domestic consumers in some localities. Industrial uses for these products also are increasing, chiefly in the heat treating of metals by the steel and automobile industries, in the ceramics industry, and, to a limited extent, for the operation of internal-combustion engines on trucks and motor cars. In the period beginning with 1927 and extending through 1937 the annual marketed production of these gases increased about 140-fold, rising from 1,091,000 to 141,505,000 gallons.[22]

The trend of the natural-gasoline industry during recent years has been toward the concentration of plant capacity in fewer hands and fewer units.[23] Between 1928 and 1938 the number of plants operated declined from 1,078 to 679, but the total capacity of the completed plants increased from 8,048,000 gallons daily to 10,732,000. The decline in the number of plants reflects chiefly the inability of the operators of small compression plants to keep going, while the increase in capacity reflects the trend toward the construction of larger and more efficient absorption plants. The trend toward larger plants has had the effect of increasing production faster than employment.

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[22]Hopkins, *op. cit.*, p. 957.

[23]G. R. Hopkins and E. M. Seeley, *Natural-Gasoline Plants in the United States, January 1, 1938* (U. S. Dept. Int., Bur. Mines, Inf. Cir. No. 7031, mimeo., July 1938), p. 1.

PROSPECTIVE CHANGES IN LABOR REQUIREMENTS

Future manpower requirements in natural-gas and natural-gasoline production will be governed largely by factors that are in themselves uncertain or partly unknown. Future employment, for example, will be influenced in important fashion by the extent to which reserves will be adequate to meet the requirements of an energy-hungry society. In addition, while we will continue to require more of our energy resources in the future, the precise level of the demand curve for a certain type of energy in future years cannot be determined with great precision. To attempt evaluation of all the factors that would affect employment would lead beyond the limits of this discussion, but the probable trends can be broadly indicated by distinguishing between the short- and long-time outlook and by passing judgment principally on factors already known and related to technical changes in natural-gas and natural-gasoline production.

In natural-gas production the outlook for the immediate future is for a moderate increase in manpower requirements. Demand shows no tendency to diminish. On the contrary, all evidence points toward further increases in the demand for natural gas both for industrial and household use. The potential applications of natural gas are enormous, and the effort to supply the growing demand is virtually certain to result in increased employment in exploration and production. Moreover, present indications are that our known reserves can supply expanding markets for at least another decade.

Over a longer view, the outlook for employment is obscured, as there are long-time tendencies making for both more and fewer jobs. Whether these forces will react to produce net trends of greater or less employment is still uncertain. Assuming a continuing rise in demand, employment opportunities in natural-gas production in the more distant future will depend upon the extent and availability of the reserves that may be discovered and developed in the more remote areas and at greater depths, and upon the volume of natural gas available from the production of oil. Moreover, the development of major reserves in remote fields and the installation of facilities for marketing natural gas from these sources will tend to increase employment opportunities. This expansion is likely to be partly offset, however, by the

increased delivery capacities that are characteristic of the deeper wells.

It also appears that, as the technique of oil recovery advances, increasingly larger volumes of natural gas should be available for commercial purposes. But here, again, powerful countercurrents are at work. There is, for example, the well-defined tendency of the oil industry to use increasingly larger proportions of natural gas in the recovery of crude petroleum. Indeed, many close observers believe that the utilization of natural gas in the recovery of oil is still in its infancy.[24] Recycling and repressuring operations which, in the past, have utilized gas that would have been vented into the atmosphere, might also be extended to reduce materially the volume of gas produced in association with oil that otherwise would be available for commercial purposes. It is probable, however, that a material increase in the utilization of natural gas as an agent in the recovery of oil in reservoirs other than those from which the gas is produced would involve a change in the competitive status of gas with respect to oil as a fuel. Although most of the gas used in recycling and repressuring operations and otherwise stored underground eventually should reach the market for use as fuel, the unknown time factor involved in its ultimate delivery into pipe lines undoubtedly will have an important influence upon day-to-day supplies.[25]

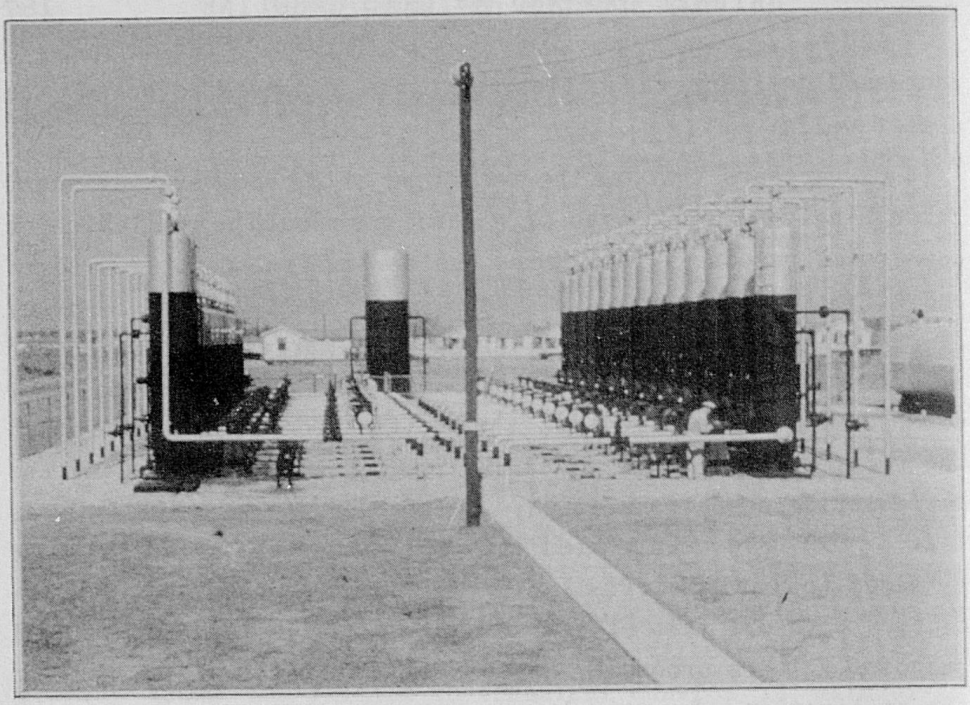
The prospects of future manpower requirements in natural-gasoline production depend upon developments in oil and gas production. Production of natural gasoline varies in direct ratio with the supply of natural gas, both dry and casing-head. Moreover, the supply of casing-head gas depends upon developments in the oil fields. Extension of proration measures and regulations governing gas-oil ratios, gas wastage, and carbon-black manufacture are influences that unquestionably will have a profound effect on the future of the natural-gasoline industry. All are, in fact, considerations that probably will curtail output and limit the construction of new plants.

Additional uncertainties regarding the future of natural gasoline arise from the uses to which it is put and from its

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[24] J. H. Dunn, *Recycling Gas, Repressuring Oil Sands, and Storing Gas in Depleted Fields, As Conservation Measures* (paper presented at Sixty-First Annual Meeting, American Bar Association, Section of Mineral Law, Cleveland, Ohio, July 25-29, 1938), p. 12.

[25] H. S. Kennedy and H. C. Fowler, "Natural Gas," *Minerals Yearbook, 1935* (U. S. Dept. Int., Bur. Mines, 1935), p. 819.



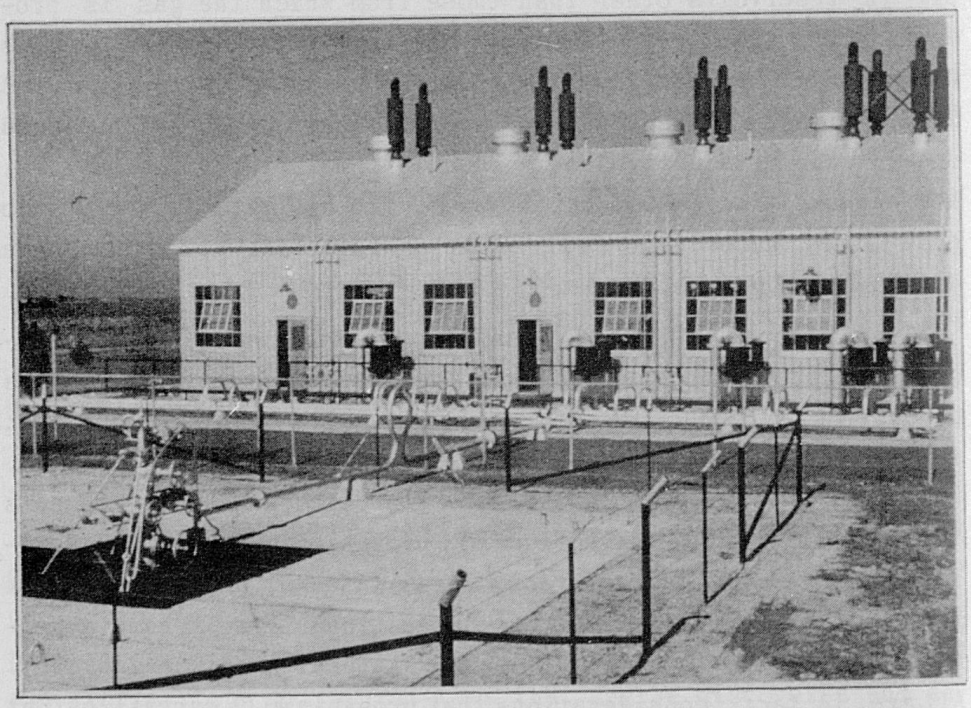


ILLUSTRATION 21.— SOME SURFACE EQUIPMENT REQUIRED
FOR A PRESSURE-MAINTENANCE PROJECT

Technologists know that the maintenance of gas pressure in an oil reservoir is an important factor aiding efficient oil recovery. In some fields, pressure-maintenance plants reinject into the oil reservoir gas that has been processed for the extraction of some of its liquid content. The above pictures illustrate some of the surface equipment used in one type of recycling project. The top view shows a central battery of oil and gas separators. After the gas has been separated from the oil and the liquids extracted from the gas, the pressure of the gas may be raised if necessary. The gas is then returned to the oil reservoir through injection wells; one of these wells, equipped with a Christmas tree, is shown at the extreme left of the lower view.

competitive position relative to other products. Although the refining industry in the past has demonstrated its ability to make itself independent of natural gasoline, the natural-gasoline industry - by improving the quality and reducing the price of its product - has maintained its competitive position, even in times of low crude-oil prices. Changes in motor-fuel specifications, however, might decrease the demand for natural gasoline. Another factor that might affect the demand for the output of the natural-gasoline industry is the possible changing quality of crude oil produced. Petroleum obtained from the deeper horizons, for example, contains a greater proportion of gasoline and lighter hydrocarbon fractions.

Despite the uncertainties and depressing influences, however, current trends in this division of the industry appear to promise rising production and expanding employment opportunities for the immediate future. This is due, first, to the steadily expanding demand for motor fuel and, second, to the growing markets for liquefied petroleum gases.

Perhaps the most significant of all possibilities for expanding employment opportunities in the natural-gasoline segment of the industry is to be found in the future of polymerization.[26] Although the polymerization process thus far has been limited principally to the utilization of still gases at refineries large volumes of vapors from natural-gasoline plants probably will be used in the future. Already this factor is playing an important role in the design and redesign of natural-gasoline plants.[27] The construction of a large number of polymerization plants as adjuncts to natural-gasoline plants would tend to increase employment in natural-gasoline production, as did the advent of the cracking process in refining.

In conclusion, the need for manpower in both natural-gas and natural-gasoline production appears likely to continue to increase over the next decade. The rate of increase probably will be considerably slower than during the twenties, but the trend is fairly certain to be upward. Over a longer view the net trend that will ultimately result from important forces that determine both increased and decreased employment is not clear, but the evidence seems to point to an extremely slow increase, if any.

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[26] This process is discussed in greater detail on pp. 281-2.

[27] J. Miller, "Present-Day Trends in Design and Construction of Natural Gasoline Plants," *The Petroleum Engineer*, Vol. IX, No. 10 (Midyear 1938), p. 66.

CHAPTER VIII

DIFFICULTIES INCIDENT TO INCREASING PRODUCTIVITY*

Not all of the notable achievements of the oil and natural-gas technologists cataloged in chapters IV to VII, inclusive, have resulted in increased output per worker employed. In fact, a substantial share of virtually every improvement in technology has been absorbed by growing difficulties experienced in the production of petroleum and natural gas. These difficulties can be classified under two major headings: (1) Increasing physical difficulties of operation and (2) legal and economic handicaps to efficient exploitation. Although adequate appraisal of these factors is not possible, since they have been largely obscured by the tremendous gains of technologic advance, they represent important influences affecting output that cannot be overlooked.

MOUNTING PHYSICAL DIFFICULTIES

In the petroleum and natural-gas industry, as in other branches of mining, an unremitting struggle is under way against mounting physical difficulties. The industry began with a generous heritage of high-grade reserves at easily accessible depths and in proximity to the important centers of consumption. With boundless faith in the bottomless generosity of nature, the early pools were riotously exploited, and the industry soon began the westward migration described in chapter III. However, a significant fact associated with this migration is that in the newer areas the producers have had to go to progressively greater depths and through increasingly troublesome formations to reach pay sands.

Increasing Depth of Wells

Most of the early wells drilled in Pennsylvania and New York were quite shallow. At Drake's discovery well, oil was reached at $69\frac{1}{2}$ feet, and most of the wells drilled in the early sixties were less than 100 feet deep.[1] In later years the depth of wells in the Appalachian field gradually increased, and there was a wide

*By G. R. Hopkins, H. O. Rogers, O. E. Kiessling, and J. S. Ross.

[1]R. Arnold and W. J. Kemnitzer, *Petroleum in the United States and Possessions* (1st ed.; New York: Harper & Bros., 1931), p. 94.

range in depths of individual wells, but most of the oil and gas produced in the field has come from depths that probably average less than 1,800 feet.[2] In the Lima-Indiana-Illinois-Michigan fields also most of the production has come from relatively shallow depths, ranging from an average of less than 1,000 feet in the Illinois and southwest Indiana field to an average of about 1,780 feet in the Michigan field. Recent important developments in the Illinois-Indiana-Michigan area, however, promise considerable future output from formations lying much deeper than those tapped by the early producers.

In the fields west of the Mississippi River the average depths of producing wells are conspicuously greater than in the older eastern fields. Typical wells of the Mid-Continent field, for example, are 10 to more than 100 percent deeper than those of the Appalachian and Ohio-Illinois-Indiana-Michigan fields, and the difference is even more pronounced in the California and Gulf Coast fields. Of the fields west of the Mississippi River, the average depth is shallowest in the Rocky Mountain region, but even here the producing wells average over 2,000 feet in depth.[3]

A vivid indication of the increasing depths that must be penetrated by the drill to meet growing national requirements for oil and gas is furnished by the generally downward curves in the upper division of figure 20. In 1935 the average depth of the shallowest producing horizon of all new fields discovered during the year was roughly 3,500 feet, approximately 1,000 feet deeper than it was necessary to go in pools discovered 10 years before and almost three times the depth of new pools brought in during the late nineties, when the record begins.[4]

No average, however, can give an adequate perspective of the increased depth of drilling. During the past 15 years the "depths commercially reachable by the drill have been more than doubled",[5] and a large part of the oil and gas now produced comes from 7,000- to 10,000-foot depths. To reach oil in California's great Kettleman Hills fields drills had to gnaw their way to producing

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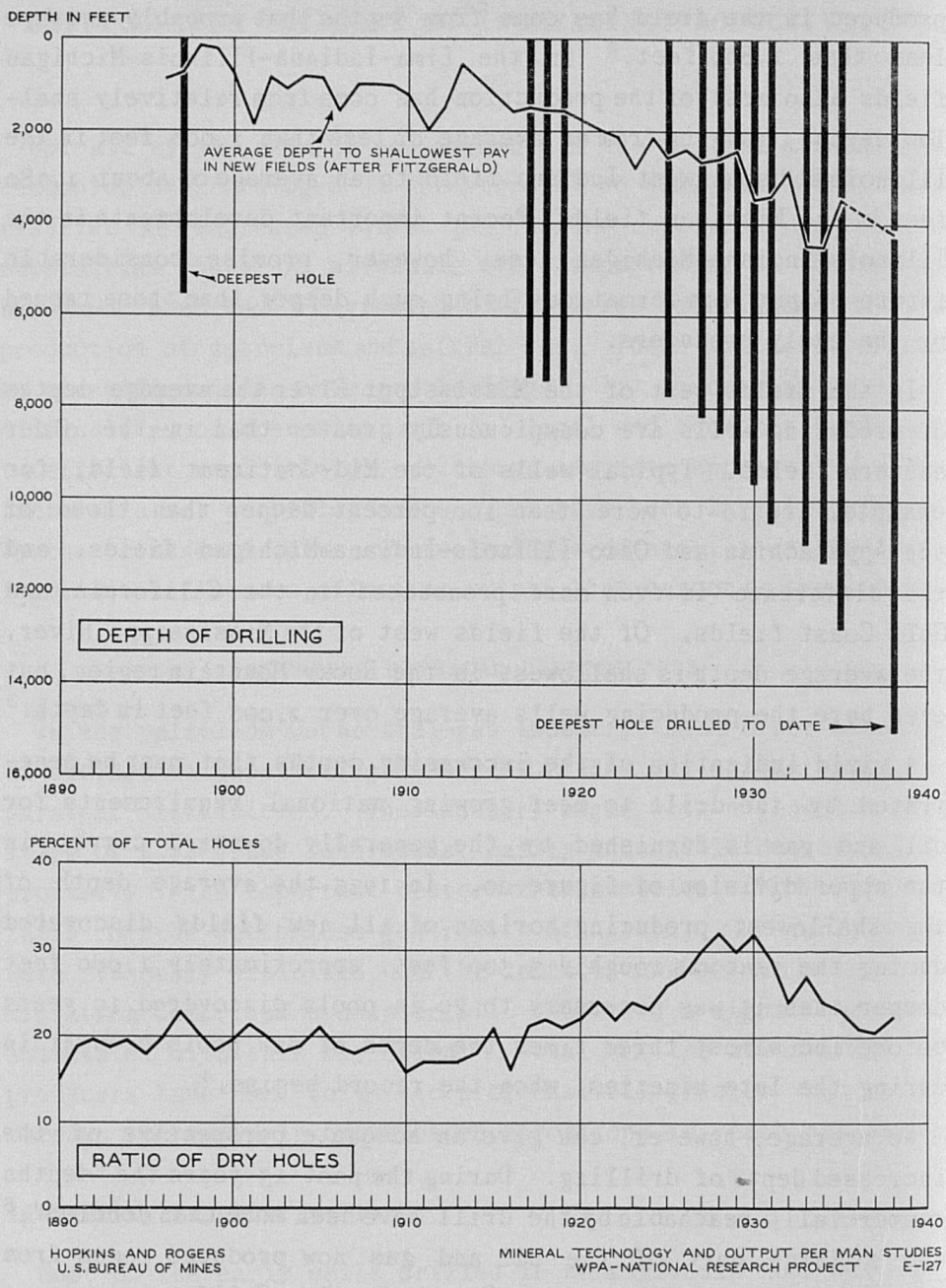
[2] *Ibid.*, p. 62

[3] *Ibid.*, p. 591

[4] Mean depths, 1896-1938, were computed by N. D. Fitzgerald, Petroleum Engineer, WPA National Research Project, from records of 706 oil pools, and include all pools for which depth of shallowest producing horizon was reported. Data for 1938 are preliminary and subject to revision.

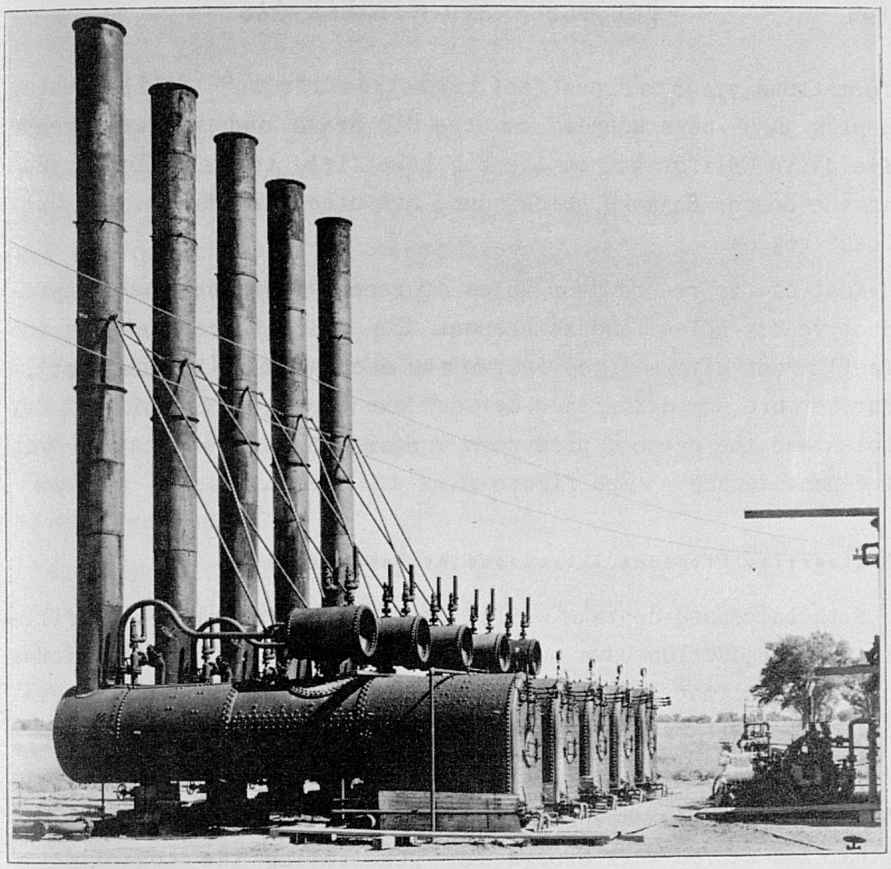
[5] J. E. Pogue, "The Economic Structure of the Petroleum Industry of the United States," *Transactions of the Third World Power Conference* (1936) (Washington, D. C.: 1938), Vol. IV, Sec. II, Paper No. 5 (U. S. A.), p. 241.

Figure 20.- INDICATORS OF INCREASING PHYSICAL DIFFICULTY EXPERIENCED IN PETROLEUM AND NATURAL-GAS PRODUCTION, 1890-1938



Since the turn of the century the maximum depth of holes drilled for oil or gas has more than doubled. At the same time, operators have had to raise their output from progressively greater depths, as suggested by the 40-year trend of average depth to the shallowest productive formation in new fields.

Another indication of increasing physical difficulties in the oil and gas industry is the long-time increase in the ratio of unproductive holes to total holes drilled. Although geological knowledge has been greatly augmented in recent decades, the percentage of dry holes drilled, even in the newer western fields, has tended slowly upward. Taking the country as a whole, the ratio increased until about 1930, when approximately a third of the completions were nonproductive. Since that time the percentage of dry holes has declined appreciably, a development primarily due to depression influences that confined drilling activities largely to areas with proved reserves. Data are from sources indicated for figure 18 and from records of the U. S. Bureau of Mines.



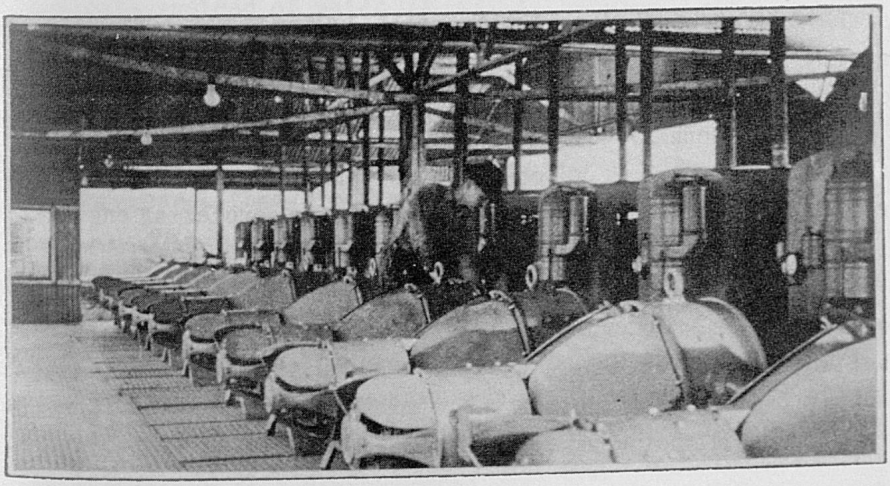


ILLUSTRATION 22.— MODERN ROTARY DRILLING REQUIRES A LARGE AMOUNT OF POWER

The upper view shows a battery of boilers that furnish steam at 500 pounds pressure per square inch for use in drilling deep wells; these boilers are equipped with superheaters for added efficiency. The drilling of a single oil well is ordinarily accomplished in such a short time and with fuel so relatively inexpensive that the economic loss from exposed boilers is not sufficient to warrant the construction of a boilerhouse; the boiler shells, however, are covered with insulating material. The lower view shows a battery of 12 natural-gas engines connected with a similar number of electric generators that have a total rated capacity of 1,200 horsepower. This power is utilized at a single rotary-drilling operation. Electricity, generated at the drilling site by Diesel or gas engines or purchased from central power stations, is being more widely used in drilling oil and gas wells.

formations 7,108 to 8,300 feet below the surface.[6] Still greater depths have been sounded in the Rio Bravo and Ventura Avenue fields in California, in the Big Lake field in west Texas, and in the Bosco, Roanoke, Dickinson, and other fields in the Gulf Coast region.

Most of the record deep holes of recent years have been unproductive dry holes, and at present the deepest producer (13,266 feet) is not within 1,500 feet of the deepest hole (15,004 feet).[7] Furthermore, the difference between the depths of the deepest dry holes and the deepest producers appears to have increased over the past decade. (See figure 18.)

Engineering Problems Introduced by Deep Drilling

With increased depth of wells, technical difficulties in drilling and production have multiplied. Many are aggravated forms of problems that have plagued the driller since the Drake era, but others are entirely new and complex.

One set of problems centers around the rotary method of drilling. As already noted in chapter V, this method supplanted cable tools (that had served well enough for penetrating the consolidated formations of limestone and indurated shales in the comparatively shallow fields of the Appalachian region) when it was necessary to reach pools at great depths or beneath semiconsolidated formations of sands, clays, soft shales, and alluvial deposits such as those in the California, Gulf Coast, and many of the Mid-Continent fields.[8] Although it is possible to penetrate great depths and resistant formations with rotary tools, many perplexing engineering problems still complicate the use of this equipment. One of the frequent difficulties, for example, has been the drilling of crooked holes, an occurrence less familiar to cable-tool drillers but until recently almost a daily event with rotary drilling.[9] Recent improvements in rotary-drilling methods now permit wells to be drilled that deviate less than 2° from the vertical, but

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[6] K. C. Heald, "Deep Well Drilling Problems and Their Solution," *The Oil Weekly*, Vol. 81, No. 13 (June 8, 1936), p. 19.

[7] The world's deepest hole, drilled to 15,004 feet, was a producer at 13,175 feet, but was plugged below this depth as a dry hole. During the past decade, however, only a few of the record deep holes penetrated producing formations at less than their maximum depths and could be plugged back as producers. Most frequently the record deep holes are simply dry holes extended to great depths before hope of finding oil and of salvaging the large investment is finally abandoned.

[8] H. C. Miller and B. E. Lindsly, "Report on Petroleum Development and Production," *Petroleum Investigation* (U. S. Congress, House of Representatives, Hearings on H. Res. 441, 73d Cong., Recess, 1934), part 2, pp. 1147-8.

[9] Heald, *op. cit.*, p. 29. See also the discussion of directional drilling, pp. 93-6.

drilling reasonably straight holes requires additional time, labor, and expense.

More serious than the crooked hole is the danger of overlooking good oil pays when drilling is done with rotary tools.[10] There are numerous examples of wells being drilled through exceptionally prolific sands where the capacity of the pay sands to produce has not been recognized and sometimes even the presence of oil has not been detected. Oversights of this kind can be reduced by frequent corings, by drill-stem and other types of tests, and by sample-taking bullets,[11] but none of these methods offers complete assurance against failure to detect valuable productive formations.

Another difficulty peculiar to rotary drilling involves keeping the mud fluid between the drill stem and the wall of the hole at the correct density and viscosity. This is one of the most complicated and important phases of rotary drilling and one that can be controlled less readily as drilling depths increase.[12] If the fluid is not of the proper consistency, the drill cuttings tend to settle at the bottom of the hole and freeze the drill stem when circulation of the mud is stopped. Moreover, when drilling is done in heaving shales, it is frequently necessary to employ chemicals instead of water in mixing the mud, but with certain types of heaving shale even this practice is not always successful. Finally, in deep drilling the column of mud must be carefully regulated to perform an important function in preventing blowouts, for it acts as a counterweight controlling the enormously high pressures that frequently characterize extreme depths.

As the rotary bit must revolve at the bottom of the hole, increased depth accentuates the technical problems of governing the weight or pressure on the cutting tool to avoid the danger of damaging the drill pipe or of sticking the bit.[13] If too much weight rests on the bit and not enough is carried by the derrick, costly twist-offs are inevitable. Excessive weight also increases the likelihood of a crooked hole. For this reason, deep-drilling

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[10] *Ibid.*, pp. 29-30.

[11] E. G. Leonardon and D. C. McCann, "Exploring Drill Holes by Sample-Taking Bullets," *Transactions of the American Institute of Mining and Metallurgical Engineers: Petroleum Development and Technology, 1939*, Vol. 132 (1939), pp. 86-9.

[12] H. N. Marsh, "Properties and Treatment of Rotary Mud," *Transactions of the American Institute of Mining and Metallurgical Engineers: Petroleum Development and Technology, 1931*, Vol. 92 (1931), pp. 234-51.

[13] R. S. Cartwright, "Rotary Drilling Problems," *Transactions of the American Institute of Mining and Metallurgical Engineers: Petroleum Development and Technology, 1928-29*, Vol. 82 (1929), pp. 9-29.

operations are now generally equipped with automatic weight indicators; heavy collars are also employed directly above the bit as an added protection against twist-offs.

Another set of problems centers around the sheer physical obstacles to attaining great depths. First there is the task of developing equipment capable of withstanding the stresses and strains involved in deep drilling. To a large extent this obstacle has been overcome, and failures due to faulty equipment are now comparatively rare. The drilling of the world's deepest well in the Wasco field in California with ordinary heavy-duty rotary equipment has demonstrated that present-day equipment can be employed for drilling 15,000-foot wells. This is considerably deeper than even the deepest of present producing wells. At present the industry is speculating on the possibilities of drilling still deeper. In this connection, however, it should be noted that even with the improved high-speed hoists now available, the task of running drill pipe in and out of a hole is a major item of expense and that the time required for this work mounts as the holes become progressively deeper. This growing item of lost time and expense may be at least partly offset in the future by improvements in the use of retractable wire-line bits and coring tools and by the possible employment of entirely new equipment, such as turbo-drills (see p. 121).

Apart from the need for adequate materials and equipment, there are numerous other problems that require further attention by the technologist. Comparatively simple tasks at shallow depths - such as reaming, underreaming, and fishing for broken tools - become major operations at great depths. In addition, temperature increases greatly with depth, in some fields reaching 300° F.[14] Although high temperature is not a serious difficulty in actual drilling, it is a complicating factor in pipe setting and cementing and, to some extent, in maintaining effective mud control.

Probably the most stubborn problems connected with deep drilling are geological. In some fields, beds of material harder than ordinary drill steel have been encountered. This difficulty is being overcome largely by surfacing the cutting edges of bits with extremely hard alloys and abrasives. In the future some adaptation of the diamond drill may be necessary. On the other hand, drilling has frequently been stopped by excessively soft

[14] Heald, *op. cit.*, p. 28.

formations; this problem becomes more severe at great depths, where compact shale formations exhibit plastic tendencies under high "earth pressures" or pressures thought to be due to the weight of the overburden.[15]

Another major technologic problem is that of lifting oil from extreme depths at reasonable cost. In the production of oil the pumping equipment used by the early producers in Pennsylvania was much the same as that for pumping water and salt brine. Pumping from greater depths usually means not only greater pressures, but also lighter oils. These factors combine to require refinements in the construction of pumps, particularly closer fits than in shallow wells. For a time during the late twenties it seemed likely that the problems involved in deep pumping would be solved only by basic changes in equipment. Improvements in the standard rod-and-tubing equipment and increased knowledge of its potentialities, however, make this method still the most generally applied for lifting oil by mechanical means. Nevertheless, a departure from the traditional pumping system is noted in the recently employed hydraulic and subsurface centrifugal pumps.

Rising Costs of Drilling and Equipping Wells

Oil and gas production involves relatively heavy fixed costs, and a major item in the total investment is the cost of drilling.[16] This cost, in turn, varies with the depth of the well, the formations penetrated, the diameter of the hole, the proximity of sources of supplies, and many other factors.[17] The long-time trend indicates a pronounced increase in the cost of drilling and equipping wells.

In the early days of the industry many shallow wells in Pennsylvania and New York were drilled for not more than $300, and up to 1880 the average cost of wells drilled in the Pennsylvania oil regions was around $1,200.[18] The average cost of early wells was somewhat higher in the Lima-Indiana field but rarely exceeded $3,500.[19]

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[15] W. E. V. Abraham, "Geological Aspects of Deep Drilling Problems," *Journal of the Institution of Petroleum Technologists*, Vol. XXIII (London: 1937), pp. 378-87.

[16] G. Ward Stocking, "Stabilization of the Oil Industry: Its Economic and Legal Aspects," *The American Economic Review*, Vol. XXIII, No. 1 (Mar. 1933), Supplement, p. 56.

[17] Miller and Lindsly, *op. cit.*, p. 1157.

[18] Arnold and Kemnitzer, *op. cit.*, p. 95.

[19] *Ibid.*, p. 243.

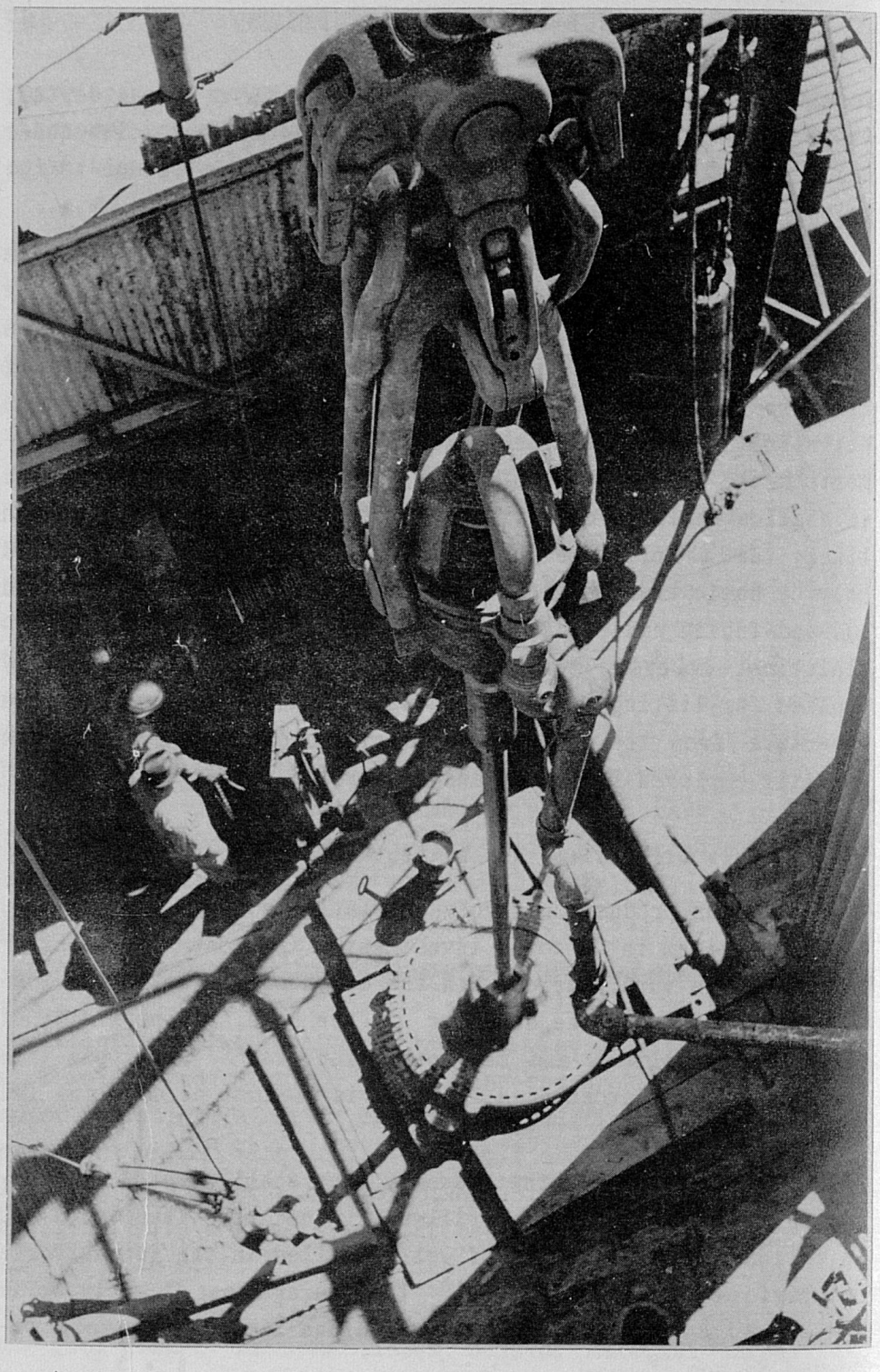


ILLUSTRATION 23.- LOOKING DOWN ON THE DERRICK FLOOR AS THE WORLD'S DEEPEST OIL WELL WAS BEING DRILLED

The circular object in the lower center is the rotary table that rotates the square "kelly" joint (which appears round in this photograph due to its rotation). The lower end of the kelly is attached to the drill pipe. The weight of the kelly, drill pipe, and bit is supported by a swivel shown suspended from a special hook near the center of the picture. The swivel also provides means for introducing mud fluid from a "hose" (made up of articulated short lengths of heavy pipe) into the hollow kelly and drill pipe. Keeping the derrick floor tidy and orderly, as shown in this view, contributes to increased efficiency and safety. This photograph was kindly supplied by the Kern County Chamber of Commerce, Bakersfield, California.

With expenses at these levels, it was not a matter of major concern if the well proved to be a failure. Today, by contrast, huge investments are frequently involved in drilling, and failures often represent serious financial loss. To drill and equip an oil well in the Kettleman Hills or Santa Fe Springs fields of California in 1931, for example, cost somewhat more than $200,000.[20] In the same year the average cost of drilling and equipping a well (less cost of pumping equipment) in the relatively shallow East Texas field, where the average drilling depth was less than 4,000 feet, was approximately $24,000.[21] On the other hand, wells less than 2,000 feet deep can still be drilled in some of the shallow eastern fields at very low cost,[22] and drilling costs of approximately $5,000 were reported for some fields in 1935 (see table 2). Although wide ranges in the extreme costs noted for various fields largely disappear when average costs are determined upon a broad geographic basis, as is done in table 3, it is noteworthy that the average cost of drilling and equipping oil wells in 1935 was $19,100.

As is shown in table 2, the cost of drilling does not depend exclusively on depth, but this appears to be the most important single factor. This point is substantiated further by supplementary data on costs of drilling as related to depth for 1931; these are abstracted and presented in table A-24.

Deep wells not only entail larger expenditures for the drilling task itself but also require larger than proportionate outlays for casing and for derrick equipment.[23] It should be noted further that the outlay for equipment for controlling and producing oil and gas under the exceedingly high pressures found at great depths entails additional capital outlay; in addition, the cost of lifting water produced with the oil increases as the fields age, and this factor may force premature abandonment of wells because of the greater cost of lifting from great depths.

Increasing Ratio of Dry Holes

Another indication of increasing physical difficulties is the long-time tendency toward a rising percentage of failures in

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[20] Miller and Lindsly, *op. cit.*, p. 1158.
[21] *Ibid.*
[22] W. H. Jeffery, *Deep Well Drilling* (3d ed.; Houston, Tex.: Gulf Publishing Co., 1931), pp. 689-90.
[23] Miller and Lindsly, *op. cit.*, p. 1158.

Table 2.- COST OF DRILLING WELLS IN SELECTED OIL FIELDS, 1935[a]

State and field	Number of wells drilled	Average cost of drilling per well	Average depth[b] (feet)	Average cost per foot[c]
California				
Long Beach	124	$35,100	4,970-8,470	$4.14
Inglewood	23	40,000	1,150-4,100	9.76
Huntington Beach	18	16,100	1,900-4,730	3.40
Midway Maricopa	42	11,400	3,500-5,500	2.07
Ventura	18	105,500	6,720-9,720	10.85
Kettleman Hills	37	156,600	6,070-8,560	18.29
Louisiana				
Rodessa	44	34,600	5,676-6,014	5.75
Gillis	30	28,700	5,180-9,242	3.11
Leesville	17	20,900	3,729	5.60
Sulphur	10	36,400	4,160	8.75
Michigan				
Crystal	92	7,200	3,190	2.26
Vernon	8	7,000	3,725	1.88
New Mexico				
Hobbs	34	21,300	3,940	5.41
Eunice	92	29,800	3,859	7.72
Jal	23	26,300	3,333	7.89
Oklahoma				
Oklahoma City	74	62,400	6,500	9.60
Seminole County	211	25,100	4,155	6.04
Fitts	197	30,000	4,300	6.98
Lucien	24	26,400	4,960	5.32
Edmond	32	50,800	6,703	7.58
Texas				
Anahuac	36	19,300	7,080	2.73
Barbers Hills	43	63,200	5,200	12.15
Cayuga	59	24,800	4,085	6.07
Conroe	59	14,500	5,150	2.82
Dickinson	17	41,700	9,000	4.63
East Texas	4,036	6,200	3,660	1.69
Government Wells	90	4,800	2,350	2.04
Greta	23	15,400	4,398	3.50
Hastings	46	19,600	6,100	3.21
Humble	16	5,300	4,800	1.10
Livingstone	43	11,500	4,276	2.69
Loma Novia	217	8,200	2,705	3.03
Panhandle	649	11,700	3,000	3.90
Pecos Valley	4	8,100	1,700	4.76
Penn	32	12,900	3,700	3.49
Plymouth	44	23,100	5,634	4.10
Raccoon Bend	38	12,200	4,100	2.98
Refugio	22	11,200	5,400	2.07
Sam Fordyce	107	5,500	2,790	1.97
Saxet	52	15,400	4,500	3.42
Seven Sisters	40	6,500	2,500	2.60
South Liberty	11	8,200	3,500	2.34
Thompsons	25	16,500	5,300	3.11
Tomball	101	14,800	5,575	2.65
Van	62	3,100	3,000	1.03
Ward County	168	12,300	2,700	4.56

[a]Data from records of U. S. Dept. Int., Bur. Mines. The cost of equipping wells is excluded.
[b]Generally represents depth to bottom of productive zones.
[c]Data for California and the Rodessa and Gillis fields in Louisiana were determined on the basis of maximum depth.

drilling.[24] Although geological knowledge has been greatly augmented and although complicated scientific techniques of subsurface prospecting have become available, the percentage of dry holes drilled has slowly tended upward during the past 3 decades (see figure 20). This is true not only for the entire country but also for most of the newer western fields. In California, for example, the proportion of dry holes was 12 percent or less in the period 1905-22; over the period 1923-30 the range was increased to 21-26 percent;[25] between 1931 and 1935 the range was 31 to 51 percent; in 1936 it was 29 percent. In Oklahoma the proportion of dry holes increased from less than 20 percent prior to 1918 to between 27 and 35 percent from 1930 to 1935; in 1936 it was 25 percent. Due to heavy concentration of drilling in East Texas (where few wells are nonproductive), the ratio of dry holes drilled in Texas after 1930 generally has been somewhat lower than during the twenties, and in 1935, 23 percent of the completions were dry holes, approximately the same proportion as in 1919. In 1936 slightly more than a fifth of Texas wells were dry holes.

Taking the country as a whole, the ratio of dry holes to producing oil and gas wells completed moved gradually upward and reached high points in 1928 and 1930, when nearly a third of the completions were nonproductive. Since 1930 the percentage of dry holes has declined appreciably, and in 1936-37 only slightly more than a fifth of the completions were dry holes.[26]

The improved showing in recent years, however, is somewhat of a statistical refraction because, during and after the depression, drilling activities were largely confined to areas of proved reserves. Thus approximately a fourth of the oil wells completed in 1936 and 1937 were in the East Texas and Bradford-Allegany fields where virtually all wells are productive. With a continued expansion of drilling activity in 1938, the ratio of dry holes has shown a slight tendency upward. (See figure 20.)

The rise in the proportion of nonproductive wells since the turn of the century has represented a growing financial loss

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[24] It is possible to prove statistically that the average volume of oil discovered per dry hole has shown a notable long-time gain. (See J. E. Pogue, *Economics of the Petroleum Industry* [New York: Chase National Bank, 1939], p. 13.) Such a determination, of course, is simply a weighting of the long-time relative increase in dry holes with the still faster growing rate of successful discovery that accompanied the westward migration of production.

[25] L. C. Snider and B. T. Brooks, *Petroleum Shortage and Its Alleviation* (New York: The Chemical Foundation, 1935), pp. 21-2.

[26] A. G. White, G. R. Hopkins, and H. A. Breakey, "Crude Petroleum and Petroleum Products," *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), pp. 836-8.

to the industry, because of both higher unit costs of drilling dry holes and an increase in the number of dry holes. In this connection it is of interest to note in table 3 that the average cost of drilling a dry hole was 50 percent greater than the cost of drilling a successful well in 1935, and that in the same year the cost of dry holes represented a net loss to the industry of not less than $84,000,000. With drilling expanding in the years after 1935, the number of dry holes and the annual financial losses therefrom have increased.

Decline in Discoveries by Random Drilling

Another indication of increasing natural difficulties is the marked decline in the number of major oil pools discovered by random drilling (see p. 68). Of the major oil fields discovered in 1922, more than a third were the result of random drilling. In 1938, however, only 2 of the 144 fields discovered during the year that had an estimated ultimate production of more than a million barrels of oil were brought in by wildcat wells located without the benefit of technical advice.

This decline is partly a reflection of the increased cost of drilling. The number of individuals who are financially able to shoulder the large investment now usually involved in drilling in areas where oil is likely to be found is definitely limited, particularly when one out of every four holes drilled turns out to be a "duster" or salt-water well. If the drilling is done in totally unproved territory the chances of failure are greatly increased. Even the Gulf Oil Corporation, which spends more than 3 million dollars a year in maintaining and equipping a large staff of geologists and geophysicists with seismographs, torsion balances, magnetometers, gravimeters, and aerial cameras, is not more than 85 percent successful in the wells that it drills.[27] It is chiefly on this account that discovery is becoming more and more the function of large-scale enterprise.

Apart from the factor of cost, the independent wildcatter is handicapped further by the fact that most of the recent discoveries have been made in areas where there have been few or no surface indications of oil and gas. As new productive formations are sought at greater depths,[28] moreover, the location of exploratory

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[27] "Gulf Oil," *Fortune*, Vol. XVI, No. 4 (Oct. 1937), p. 142.

[28] Data covering a large segment of the industry indicate that the average depth of exploratory (wildcat) wells increased from 3,540 to 4,132 feet between 1935 and 1938. See F. H. Lahee, "Wildcat Drilling in 1938," *The Oil and Gas Journal*, Vol. 37, No. 45 (Mar. 23, 1939), p. 48.

Table 8.- COST OF DRILLING AND EQUIPPING OIL WELLS AND COST OF DRILLING DRY HOLES, BY STATE, 1935[a]

State	Number of oil wells drilled	Cost of drilling oil wells				Cost of equipping oil wells		Total cost		Cost of drilling dry holes[b]		
		Wages	Other costs[c]	Total	Average per well	Total	Average per well	Total	Average per well	Number of dry holes drilled	Total cost	Average cost per hole
United States	15,108	$55,648,000	$115,321,000	$171,176,000[d]	$11,300	$117,731,000	$7,800	$288,907,000	$19,100	4,891	$84,470,000	$17,300
Arkansas	40	117,000	415,000	532,000	13,300	297,000	7,400	829,000	20,700	73	1,347,000	18,500
California	729	8,952,000	21,916,000	30,868,000	42,300	17,180,000	23,600	48,048,000	65,900	347	25,339,000	73,000
Colorado	11	n.a.	n.a.	207,000	18,800	70,000	6,400	277,000	25,200	6	120,000	20,000
Illinois	5	6,000	2,000	8,000	1,600	5,000	1,000	13,000	2,600	6	12,000	2,000
Indiana	37	39,000	59,000	98,000	2,600	17,000	500	115,000	3,100	86	183,000	2,100
Kansas	890	1,757,000	7,487,000	9,244,000	10,400	8,687,000	9,800	17,931,000	20,100	281	4,215,000	15,000
Eastern	245	147,000	625,000	772,000	3,200	716,000	2,900	1,488,000	6,100	n.a.	n.a.	n.a.
Central	645	1,610,000	6,862,000	8,472,000	13,100	7,971,000	12,400	16,443,000	25,500	n.a.	n.a.	n.a.
Kentucky	167	74,000	99,000	173,000	1,000	112,000	700	285,000	1,700	70	140,000	2,000
Louisiana	344	3,587,000	6,662,000	10,249,000	29,800	6,347,000	18,400	16,596,000	48,200	249	7,059,000	28,300
Northern	124	943,000	1,752,000	2,695,000	21,700	1,878,000	15,100	4,573,000	36,900	121	2,000,000	16,500
Gulf	220	2,644,000	4,910,000	7,554,000	34,300	4,469,000	20,300	12,023,000	54,600	128	5,059,000	39,500
Michigan	322	1,078,000	718,000	1,796,000	5,600	2,189,000	6,800	3,985,000	12,400	168	1,337,000	8,000
Montana	131	567,000	851,000	1,418,000	10,800	944,000	7,200	2,362,000	18,000	38	388,000	10,200
New Mexico	262	1,958,000	3,975,000	5,933,000	22,600	3,348,000	12,800	9,281,000	35,400	71	2,238,000	31,500
Ohio	299	281,000	330,000	611,000	2,000	565,000	1,900	1,176,000	3,900	192	343,000	1,800
Oklahoma	1,321	7,440,000	22,322,000	29,762,000	22,500	15,186,000	11,500	44,948,000	34,000	579	11,194,000	19,300
Pennsylvania	1,956	2,188,000	1,585,000	3,773,000	1,900	2,877,000	1,500	6,650,000	3,400	45	77,000	1,700
Texas	8,421	27,120,000	48,214,000	75,334,000	8,900	58,829,000	7,000	134,163,000	15,900	2,538	29,740,000	11,700
West Virginia	115	127,000	150,000	277,000	2,400	214,000	1,900	491,000	4,300	114	228,000	2,000
Wyoming	58	357,000	536,000	893,000	15,400	864,000	14,900	1,757,000	30,300	28	510,000	18,200

[a] Data are from the records of the U. S. Dept. Int., Bur. Mines, and cover wells drilled and equipped by producers and on contract.

[b] Excludes data for 20 dry holes reported for other States for which cost data were not available.

[c] Includes costs of roads, haulage, fuel, water, supplies, tools, and mud.

[d] Includes $207,000 for Colorado for which "wages" and "other costs" were not available.

n.a. Data not available.

wells without the type of technical advice that can be provided by a large organization with ample financial resources is characterized by a high degree of failure. Lahee has shown, for example, that where wildcat wells were drilled in unproved territory without the benefit of technical advice in 1937 only "6.1 per cent were successful in finding oil or gas; whereas, of the holes located on technical advice, 18.3 per cent discovered oil or gas."[29] Notwithstanding these disadvantages, it is noteworthy that the phenomenal East Texas field, the greatest producing field in the world, was discovered in 1930 as a result of random drilling. It appears likely, moreover, that successful wildcat wells will be brought in from time to time, but that the tendency for random drilling to perform a progressively less important function will continue in the future.

LEGAL AND ECONOMIC HANDICAPS

If there are tendencies suggesting growing physical hazards to oil and gas production, there are also serious inefficiencies introduced by the legal and economic arrangements under which the industry has been expected to function. These complications arose primarily from attempting to make the industry fit into the type of competitive pattern conceived and explained by many of the nineteenth century economists. From the beginning, however, there was difficulty in reconciling the economic and legal arrangements of exploitation with the physical characteristics of an oil or gas pool in order to obtain efficient production. Private property, for example, is thought of in familiar terms by the farmer, the coal operator, and the manufacturer, but appears as something different to the oil and gas producer when the courts hold that no ownership exists until the oil and gas are reduced to possession.[30] Furthermore, although according to the postulates of free enterprise competition is the mechanism that holds profits in leash and accommodates production to market demands, in the petroleum and natural-gas industry competition has proved an ineffective governor. In general, the industry has persistently refused to respond to what is sometimes described as "the automatic operation of economic laws." At the same time the practical arrangements under which production has been carried on

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[29] F. H. Lahee, "Further Data on Wildcat Drilling in 1937," *Bulletin of the American Association of Petroleum Geologists*, Vol. 22, No. 9 (Sept. 1938), p. 1235.

[30] O. E. Kiessling, *Cooperative Development of Oil Pools* (New York: American Institute of Mining and Metallurgical Engineers, Tech. Pub. No. 28, 1927), p. 6.

usually effectively precluded application of the best engineering knowledge to obtain maximum efficiency[31] and commonly involved losses on a spectacular scale.

Competitive Drilling and the Law of Capture

Technically efficient production of oil and gas demands treatment of each pool as a geologic unit;[32] this unit is a single gigantic engine.[33] Before being tapped by a drill, a typical pool represents an adjustment of forces held in balance with the gas uppermost, the oil next, and water at the outer limits of the productive area. This equilibrium is maintained under pressure, and when the reservoir is punctured by a drill, the oil, gas, and water flow through the sands to the point of lower pressure at the well bore.[34] Moreover, the movements of oil, gas, and water occur without regard to surface property lines.[35] To date the quickest and most effective method discovered for dissipating the potentialities of an oil pool is to ignore the characteristic behavior of oil and gas and subject the pool to the ravages of competitive drilling. Yet, because certain early jurists (who acted to determine the basic property rights at a time when the physical conditions underground were not understood) thought they detected a resemblance between oil and gas and wild game and percolating waters, the highly competitive form of development and operation of oil and gas properties was the general procedure in this country until recent years.[36]

The viewpoint of this survey as well as limitations of space preclude inclusion here of any extended discussion of competitive drilling. This subject, moreover, has been covered extensively in the technical press and in other Government reports. It is important, however, to note briefly some of the principal ways in

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[31] As here used "efficiency" refers to obtaining a maximum production of oil and gas at a minimum of cost during the life of a pool. This point is important to the discussion because, apart from questions pertaining to the wise use of irreplaceable resources known to be limited in supply, it has bearing on the quantity of oil produced in the past. Also, a change in economic and legal arrangements in the future might materially affect the amount of employment and the output per worker.

[32] Kiessling, *op. cit.*, p. 8.

[33] N. Ely, "The Conservation of Oil," *Harvard Law Review*, Vol. LI, No. 7 (May 1938), pp. 1219-20.

[34] R. A. Cattell and H. C. Fowler, "Fluid-Energy Relations in Production of Petroleum and Natural Gas," *Minerals Yearbook, 1934* (U. S. Dept. Int., Bur. Mines, 1934), pp. 710-11.

[35] Stocking, *op. cit.*, p. 57.

[36] Kiessling, *op. cit.*, p. 5. One writer has made the interesting observation that the offspring of the early judicial decisions has been accepted as the common law in regard to oil even in States that have repudiated the parent doctrine on other matters (Ely, *op. cit.*, p. 1219).

which competitive exploitation has blocked application of the best available technology and hence decreased potential production and output per man. Likewise, since a high ultimate yield and long life of a pool tend to stabilize and prolong employment opportunities in a given area, some consideration should be given to the losses that have followed in the wake of competitive drilling.

Under the "law of capture", once an oil pool was discovered owners of the property overlying the pool were impelled to drill many wells as rapidly as possible, to forestall drainage by the owner of a neighboring tract.[37] In fields where the surface land was parceled out among competing owners, virtually no regard was given to efficient extraction in accord with physical conditions of the pool. Instead, about the only consideration that influenced the operators was their desire to outdrill their neighbors.[38] Although a great deal remains to be learned about the problem of well spacing, it is now generally recognized that in many fields overcrowding has not permitted the most effective use of reservoir energy for production.[39] For the industry as a whole, there can be no doubt that if well spacing in the past had been governed by engineering principles instead of feverish efforts to capture oil and gas from neighboring lands, the ultimate yield of the pools would have been at least as great as it was, and capital and labor requirements of the industry would have been much smaller.

Competitive drilling and production have also hampered the application of efficient technology by their tendency to force wide-open flow after the wells have been completed. In most fields gas is the major expulsive agent, and its effective utilization reduces the ultimate cost of recovery and increases the ultimate yield.[40] When the wells are allowed to flow without restriction, however, the efficient use of gas as an expulsive agent is impossible, chiefly because it moves faster and tends to by-pass the oil without performing any effective work in bringing the oil to the surface.[41] If the gas is not properly controlled

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[37] S. Chase, *The Tragedy of Waste* (New York: The Macmillan Co., 1927), p. 250.

[38] Miller and Lindsly, *op. cit.*, pp. 1131-2.

[39] T. V. Moore, R. J. Schilthuis, and William Hurst, "The Determination of Permeability From Field Data," *Proceedings of the American Petroleum Institute*, Vol. 14M (Division of Production, third midyear meeting, Tulsa, Okla., May 17-19, 1933, Prod. Bull. No. 211, May 1933), sec. IV, pp. 10-1. For additional evidence see E. Wahlstrom, "Development and Production Practice, Hobbs Field, New Mexico," *The Oil Weekly*, Vol. 69, No. 6 (Apr. 24, 1933), p. 28; and J. R. Suman, "The Well Spacing Problem," *The Oil Weekly*, Vol. 73, No. 11 (May 28, 1934), p. 43.

[40] Cattell and Fowler, *op. cit.*, p. 708.

[41] Miller and Lindsly, *op. cit.*, p. 1168.

to perform important functions in production, large amounts of oil frequently are left in the reservoir sands, and this oil sometimes cannot be brought to the surface even by secondary recovery methods. Loss or improper harnessing of the gas energy of a reservoir has caused premature abandonment of certain fields with an accompanying loss of employment.

Employment has also been influenced in important fashion by certain other wasteful results of competitive drilling. Occasionally, due to defective wells, pools have been ruined by the invasion of water into the productive formations and by the migration of the oil and gas from productive strata to beds where they cannot be reclaimed.[42] This and other types of underground losses have curtailed the ultimate recovery of pools and reduced the oil-per-unit-of-labor ratio below that which might have been potentially possible. The output per man has likewise been affected by the use of inefficient equipment and by the erection of excessive drilling and storage facilities above ground.

From a short-term viewpoint, competitive drilling appears to increase the output of workers in new fields of flush production. Flush-production areas, however, are notoriously short-lived and usually produce much less oil than would have been obtained easily and for a longer period under a conservative drilling campaign. Furthermore, as production shifts from older to newly discovered pools, the oil-field workers are forced to migrate frequently.[43] Although relatively short distances are usually involved in these movements, they are quite often attended by serious problems. Thus, over a relatively long-time period of 2 to 3 decades, competitive drilling of oil pools makes both for job insecurity and for a lower average long-time yield per man than could be attained with efficient engineering.

Trend Toward Control

Partly in recognition of some of the evils resulting from unrestrained competitive drilling for oil and gas, control over production has tightened appreciably in recent years. This development has been considered from the viewpoint of production engineering in chapter VI (pp. 159-63). An important departure

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[42] National Resources Board, *A Report on National Planning and Public Works In Relation to Natural Resources and Including Land Use and Water Resources, With Findings and Recommendations* (Dec. 1, 1934), p. 406.

[43] C. Goodrich, B. W. Allin, and Others, *Migration and Economic Opportunity* (Philadelphia, Pa.: University of Pennsylvania Press, 1936), p. 259.

from the competitive ideal came in 1927,[44] a year after the greater Seminole field of Oklahoma began to oversupply a market already acutely distressed with a flood of oil.[45] With stocks of crude at abnormal heights and prices dropping, the Corporation Commission of Oklahoma issued an order that restricted production in the greater Seminole field to 450,000 barrels a day and provided "that each lease covered by the plan may produce the same proportion of the allowable production which the total production of the lease bears to the total potential production of the field."[46]

From this beginning, proration spread rapidly. Its influence now dominates the industry and proration measures have been enacted in nearly all the important producing States. Texas, Oklahoma, Kansas, New Mexico, Louisiana, Mississippi, Michigan, and Arkansas have proration statutes of roughly the same general pattern. These States - with California,[47] Illinois, and Wyoming - are those in which flush fields have been developed during the past 2 decades.[48]

In the initial stages of proration, each State established and allocated its own quotas with regard principally to local problems rather than to the national market. This practice not only resulted in maladjustment between production and consumption on a national scale but also brought complaints of discrimination among different pools within the same States; in fact, open rebellion against proration orders broke out in many quarters. The problem was met in part through the issuance, beginning in 1930, of Federal Oil Conservation Board "estimates" of consumption for 3- to 9-month periods in advance, prepared by a volunteer committee. These estimates, which amounted to recommendations, were continued through 1932 and followed by more vigorous controls under NRA. With the operation of the Petroleum Code terminated in 1935, coordination was strengthened by an oil-conservation compact entered into by Texas, Oklahoma, California, Kansas,

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[44]The pattern of proration originated in Oklahoma in 1914, when discovery of the Cushing and Healdton pools demoralized the local market. An act providing for quotas was passed by the Oklahoma State Legislature in 1915, but the application of control was allowed to lapse.

[45]G. W. Stocking, "Chaos in the Oil Industry," *The Nation*, Vol. CXXXVI, No. 3544 (June 7, 1933), p. 634.

[46]Miller and Lindsly, *op. cit.*, p. 1273.

[47]A proration law that had been enacted was repealed by the California Legislature in 1932; since that time, except for brief intervals, proration in California has continued on a voluntary basis. See E. DeGolyer, N. Robinson, R. Hardwicke, and M. W. Watkins, "Organization of Production, Refining, and Distribution of Petroleum and Petroleum Products," *Transactions of the Third World Power Conference* (Washington, D. C.: 1938), Vol. IV, Sec. II, Paper No. 5 (U. S. A.), p. 200.

[48]Ely, *op. cit.*, pp. 1225-6.

New Mexico, Colorado, and Illinois on February 16, 1935. This compact, commonly termed the Interstate Oil Compact, was not ratified by California and lacked the adherence of Louisiana, Wyoming, Arkansas, and Michigan of the major producing States. Sessions of the Compact Commission have been attended, however, by representatives of these States, as well as of Pennsylvania and Indiana, and Ely reports that it "has functioned as a reasonably satisfactory clearing house."[49] According to the same observer, the essential meaning of the cumbersome language of the compact agreement is "that the Commission is authorized to bring together the regulatory bodies of the States for discussion of the Bureau of Mines' allocations, and to try to reach an agreement to put them in effect."[50] The Compact was renewed in 1937 in the identical form in which it had been executed in 1935; the agreement approved in July 1939 for another 2-year extension to September 1, 1941, omitted Illinois and included Michigan in the list of member States.[51]

Production control has also been strengthened by Federal regulation of commerce in oil produced in violation of State production quotas.[52] Federal regulation of "hot oil" was first enacted as section 9(c) of the National Industrial Recovery Act and invalidated in 1935 by the decision in Panama Refining Co. *v.* Ryan (293 U. S. 388). The policy of the law was then embodied in the Connally Hot-Oil Act of 1935, which was reenacted in 1937. The Connally Act declared to be "contraband" all oil and oil products produced or shipped in violation of State laws, regulations or orders; the statute is enforced by the United States Interior Department through a system of "tenders" or permits to ship. In January 1939, the National Resources Committee recommended that "the Connally Act be extended for such time as may be necessary . . . . .",[53] and necessary legislation continuing the act through June 30, 1942, was passed by Congress and approved by the President on June 29, 1939.

Although differing in detail among areas and periods, at the base of current production-control regulations is the power of

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[49] *Ibid.*, pp. 1215-7.

[50] *Ibid.*, p. 1216.

[51] U. S. Congress, Senate, "Agreement to Extend Interstate Compact to Conserve Oil and Gas," *Congressional Record*, 76th Cong., 1st sess., Vol. 84, No. 120 (June 15, 1939), pp. 10171-2.

[52] Pogue, *The Economic Structure of the Petroleum Industry of the United States*, p. 238; see also Ely, *op. cit.*, pp. 1217-8, 1234.

[53] See National Resources Committee, Release No. 065, mimeo., p. 2, accompanying report *Energy Resources and National Policy* (mimeo., Jan. 1939).

the State Government to restrict the output of the individual well. All such measures have been launched under the banner of conservation and ostensibly, at least, have been designed to correct the most glaring defects of unrestricted competition.[54] To require that the major objective remain clear and be easily attained when each action represented a myriad of personal judgments and of conflicting legal and economic relationships was to ask more than can be reasonably expected. Where the restrictive measures have been based upon good engineering practices, there is proof that the program of controlled production has tended to reduce both physical and economic waste and has promoted greater ultimate recovery.[55] On the other hand, the desire to conserve has been frequently tempered with compromise, and there is evidence of widely varying success of control arrangements in curbing waste. As noted in chapter VI (pp. 161-3), losses due to defects in the control of drilling comprise one of the most serious indictments against the present system of development. Certainly the curtailment program that has been pursued cannot be viewed as a technically ideal conservation policy for promoting maximum efficiency in the recovery of oil and gas.[56]

Failure of production to conform more closely to standards of engineering efficiency has in the past represented a tendency that operated to depress somewhat the rise of output per man and to increase the ratio of labor to output. At the same time the possibility remains for notable progress in overcoming the legal and economic handicaps to better engineering. This suggests that in the future an added increment of output is likely to be realized that will affect the trends of employment and output per man.

THE WORKER'S STAKE IN WASTE PREVENTION AND PRODUCTION CONTROL

Aside from the broad general interest of consumers in practices that needlessly waste future potential supplies of motor fuel, oil-field workers have a direct personal concern in the wise and orderly use of oil and gas resources. The application of techniques that lengthen the life of oil and gas reserves, for example, is good insurance for long-time future employment. More-

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[54] Stocking, "Stabilization of the Oil Industry," p. 59.

[55] H. C. Fowler and R. A. Cattell, "Influences of Petroleum Technology Upon Composite Interest in Oil," *Minerals Yearbook, 1935* (U. S. Dept. Int., Bur. Mines, 1935), p. 789.

[56] M. W. Watkins, *Oil: Stabilization or Conservation?* (New York: Harper & Bros., 1937), p. 252.

over, the type of efficient engineering that can be applied in accordance with a carefully designed conservative plan of development under a wise production-control program also means greater short-term stability of the job.

That the interest of the employees is now closely related to the future of production control can be illustrated simply. For example, if such producers as East Texas, Conroe, Yates, Oklahoma City, Kettleman Hills, and other major fields were to operate without restriction at maximum capacity, the waste of oil and gas would be enormous, and the national market would virtually be drowned in oil; in fact, uncontrolled production from three of these producers - East Texas, Oklahoma City, and Kettleman Hills - would be enough to demoralize prices and ruin many producing companies.[57] How long such fields could supply demand is a matter of speculation, but it would probably be long enough to close a large part, if not all, of the 216,000 stripper wells in operation in 1935.[58] This would mean that about 25,000 workers would lose their jobs. To some extent, moreover, the loss of employment would be permanent, because much of the oil left in the ground at the shut-in wells would probably become irrecoverable. The displaced workers could not expect to find jobs in other flush fields, since production from existing areas could be stepped up considerably without a material increase in the number of workers employed.

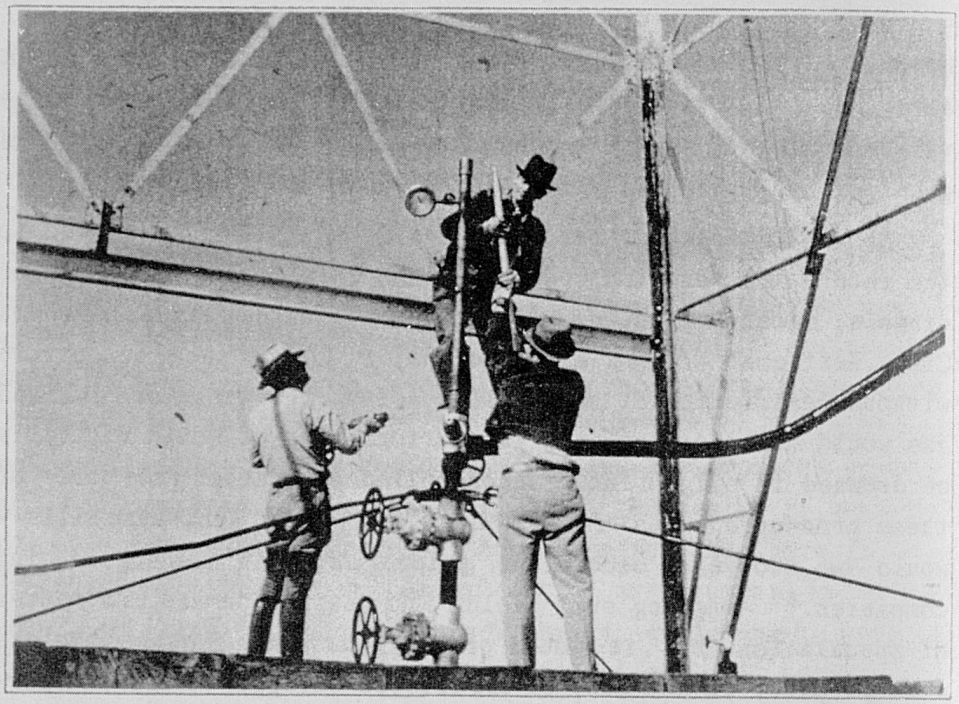
Although a return to the earlier forms of competitive drilling and flush production would produce unfavorable results for labor, a very rapid extension of efficient engineering would also have an unsettling effect. It has been noted, for example (pp. 161-2), that production control by proration still permits excessive drilling and other forms of capital outlays that are not necessary from a strictly technical viewpoint. The volume of employment due to this factor is quite large, and too rapid elimination of such work would be accompanied by the usual problems of employment readjustment.

It is sometimes pointed out that any scheme of production control involves at least a temporary or immediate increase in employment opportunities, which raises the question of whether such new employment offsets the labor saved by the better engineering

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[57] Miller and Lindsly, *op. cit.*, p. 1305.

[58] See p. 46; see also "Statement of Hon. Harold L. Ickes, Secretary of the Interior, Administrator for the Petroleum Industry," *Petroleum Investigation*, part 1, p. 182.



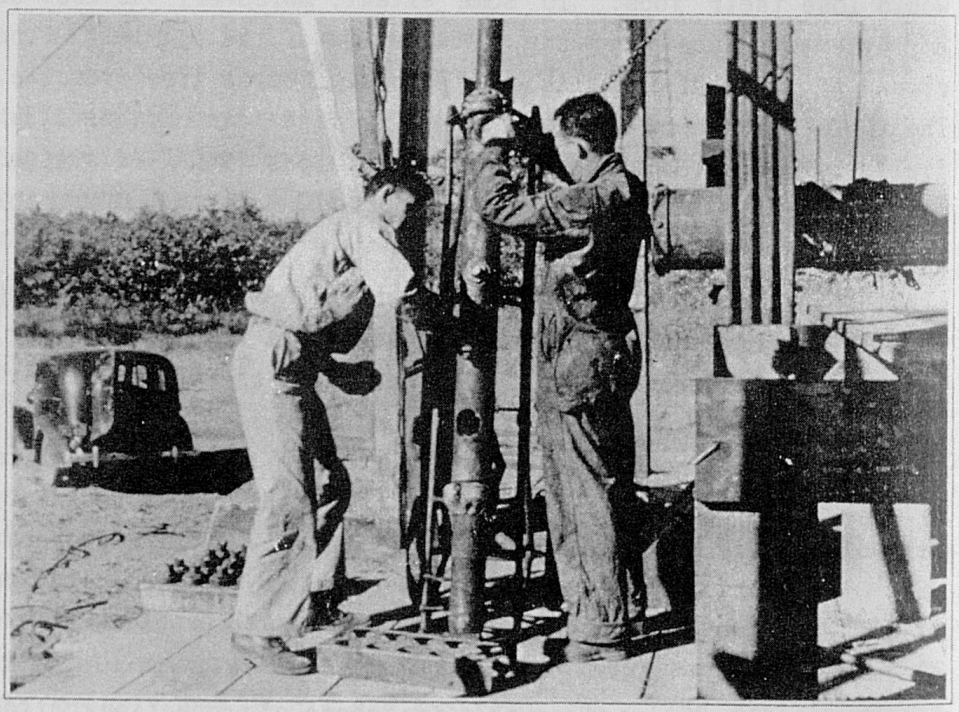


ILLUSTRATION 24.- DETERMINING BOTTOM-HOLE PRESSURES
AND LOADING A GUN PERFORATOR

Adequate data on bottom-hole pressures are important in efficient production engineering. The upper view shows steps preliminary to insertion of a gauge into an oil well for recording reservoir pressures. The gauge has just been passed to the man in the upper center. It will be lowered into the well through the "lubricator" (the pipe with the dial-faced gauge attached to the wellhead) which is simply a device for permitting entry into the well against pressure. The lower view shows workmen loading a gun perforator with firing chambers containing large bullets. This device is used to perforate casing at desired points and for other purposes.

the control arrangement makes possible. Under proration, for example, most companies have had to hire additional field men to make the measurements required, more technicians have been needed to direct the operation of wells at restricted rates of flow, and more clerical employment was provided as the needs for records multiplied. Technical and clerical personnel was also recruited for State agencies charged with the administration of laws and regulations. The additional employment, however, appears small beside the broad general savings that a more stabilized scheme of production has made possible. This point is emphasized notably by the more than threefold gain in output in 1937 in comparison with 1919, although over the same period the number of wage earners increased less than 50 percent.

Over the long run, the stake of the workingman is definitely in waste prevention and in efficient production control. When the essence is rendered from the many present conflicting forces, interests, and opinions in the industry, it still appears that the larger the quantity of oil or gas made available for production by conservation engineering, the longer man will be able to work at the job of producing. Speaking from a statistical viewpoint and ignoring the influence of factors that affect the status of individual workers (changing skills, for example), job security and tenure tend to improve as the life of engineering activities at different sites is extended.

RESULTS OF THE STRUGGLE AGAINST HANDICAPS TO EFFICIENT PRODUCTION AND AGAINST INCREASING PHYSICAL DIFFICULTIES

To the present, technology, plus a generous nature, has been winning handily over the forces that tend to increase costs. Despite legal and economic obstacles to efficient production and the growing natural difficulties noted, the richness of our petroleum and natural-gas resources, coupled with the achievements of the technologists, has been more than enough to provide increased abundance. The best measure of the success of technology has been furnished by the record of increasing output per worker employed, presented in chapter II. The trend of prices, moreover, furnishes another rough yardstick for measuring the achievements of technology. For short-term purposes, of course, the test of price is crude because, as previously indicated, costs are often a curiously irrelevant item in the construction of prices. On

this account prices of petroleum products frequently fluctuate convulsively, reflecting surpluses and deficits in supply as well as the relative success of efforts to regulate output.[59] However, the long-time price movement, particularly when shown in relation to prices of other commodities, should disclose whether technology is winning over the difficulties incident to production.

From the upper division of figure 21 it appears that crude oil has become cheaper as the industry has matured. There was a sharp drop in the well price during the first 20 years of the industry's commercial existence and the general trend was downward until the late eighties.[60] During the following decade the trend was moderately upward until Spindletop was brought in at the turn of the century. A rapid succession of important discoveries kept prices on the downgrade until the outbreak of the World War, when the trend was suddenly reversed and the average price rose to a peak of $3.07 a barrel in 1920. Prices at this level stimulated a vigorous search for oil that resulted in the discovery of a large number of pools of major importance. As a result, the price trend was sharply downward until proration was adopted. Since 1927 changes in the price of crude oil are strongly influenced by the success or failure of the control measures that have been established and that "tended to put a floor under oil prices."[61] During the period 1928-37 the range has been from an average of 65 cents a barrel in 1931 to $1.27 in 1929. In 1937 the average was $1.18 in contrast with prices of $5.00 or more per barrel that prevailed during most of the sixties and seventies.

Not only has the long-time price trend of raw petroleum at the well been generally downward, but since the early 1920's there has also been a decline in the wholesale prices of petroleum products in relation to the wholesale prices of other commodities. A comparison of the composite wholesale-price index of representative petroleum products with the all-commodity index shows that during the World War and prior to the discovery of a succession of great pools the index for petroleum products closely paralleled the all-commodity index. In the 1½ decades, however, the prices of petroleum products have been below the general price level, and the breach has been comparatively wide since 1926.

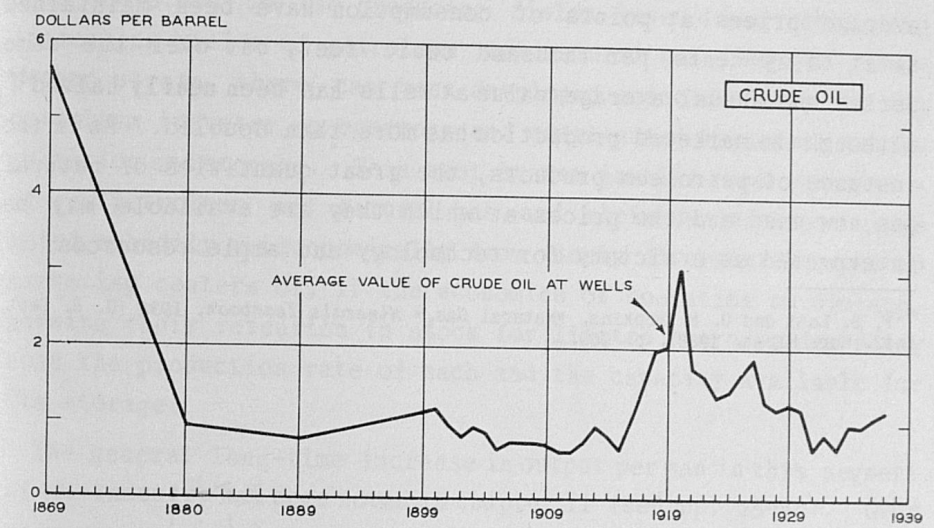
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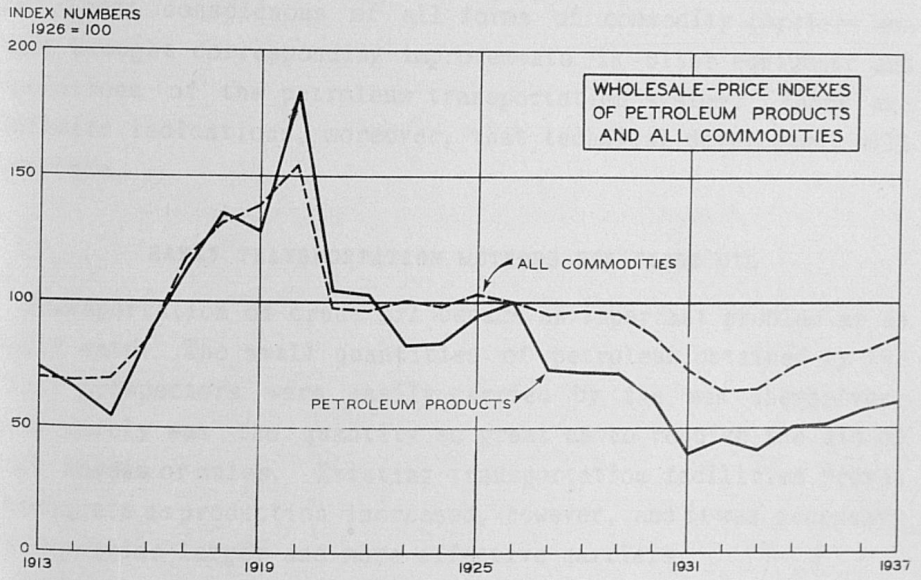
[59] E. G. Nourse and H. B. Drury, *Industrial Price Policies and Economic Progress* (Washington, D. C.: The Brookings Institution, 1938), pp 192-4.

[60] The trend during the first decade of the industry's existence, when prices fluctuated widely between 49 cents and $16 a barrel, is not shown on the chart.

[61] Nourse and Drury, *op. cit.*, p. 194.

Figure 21.- LONG-TIME CHANGES IN PRICES OF CRUDE PETROLEUM AND PETROLEUM PRODUCTS RELATIVE TO THE GENERAL PRICE LEVEL IN THE UNITED STATES, 1869-1937





HOPKINS AND ROGERS
U.S. BUREAU OF MINES

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
WPA-NATIONAL RESEARCH PROJECT E-128

BASED ON TABLES A-6, A-25

Although this approach suggests a complete victory for engineering, the results are not always clear-cut. Prices of natural gas, for example, generally increased from 1906, when the record begins, through the early twenties. From 1923 to 1936 annual average prices at points of consumption have been maintained at 21 to 25 cents per thousand cubic feet, but over the same period the annual average value at wells has been nearly halved[62] although the marketed production has more than doubled. As in the instance of petroleum products, the great quantities of natural gas now used and the prices at which they are available may be interpreted as a victory for technology and ample resources.

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[62] F. S. Lott and G. R. Hopkins, "Natural Gas," *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), p. 909.

CHAPTER IX

ADVANCES IN TRANSPORTATION AND STORAGE TECHNIQUES*

As operators in the producing fields have drawn constantly increasing yields of petroleum and natural gas from the underground strata, there has been developed coincidentally in the petroleum industry an enormous and complicated system of transportation and storage. This vast system enables great quantities of raw petroleum and natural gas and their derivatives to be moved speedily and economically from widely divergent sources to marketing centers or, if the economics of operation so dictate, permits their retention in stock for limited periods, depending upon the production rate of each and the capacity available for its storage.

The general long-time increase in output per man in this segment of the industry has been noted in chapter II (see pp. 28-30). Over 75 years many technical advances have transformed early crude-petroleum pipe lines into what are now probably the most efficient and least conspicuous of all forms of commodity carriers and have brought corresponding improvements in other equipment and operations of the petroleum transportation system. There are definite indications, moreover, that technical development will continue.

EARLY TRANSPORTATION METHODS FOR CRUDE OIL

Transportation of crude oil became an important problem at an early date. The small quantities of petroleum obtained by the first prospectors were easily carried by the men themselves; only rarely was the quantity so great as to require the aid of pack horses or mules. Existing transportation facilities proved inadequate as production increased, however, and it was necessary to improvise larger and more effective carriers.

The first commercially productive oil well and its contemporaries were situated along the banks of Oil Creek, in Pennsylvania, a tributary of the Allegheny River. The stream flowing toward the river offered a simple means of transport; early shipments were

*By R. Sneddon, Editor, *Union Oil Bulletin*, Union Oil Company of California, Los Angeles, California; R. L. Kiessling; J. S. Ross; and G. R. Hopkins.

made by merely loading the oil, either in bulk or in barrels, on barges that floated downstream with the current. But as the producing territory extended farther and farther away from the banks of the stream, large-scale teaming operations were undertaken.

The teaming operations first consisted of hauling barrels and open tubs - or any other vessels that would hold oil - from the wells to the creek bank, whence they were loaded on barges. Shipment by wagon team was hazardous and expensive in those days. The dirt roads became almost impassable, as the combined action of hoofs, wheels, and rain turned them into rivers of mud. Despite these difficulties, at one time 6,000 teams and wagons engaged in the traffic.[1]

Most teamsters simply carried on their wagons the barrels, open tubs, and similar containers loaded with oil, and little progress was made toward the development of the specially built bulk-tank wagon. The first notable use of the tank wagon was recorded in 1875, when a pipe-line owner, unable to secure a right-of-way across a railroad track, built storage tanks on either side of the railway and hauled his oil over the public highway between these points in a tank wagon of his own design.[2] The exact size or form of this first vehicle is not known, but observers reported that the operator eventually controlled a small fleet of such wagons with a total carrying capacity of 1,000 barrels.[3]

DEVELOPMENT OF TANK WAGONS, TRUCKS, AND CARS

Through a sequence of changes (closely paralleling developments in storage-tank construction) the crude tank wagon slowly evolved into the efficient tank truck of today. The first important advance was the change from open boxes, constructed of heavy pine planks on flat-bed wagons, to closed-type containers, also of wood. Then came the transition from wood to metal construction and later a change from vertical to horizontal tanks. A gradual increase in the capacity of the container accompanied the construction advances. The pay load, which was very much limited when horse-drawn vehicles were used, expanded notably with the use of automotive power, and some of the huge all-metal compartment

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[1] "Petroleum From Well to Market," *Oil* (New York: American Petroleum Institute, 1930), p. 148.

[2] "Three Pipe Lines to Eastern Seabord Featured Active Transportation Era," *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934), p. 55.

[3] *Ibid.*

truck-and-trailer combinations seen today can haul a 6,000-gallon load. At present, tank trucks are used principally to transport refined products and usually are employed only for moving crude oil from outlying producing sections where no pipe line is available.

By 1865 the car tank mounted on a railway flatcar was already an accessory of the petroleum transportation system. The original railroad oil car consisted of two small 40- to 50-barrel wooden tanks mounted on a flat-bed railway car, one tank being placed directly over each set of trucks.[4] A year later a Titusville firm was awarded a contract for manufacturing 60 tank cars for the Oil Creek Railroad. The tanks on these cars were of iron and had a capacity of about 90 barrels each. They were fitted with a new kind of valve that could be opened only with a special wrench and proved much more effective than earlier types in eliminating transit losses from spillage, fire, and theft.[5] In a short time - in the late sixties - the horizontal cylindrical tank was developed, in much the same form as we see it today, even to the dome, which was designed to permit expansion of the contents without damage to the shell. During the 6 decades that began in the early seventies, the major improvements have been in strengthening the carriage and the tank, which is now manufactured of double-riveted steel sheets. The average capacity of cars has been increased from 8,000 to 10,000 gallons in the last 10 years.

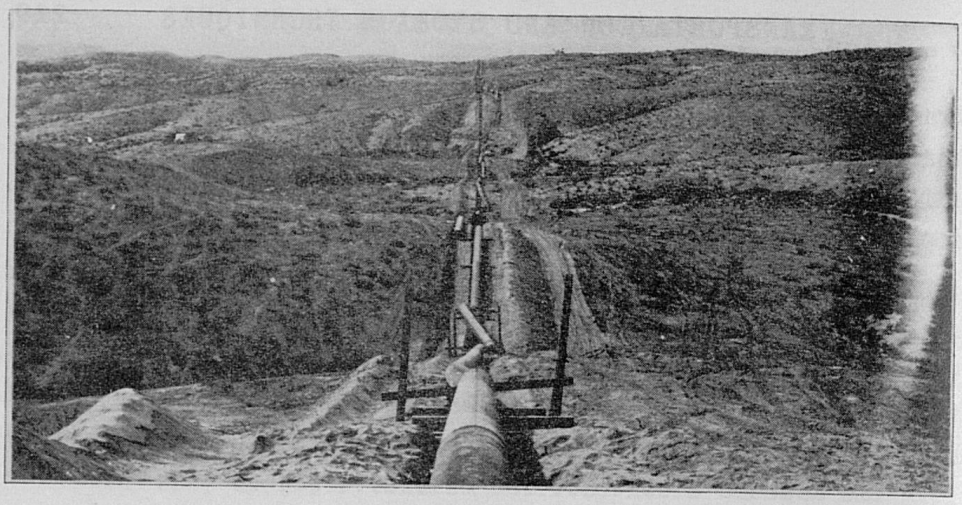
Tank cars now are made to transport a wide variety of hydrocarbon products, ranging from light gases in liquefied form to the heaviest asphaltic substances.[6] The highly volatile products usually are carried in cylindrical tanks built for high pressure, with gastight fittings, and the heavy viscous materials are transported in containers equipped with steam coils, so that the temperature may be maintained high enough to keep the contents fluid for easy delivery. Special compartment tank cars also are used widely for carrying several commodities of differing characteristics at the same time. For the movement of certain corrosive products, cars of aluminum or special noncorrosive alloys are employed. In 1937, 153,820 railroad tank cars were in

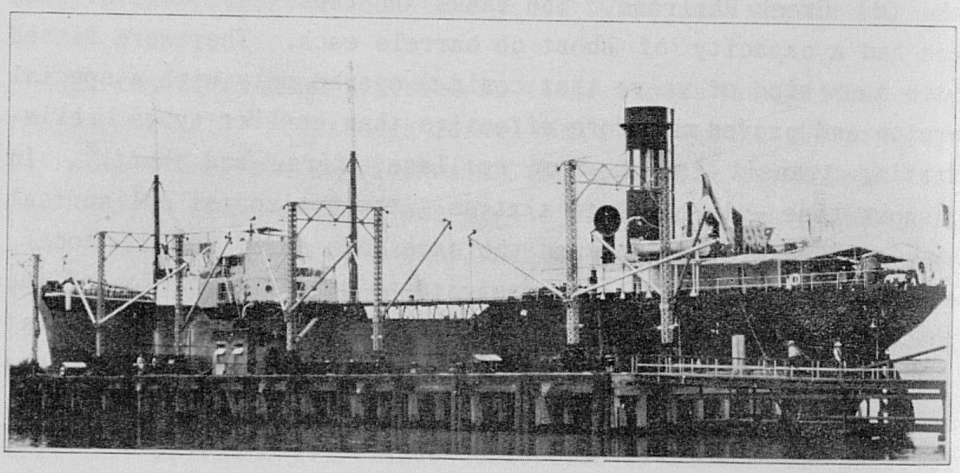
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[4] "Development of Tank Cars From Tub Type on Railroad Flat Cars Started in 1865," *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934), p. 23.

[5] *Ibid.*

[6] Except for "liquefied petroleum gases" (butane, propane), which is a special subject, and rare gases such as helium, the weight of containers that will withstand high pressures prohibits shipment of gas by rail.





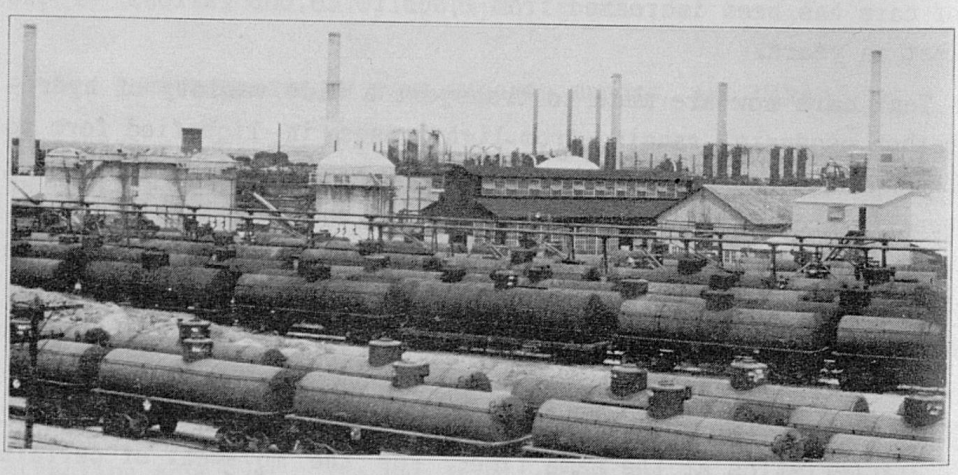


ILLUSTRATION 25.— PIPE LINES, TANK SHIPS, AND RAILROADS ARE IMPORTANT IN TRANSPORTATION IN THE OIL AND GAS INDUSTRY

All of the natural gas and the largest proportion of crude oil produced in the United States move to market through pipe lines. The quantity of oil shipped by tank ship has increased notably. Railroads have declined in relative importance as carriers of crude oil, but they are important in the distribution of gasoline and other petroleum products. In addition to pipe lines, tank ships, and tank cars, river barges and automotive trucks are used widely in the transportation of crude oil and petroleum products.

The upper view shows a pipe line under construction. In the middle view a tank ship is taking on cargo. The bottom view shows tank cars outside a refinery in the Rocky Mountain area.

operation,[7] and in 1936 the total tank-car shipments of petroleum and petroleum products exceeded 60 million tons; in the same year 6.4 percent of the railroad freight tonnage hauled was "petroleum freight", and 8.2 percent of the railroads' freight revenue came from this source.[8]

The relative position of the railroad transportation of petroleum and its products appears to have declined during the past 1½ decades. According to the chairman of the Interstate Commerce Commission:

> Taking the average annual tonnage of the three-year period 1923–25 as a base . . . . it was found . . . . in 1936 [that crude petroleum] . . . . was only . . . . 37.1 per cent of the base year, or a reduction of 62.9 per cent. . . . .
>
> A similar computation for refined petroleum and its products shows that although the 1936 tonnage produced . . . . was 63.1 per cent greater than in the 1923–25 period, the railroad tonnage of this class of commodities increased only 28 per cent. . . . .
>
> Of the total crude petroleum produced in the base period . . . . 8.3 per cent was hauled by the railways and in 1937, 2.1 per cent.
>
> . . . . in 1928 . . . . [the railroads] hauled 86.1 per cent of the . . . . gasoline, and in 1937, 53.6 per cent.[9]

Despite the decreasing share of the total output of petroleum and derivative products shipped by rail, the railroad revenue from this class of traffic in 1937 was greater than from all grain and flour combined.[10]

DEVELOPMENT OF OIL PIPE LINES

The crude system of river portage used on Oil Creek became more and more precarious and cumbersome as the producing territory extended and as output rose. The stream was narrow and shallow in the dry seasons; to provide enough water to float the large fleet of barges that was increasing with every new well completion, a number of dams - built at intervals on the stream and operated by the lumber mills in the vicinity - were

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[7] American Petroleum Institute, *Petroleum Facts and Figures* (5th ed.; New York: 1937), p. 148.

[8] *Ibid.*, p. 147.

[9] W. M. W. Splawn, "Transportation by Pipe Lines," *The Oil and Gas Journal*, Vol. 37, No. 19 (Sept. 22, 1938), p. 66.

[10] *Ibid.*

used to impound water that was released as "pond freshets." In the impounded stretches behind the dams, the barges and crude dugouts were first loaded with crude oil from the wells, either in bulk or in barrels. When this operation was completed, the dams were broken as nearly simultaneously as possible, and the rush of water carried the vessels with their cargoes downstream. Such a form of transportation failed to meet reasonable standards of efficiency, economy, and safety. At one time over 2,000 barges of all sorts were engaged in the river traffic,[11] and chaos resulted when this sizable fleet was turned loose in the narrow waterway. Collisions were inevitable, and many boats, cargoes, and human lives were lost.

Pioneer Experiments With Pipe Lines

The disasters of the river traffic and of rough roads inaugurated a search for alternative methods of transport that was stimulated further by the meteoric rise of haulage rates.[12] The urgent need for a less costly and more efficient method of moving oil brought from Gen. S. D. Karns in 1860 (at Parkersburg, West Virginia) the suggestion of using lengths of pipes that had been connected.[13] Although his original plan never actually materialized, General Karns pictured an all-metal line that would gravitate oil a distance of 36 miles.

In 1862 J. L. Hutchinson attempted to interest certain operators in the Titusville producing area in the construction of a pipe line to test the efficacy of a pump he had developed for forcing oil through such a line.[14] In 1863 a producer was finally persuaded to lay the first crude-oil pipe line on record. This line consisted of 2 miles of 2-inch pipe, through which Hutchinson attempted to send the crude oil by means of three of his "force pumps", situated at convenient intervals along its length. The pipe was so poorly jointed and leaks caused such a reduction of pressure and loss of fluid that the line was a failure. In the same year the Western Transportation Co. of Oil Creek constructed a 4-inch line 3 miles long down the side of Oil Creek, but this

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[11] "Transportation Problems of First Era Make Today's Difficulties Seem Simple," *The Oil and Gas Journal*, Vol. 33, No. 14, (Aug. 23, 1934), p. 21.

[12] The cost of teaming a barrel of oil for a distance of 4 miles sometimes ran as high as $3.00. See R. S. McBeth, *Oil: The New Monarch of Motion* (New York: Markets Publishing Corp., 1919), pp. 165-6.

[13] "Transportation Problems of First Era Make Today's Difficulties Seem Simple," p. 22.

[14] *Ibid.*

also was unsuccessful.[15] These early attempts failed to meet the hopes of the promoters, but each effort contributed new knowledge and continued experimentation led ultimately to success.

First Successful Pipe Line

In 1865 Samuel Van Syckel began the construction of a 2-inch wrought-iron line 5 miles long from Pithole, Pennsylvania, to a producing area known as the Miller farm.[16] At least portions of this line were laid in a ditch 2 feet deep to be beyond the reach of plows and other farm implements.[17] Before the project was completed the pipe was disconnected and partly destroyed by teamsters who considered that this innovation was a serious threat to their business. Van Syckel placed an armed patrol along the line, restored and relaid the broken pipe, and completed what was to be the first successful long-distance pipe line. Oil was pumped through this line in two stages at the rate of 30 or 40 barrels an hour. Stimulated by the success of Van Syckel, other operators began to lay lines to the nearest railroad terminals; these lines were completed despite opposition from the teamsters that on occasions flared into open violence.[18]

After the success of Van Syckel, pipe-line transportation grew rapidly, and the more adept the pioneer constructors became, the farther afield the operators dared to go in their petroleum explorations. In the decade following 1865 a network of pipe lines covered the territory surrounding Oil Creek. Producers constructed and operated their own lines, refiners laid lines into the producing areas for the benefit of operators who could not afford to construct lines themselves, and individuals or companies that were neither producers nor refiners laid lines and established themselves specifically as transportation agencies.

Beginning of Longer and Larger Lines

All of the first pipe lines were of small diameter, and the land on which they were laid was comparatively level, but the extension of producing areas and the discovery of new fields

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[15] *Ibid.*

[16] *Ibid.* See also *The Derrick's Hand-Book of Petroleum: Petroleum Developments From 1859 to 1898* (Oil City, Pa.: Derrick Publishing Co. 1898), p. 52.

[17] This practice of burying the pipe is still followed today in constructing pipe lines in farming areas.

[18] McBeth, *op. cit.*, p. 170.

eventually required pipes of greater capacity and the traversing of hilly - even mountainous - terrain. With hundreds of miles of small lines of varying length in operation, the trend turned toward the installation of longer and larger lines. If oil could be transported from the field to the local distributing depots, why couldn't it be transported from these depots to the seaboard or to the large refinery terminals? This meant crossing the Allegheny Mountains, a task that was achieved in 1879 when the Tide Water Pipe Co., Ltd., constructed a line from Coryville, in the Pennsylvania producing area, over the Allegheny Mountains to Williamsport, Pennsylvania.[19] Not only was the line laid with comparatively primitive equipment and over difficult obstacles, but it also required the development of the first pumps for high-pressure pipe-line transportation. While this line was being laid other projects were being started, and in a short time a number of comparatively long-distance (judged by the standards of the period) pipe-line companies were operating in the oil regions. These projects grew out of the high transport rates in this early era that stimulated organization of relatively large pipe-line transportation companies, of which the Tide Water Pipe Co., Ltd., mentioned above, was the first. The company was organized by a group of men, mostly operators in the oil field, who felt that the income to be derived from rendering transportation service was more permanent than that from actually producing petroleum.

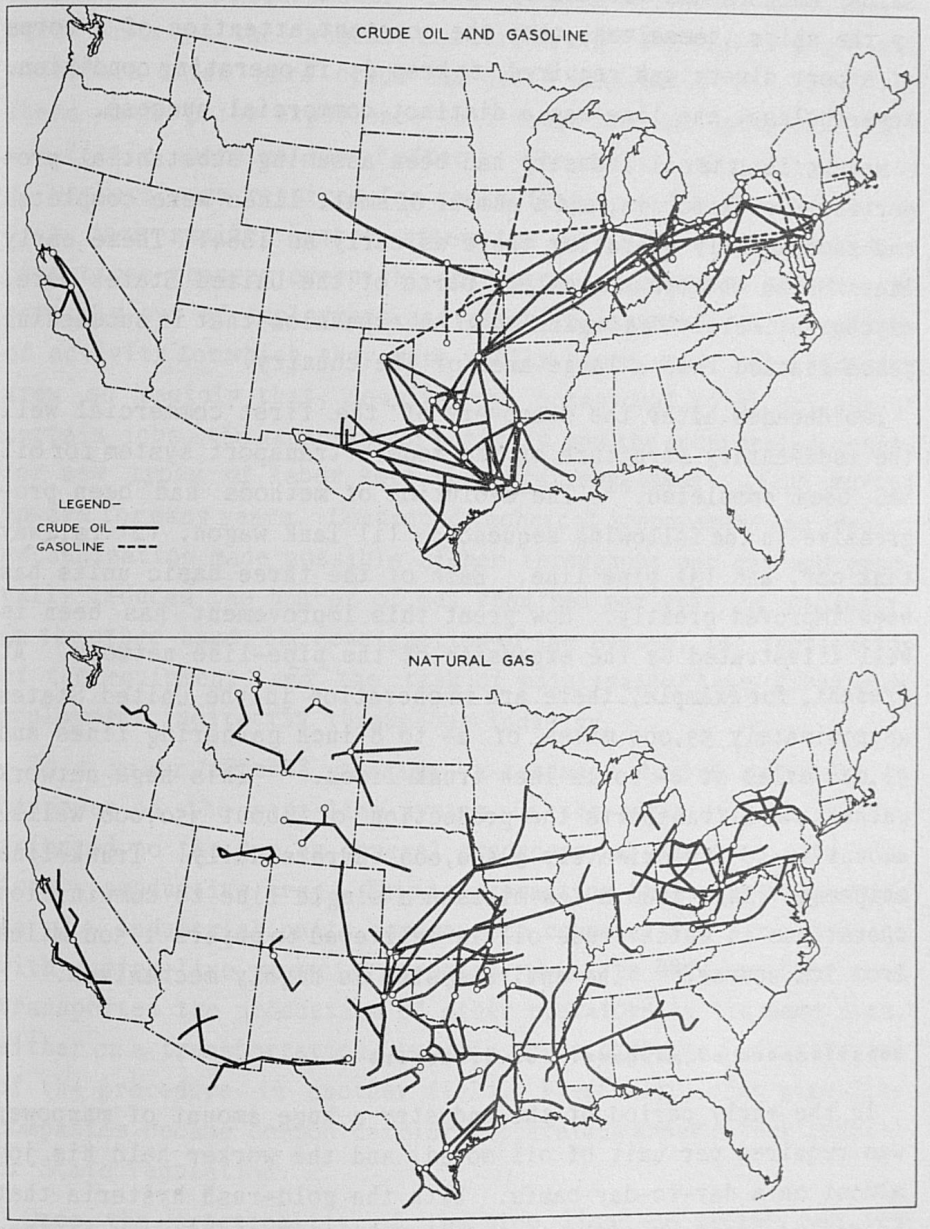
Up to the time the Tide Water Co. line was completed in 1879, the largest pipe in use in any effective system was 3 inches in diameter, and the fittings and accessories for the new 6-inch line over the Alleghenies had to be manufactured under a special order. The building of more powerful pumps to inject oil against the pressure of columns of fluid of considerable height was a difficult problem, and the spacing of pump stations to divide the total distance into negotiable increments tested existing engineering skill and knowledge of hydrostatics. The development of large-size valves and fittings required ingenuity, and the erection of large storage tanks at the stations and terminals was an entirely new effort in transportation technology.

Inspired by the success of the Tide Water Co. experiment, the National Transit Co., a subsidiary of the Standard Oil Co., built two 6-inch lines from Olean, New York, to New York City and Bayonne.

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[19] "Three Pipe Lines to Eastern Seaboard Featured Active Transportation Era," pp. 55-6.

Figure 22.- PRINCIPAL PIPE-LINE MOVEMENT OF CRUDE OIL, GASOLINE, AND NATURAL GAS, JANUARY 1, 1939



These lines, the first to reach the Atlantic seaboard,[20] were completed in 1881. Part of the Williamsport-Bayonne line was laid across Newark Bay and Staten Island Sound by means of canal

[20] Although the line of the Tide Water Pipe Co. reached Williamsport in 1879, legal difficulties delayed an extension to Bayonne, New Jersey, until 9 years later.

boats, and this particular section was undoubtedly the first marine pipe line. It was continually being caught and broken by ships' anchors and frequently was rammed in the shallower depths by the ships themselves; thus the constant attention of a corps of expert divers was required to keep it in operating condition. Nevertheless, the line was a distinct commercial success.

Meanwhile, the oil industry had been assuming substantial proportions in California, and a number of small lines were completed and successfully operating there as early as 1884. These early lines in the eastern and western parts of the United States were, of course, merely the beginning of an expansion that in succeeding years reached into a large area of the country.

Two decades after the discovery of the first commercial well the rudimentary structure of the modern transport system for oil had been completed.[21] The evolution of methods had been progressive in the following sequence: (1) Tank wagon, (2) railway tank car, and (3) pipe line. Each of the three basic units has been improved greatly. How great this improvement has been is well illustrated by the expansion of the pipe-line network. At present, for example, there are in operation in the United States approximately 53,000 miles of 2- to 8-inch gathering lines and 58,000 miles of 4- to 12-inch trunk lines.[22] This huge network gathers and transports the production of about 350,000 wells, amounting to approximately 3,500,000 barrels daily. Trunk-line shipments range from a few miles on a single line to combination operations in which crude oil is delivered to buyers 1,500 miles from its source.[23] The entire system is highly mechanized.

Requirements of Manpower for Transport

In the early period of the industry a huge amount of manpower was required per unit of oil moved, and the worker held his job almost on a day-to-day basis. With the gold-rush hysteria that prevailed, economy of labor and stability of the job were minor considerations (if they were thought of at all) in the struggle

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[21] Natural-gas transmission is discussed in a subsequent section of this chapter.

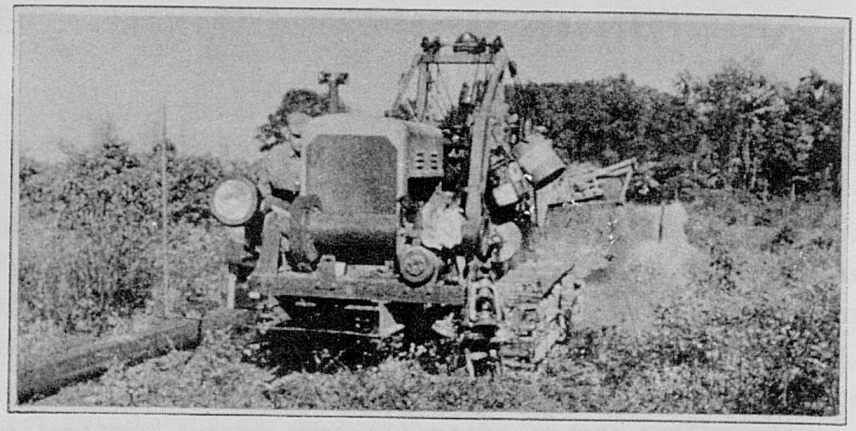
[22] Lines with smaller diameters are also in use (see p. 232). Whereas gathering lines formerly averaged about 2 inches in diameter, the average today is about 4 inches, with a tendency toward 6-inch lines. The average diameter of trunk lines for transporting crude oil increased from 8 inches in 1931 to 8.3 inches in 1936, with some lines running larger than 12 inches in diameter. The diameters of gas pipe lines are much larger and in a few instances are as high as 36 inches.

[23] "The Pipe Liners' 24 Hours," *The Oil and Gas Journal*, Vol. 36, No. 18 (Sept. 16, 1937), p. 89.

to get oil to market and to develop more efficient transportation devices. Men were their own artisans, as there were no standardized parts or equipment. They fashioned their own containers, built their own tank wagons, and forged their own tools. Available materials often were crude and quite inadequate for the need. There was no prior experience that could be drawn upon, and there was little coordination of effort. The result was that hundreds of workers were required for tasks that soon could be performed by a much smaller number after the work became systematized. Situations changed overnight, throwing large groups of men temporarily out of employment and establishing new groups in types of activity for which they were wholly unprepared. The industry grew so rapidly that, despite the occasional total eclipse of certain jobs, the expansion of activity and the accelerated demand for new types of labor kept the total employment trend moving upward for many years. Continued technical improvement and greater mechanization made possible higher throughput per man and gradually reduced the number of men required per unit of capacity. On the other hand, the construction of the system, the fabrication of the equipment, and the task of maintenance have given wide employment indirectly throughout industry.

To a minor extent, perhaps, a tendency toward reduction in manpower on the pipe-line system in the early days may be attributed to the use by several producers of the same pipe line from a productive area. This is a practice that grew more common as the industrial units became more cooperative. One company with a pipe-line capacity greater than its own specific need transported the production of other operators in the same area, either on a transportation fee basis or in exchange for a reversal of the procedure in another field. Eventually, most pipe-line companies became common carriers, operating under either Federal or State regulation.

Once the practicality of the pipe line was proved and the industry settled down to the larger use of this method, inventive minds turned to the problems of eliminating deficiencies, such as leaky joints, and of reducing the cost of construction, operation, and maintenance. The result has been an almost uninterrupted series of technical advances from about 1880 to the present. Some of these advances simply overcame existing technical difficulties, but most of them represented definite new improvements that greatly reduced the amount of labor required. Not only



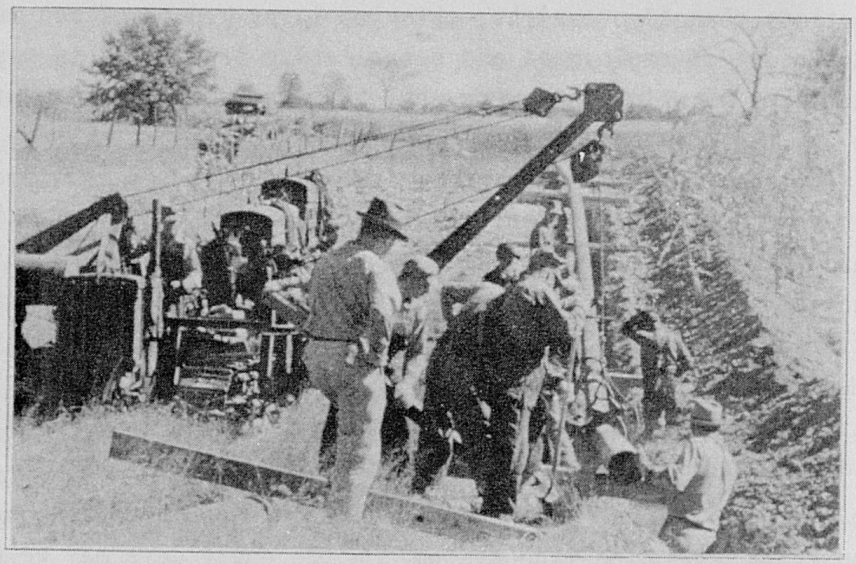




ILLUSTRATION 26.— MACHINES ARE IMPORTANT AIDS IN MODERN PIPE-LINE CONSTRUCTION

Ditching and laying machines and welding are used in modern pipe-line construction. They have made possible the building of larger and stronger lines than could be constructed with hand ditching and threaded pipe; savings in time and cost also have been factors in their increased use. The large labor crews working with pick and shovel and with tongs and sledge have largely disappeared.

The upper view shows a ditching machine in use in the Mid-Continent area. The middle view shows a mobile hoist assisting in the laying of pipe. In the lower view, electrical welding is being employed to obtain a leakproof and sturdy joint. These views depict operations in progress in 1939.

were fewer men able to lay more line or to transport more oil but the increasing mechanical complexity of pipe lines greatly reduced the number of jobs available to the general laborer and increased the number of highly skilled workers.

Changes in Construction and Maintenance Methods and Their Effects Upon Labor Requirements.- The laying of the early lines was an undertaking that required the services of strong men. Brawn was more a necessity than engineering skill. Men literally had to carve their own roads. Pipe was heavy, and the task of hauling $17\frac{1}{2}$-foot joints of pipe one at a time by horse or mule team over mountain trails, stringing them out along the route, and eventually screwing them together, was slow and tedious. Adequate tools had not yet been developed. Ditches were dug with the pick-and-shovel method. The construction of even fairly short lines required more than a thousand men.

As late as 1919, 75 men, consisting of a foreman, stabbers, tongmen, ropemen, barmen, jackmen, etc., commonly constituted the pipe-laying crew. Such a group of men was able to lay out and screw together in 1 day 200 to 250 joints of pipe, 20 feet long. They were preceded and followed by another crew, often numbering 150, that dug and later, using picks and shovels, backfilled the ditches in which the pipe lines were laid.

The first major technical advance in the actual laying of pipe was the development of the make-up machine, a device for screwing the joints together, which performed the work formerly done by a large gang of men employing brute strength and chain tongs. About the same time was introduced the automotive truck that did the work of dozens of teams and teamsters in hauling pipe to the job. Next followed the tractor, by which stringing and other incidental operations became the work of one or two men instead of another crew of teamsters. Finally, mechanical excavators and ditch diggers virtually eliminated picks and shovels and substituted two operators with sometimes a helper apiece for the large pick-and-shovel crew.

The problem of joining pipe was not solved by the screw joint or the make-up machine. Despite continued experimentation and the use of every conceivable type of union - screw joints, flanges, and bell-and-spigot ends - difficulties persisted. The most important advance in joining technique was the introduction of line welding. To the natural-gas industry - advancing coincidentally

with the oil industry in the technique of building pipe lines - goes the credit for this departure, which now has become almost universal practice.[24]

With the improvement in the quality of line pipe, transportation companies paid considerable attention to the whole subject of leaky joints. Frequently lines were uncovered that were in perfect shape in all respects except that leakage apparently could not be stopped at the joints. The technique of oxyacetylene welding of pipe-line joints had been used on city gas lines as early as 1911[25] and later had been further developed in the construction of relatively short oil lines. Beginning in about 1925 oxyacetylene welding was an important factor in the construction of long-distance pipe lines for the transmission of natural gas. In applying this method, pipe was first alined with a small space between joints. This space was then filled with Norway iron by means of the torch. These joints proved satisfactory beyond expectation, and tests showed that the new sections were stronger than the original pipe. With the general use of welded joints and the subsequent adoption of seamless pipe, which eliminated all unnecessary internal friction, pipe lines had almost reached their present excellence.

Beginning in 1928, electric welding brought further improvements to pipe-line construction methods by permitting crude-oil lines to be patched without the necessity of first emptying them,[26] due to the fact that in oxyacetylene welding it is necessary to preheat a large area of pipe in the vicinity of the weld, almost to the fusion point, whereas in electric-arc welding the torch is directed over a comparatively small area. With the last method there is little likelihood that a section of the pipe itself may be softened to the point where it will rupture, allowing the oil to escape and ignite. The electric torch was adopted quickly and extensively, first for welding bell-and-spigot joints of large-size pipe for gas transmission; by 1933 it was being used just as extensively to weld butt-end oil lines and is now employed widely for this purpose. Large-diameter, light-walled, high-pressure steel pipe, beveled for welding, is now the generally

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[24] Federal Oil Conservation Board, R. L. Wilbur, chmn., *Report IV* (U. S. Dept. Int., May 28, 1930), pp. 13-4.

[25] "Introduction of Welding in Construction and Gasoline Lines Feature of Fourth Era," *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934), p. 123.

[26] T. P. Sanders, "Electric Welding of Pipe Lines," *The Oil and Gas Journal*, Vol. 37, No. 19 (Sept. 22, 1938), p. 202.

preferred line material, but much larger diameter pipe is used in natural-gas trunk lines than in oil lines.

More efficient methods of handling pipe have been related to improvements in welding. Recently the stove-pipe method of pipe handling has been used extensively.[27] Before 1936 solid welding practice required making up the line in 200-foot sections and tying these sections into the line. By the stove-pipe method, especially adapted to hilly or uneven country, the joints are handled individually and are welded into the line one at a time.

Proper welding requires a high degree of technical skill and, in addition, a fair knowledge of the specific metallurgy involved. Research work on the problem appears to have caused knowledge to outdistance practice, and good electric welders are at a premium. This is an exception to the general employment situation, however, for the whole tendency of development in the art of laying lines, the improvement of line pipe, the elimination of line losses, and other advances has been to save labor.

Another significant change was an increase in the length of the pipe joints. At first most joints were 20 feet long, but gradually they were increased to the present standard of 40 feet. This change reduced much of the handling work, for it is almost as easy to handle a 40-foot length as one of 20 feet.

A number of methods have been employed for extending the life of the pipe. Covering the pipe with special types of coatings or wrapping it with asphalt-impregnated paper (a machine job that at one time was performed by hand) protects the line from corrosion.[28] Soil analyses have indicated the location of corrosive land areas that might be avoided advantageously in laying the pipe. For unduly corrosive areas that cannot be avoided, pipe is manufactured of materials that are especially resistant to corrosion.

Recent improvements in equipment have simplified the task of reconditioning. The line may be spotted by the radio pipe-line finder and uncovered with a ditching machine equipped with a stripping shoe that removes the dirt from the top of the pipe. Tractors equipped with side booms are used to raise the pipe from the ditch, and cleaning machines - equipped with knives - remove rust and dirt. "The pipe cleaning machine reduced pipe cleaning

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[27] D. H. Stormont, "Recondition 30-Mile Line," *The Oil and Gas Journal*, Vol. 37, No. 19 (Sept. 22, 1938), pp. 198-9.

[28] *Ibid.*

from several dollars per joint to a few cents . . . . ."[29] Most of this saving was represented by a reduction in labor required for the task.

For a long time the rapid corrosion of pipe lines in some localities was accepted as one of the natural hazards of the business. Then investigators discovered that this corrosion was not due to ordinary oxidation or chemical action but to electrolysis. This caused current to flow from the pipe to the soil or from one section of pipe to another, and the current carried iron from the pipe or from one section of pipe to another section in such a manner as to weaken the line at certain points. To overcome this action all that is necessary is to provide a source of electrical energy sufficient to raise the potential of the surrounding soil a fraction of a volt above that of the pipe. This reverses the existing condition, causing current to flow to the pipe and preventing electrolytic action.

Pipe lines of greatly varying sizes and diameters are now employed for special purposes. The more common diameters, perhaps, are 8 and 10 inches, but pipes are manufactured and have specific uses in all sizes from 1 to 16 inches for oil lines and from 2 to 36 inches for gas lines. The larger the line, the greater the throughput with the same difference in pumping pressure. That the general transition to larger diameters has a powerful economic basis is indicated by the following conclusion from a recent report of the U. S. Bureau of Mines:[30]

> The use of larger pipe . . . . is encouraged by the relationship of operating costs to initial investment. When it can be anticipated that the useful life of a proposed trunk line of given capacity will be perhaps 20 years or more, it is often advantageous to increase the initial investment above a necessary minimum in order to reduce the annual cost of operating the line. For example, an 8-inch line with pump stations at 40-mile intervals might be adequate to handle 20,000 barrels of oil per day. A 10- or 12-inch line would cost more but could carry this volume with a much smaller number of stations and consequently a lower payroll and maintenance expense.

Another advantage favoring the larger line, of course, is its ability to handle larger volumes of oil should this become necessary.

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[29] H. B. Trefz, "Maintenance of Pipe Lines," *The Oil and Gas Journal*, Vol. 37, No. 19 (Sept. 22, 1938), p. 210.

[30] *Survey of Crude Oil in Storage, 1936-1937* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3417, mimeo., Sept. 1938), p. 46.

Development of Pumping Equipment

The improvement of pumping facilities has been a major factor in the expansion of pipe-line transport. The first pumps used were of the flywheel type,[31] but they were quickly discarded in favor of single-cylinder, direct-acting steam pumps.[32] Between 1865 and 1875, or as long as comparatively short-distance, low-pressure lines were the vogue, these pumps proved fairly satisfactory, but with the introduction of the large trunk-line systems they became totally inadequate. The effect of the single-cylinder piston is to produce a series of short pushes almost equivalent to blows, with a substantial interval between each, during which the moving column of oil stops. The series of shocks so produced in the high-pressure lines was enough to ruin the pumps themselves, produce costly leaks, burst the lines, and generally interfere with operation.

The next development - the twin-cylinder reciprocating-type steam pump - was directly designed to amend the inherent faults of its predecessor and appeared about 1877. With the two cylinders, one stroke ends when the other begins, so that the movement of oil is continuous and the shocks are eliminated. These pumps are used extensively at present on properties where steam is available for moving oil from the well tanks through the gathering lines, and they are also in general use throughout the industry. They are not highly economical to operate, however, and they were supplanted in the pipe-line stations about 1891 by the more efficient crank-and-flywheel pump engines. These large horizontal engines, still found in many pump stations, can force great volumes of oil through the lines at high pressure and at low cost. A test on such a pump in 1914 indicated that the steam raised by 1 barrel of fuel oil could force 1,000 barrels of oil into the pipe line against a constant pressure of 600 pounds.

In turn, however, flywheel engines were also replaced in many operations by low-compression, internal-combustion engines, burning gas or oil. The first recorded installation of this type

[31] R. F. Bacon and W. A. Hamor, *The American Petroleum Industry* (1st ed.; New York: McGraw-Hill Book Co., 1916), I, 246.

[32] It is not always necessary to employ pumps to move oil, for when the well-receiving tanks are installed on an elevation above the pump-station tanks the oil can be moved from the upper to the lower level by gravity. Under these conditions the liquid simply flows down through the pipe as any liquid flows downhill, so that it is only necessary to open the well-tank outlet and the station-tank inlet, and the transfer takes place automatically. This gravitation method of transporting oil from one level to another is commonly practiced in all phases of the oil industry where differences in elevation permit, but under all other circumstances pumps of some type are required.

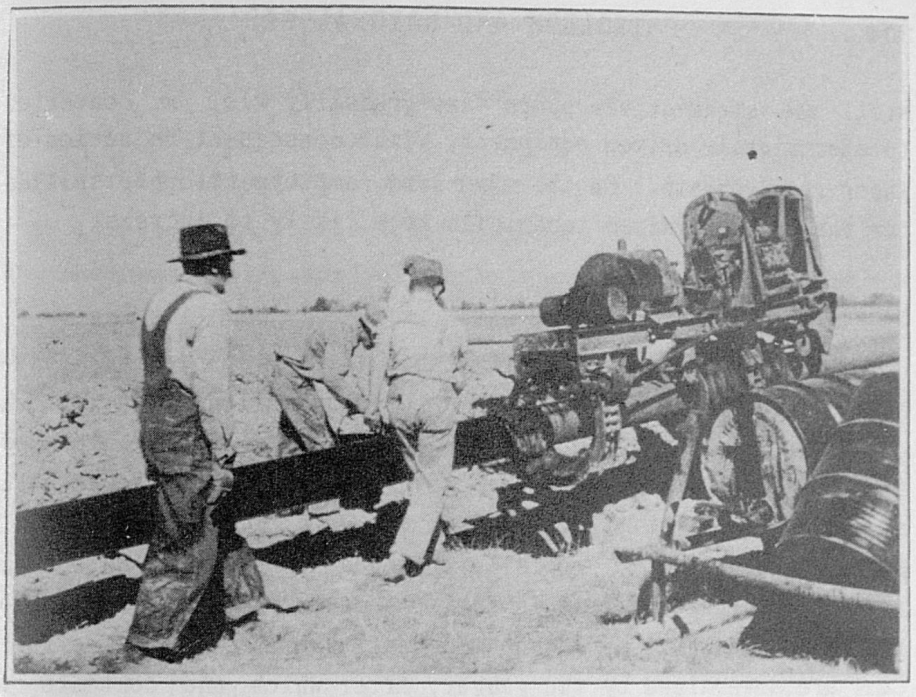
took place in 1901. Sometimes two engines were maintained at the pumping stations - one gas-burning engine and an oil-burning machine to be used as an auxiliary during gas shortages. The next advance was to high-compression, internal-combustion engines that represented greater power output and fuel economy, and gradually through additional modifications and advances came the semi-Diesel and Diesel-type engines.

These improvements in driving mechanisms, and the consequent availability of greater power at lower cost, permitted the coincidental development of greater pump capacity. The Diesel engines, for example, enabled the operators to use heavier, and hence cheaper, oils for fuel and demonstrated that they were efficient and economical. The whole process of technologic advance in every phase of transportation has been directed toward movement of the greatest possible quantity of oil in the shortest time with the utmost economy. The last qualification involves consideration of initial cost, operating cost (including labor), and maintenance cost (also including labor), and every step in the process of development has tended toward the reduction of one or more of these items.

The next important advance in pump-station machinery development was the introduction of the electric drive. The use of electric motors to drive plunger pumps has simplified the operation of pumping equipment and permitted definite curtailment of the labor required for this work. Then came the small, light centrifugal pump that required less room and operated effectively with much lower maintenance costs than earlier types. The combination of the electric motor drive and the centrifugal pump is now a popular installation in pipe-line stations.

A comparatively recent development is a unitized, fluid-cooled pump, which consists of a multiple-stage centrifugal pump operated by an induction motor, cooled by the fluid being pumped. This unit is comparatively small and compact and can be installed in a few hours. It has low initial and operating costs, is exceedingly simple to install and operate, and requires minimum attention.

The future trend of technical progress in pumping doubtless will continue in the direction of more simplified equipment and greater economy and efficiency of operation. Larger quantities of oil probably will be moved with less labor, and the possibility that more pumpers, gaugers, engineers, and firemen will be required is not promising. For example, many pipe-line stations



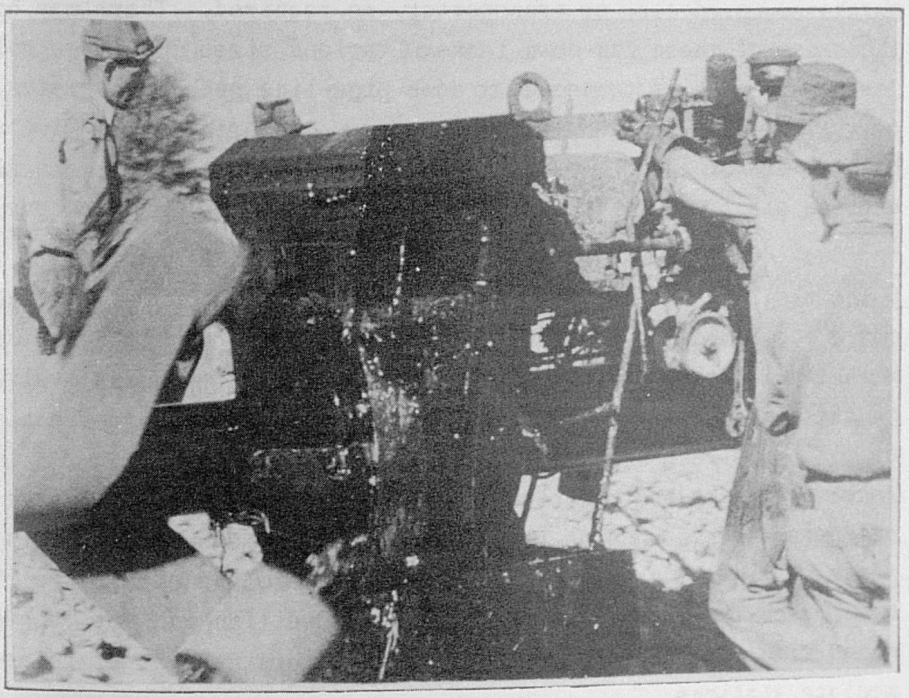


ILLUSTRATION 27.- RECONDITIONING A PIPE LINE

Pipe lines are sometimes reconditioned with special equipment utilized for this operation. After the pipe line has been uncovered and raised above ground level, it is scraped clean by a machine and joints are replaced where necessary. It is then treated with a protective compound and wrapped for further protection in felt or other suitable material. The top view shows a machine for spreading the compound (commonly called "dope") on the pipe. The "doping" machine is followed by two men working with hand brushes who paint over portions of pipe not covered by the machine. Doping and covering with felt or other suitable material may be done by a single machine, as in the bottom view.

still use steam-driven pumps that gradually will be converted to electrically driven equipment, with a consequent reduction of labor requirements. On the other hand, employment opportunities for the highly trained technician seem likely to increase.

Modern Pipe-Line Operation

To indicate more specifically the nature of pipe-line transportation, a brief explanation of the operation of a typical gathering and trunk-line system is given. As oil is produced from the wells in the field, it is ordinarily conducted through a pipe known as the "flow line" to run-down or receiving tanks. Each well or group of wells is provided with two or more such tanks,[33] so that when one is full the stream may be diverted to another. Meanwhile the amount and quality of the oil in the full tank are determined by the gauger, after which the contents of the tank are ready to be pumped into the pipe line of the lessee, purchaser, producer, or transporter, as required. There may be thousands of these run-down tanks of various sizes in a large oil field, and each is connected to some pipe-line gathering system. As the name implies, the function of a gathering system is to collect all of the oil with which it is concerned into a central storage plant, whence it may then be pumped through the main trunk lines to a tank farm, marine terminal, or refinery storage.

The whole system of pipe-line transportation and storage is under the immediate control of the dispatcher, who is familiar with the location of every tank, pipe line, and essential valve on the system and who is accountable for the various movements of oil. His responsibilities have been increased greatly in recent years by the practice of "slugging" crude oil and other products through the pipe lines on tender. Large individual shipments of oil (and gasoline in the case of gasoline pipe lines)[34] must reach their destination in proper condition and not become mixed with other shipments at either the terminals or at intermediate stations.

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[33] Another reason for having an adequate number of lease tanks is to provide for proper division of the oil produced among the operators and the fee or royalty owners. If both the royalty rights and surface rights of a given area were in the control of one party and the entire pool were operated under one management, a large number of lease tanks would not be needed.

[34] The dispatcher on a natural-gas transmission line also plays an important role, especially in winter when the load-factor problems are greatest and continued supply is essential to service.

NATURAL-GAS AND GASOLINE PIPE LINES

Natural-Gas Pipe Lines

As already noted, the construction of a pipe line, whether for the movement of oil, natural gas, or gasoline, requires attention to many of the same engineering and economic considerations. The development of gas pipe lines has been particularly important, however, for "there is only one way to transport natural gas and that is by pipe lines."[35]

The particular business of natural-gas transmission and distribution, although actually older than the oil industry itself, did not become important until after 1900. In fact, the extension of gas pipe lines and the rise of natural gas from local to national importance have been largely developments of the post-war period.[36] Through the first 2 decades of the present century production centered largely in the eastern States, and as late as 1921 two observers reported that production had shown no upward trend for a number of years and that "the industry has now probably reached its peak."[37] Less than $1\frac{1}{2}$ decades after this forecast the marketed production of natural gas had approximately quadrupled, and the geographic limits of its distribution had become almost Nation-wide.

Early problems in transmitting natural gas arose over difficulties in maintaining pressure. For example, the pressure at the well might be gauged, but the volume at the terminus was difficult to control. Moreover, gas pressure drops as the gas travels, and this raised technical problems of maintaining even pressures. The first deliveries of natural gas were completed without additional compression, as the gas was forced through the lines by the original well pressure; as the number of consumers increased and the line was extended, this proved an inadequate system of delivery. An important advance in the pipe-line movement of gas was introduction of the compressor to maintain desired

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[35] E. B. Swanson, "The Natural-Gas Invasion: An Example of the Sudden Expansion of Transport," *Mineral Economics: Lectures Under the Auspices of the Brookings Institution* (1st ed.; New York: McGraw-Hill Book Co., 1932), p. 98.

[36] G. R. Hopkins, H. S. Kennedy, and H. C. Fowler, "Memorandum Regarding the Natural-Gas Industry," *Relation of Holding Companies to Operating Companies in Power and Gas Affecting Control* (U. S. Congress, House of Representatives, House Report No. 827, 73d Cong., 2d sess., 1934), vol. 4, part 4, pp. VII-XXXIV.

[37] R. S. McBride and E. G. Sievers, "Natural Gas in 1919-1921," *Mineral Resources of the United States, 1921* (U. S. Dept. Int., Geol. Survey, 1924), part II, p. 339.

pressures in the pipe line. Another important advance was the introduction, about 1893, of a delivery regulator - a device that controlled the pressure at the point of delivery. Before this apparatus was developed, turning on the gas in the kitchen was an uncertain and sometimes hazardous operation that might produce a searing blast or possibly nothing at all.

Improvements in the technology of natural-gas pipe-line construction and operation closely paralleled similar developments in the crude-oil pipe-line field. Starting with wooden-box lines and hollow logs joined with iron sleeves or connectors, progress continued through the adoption of small screw lines and other types of jointed lines to the large, light, seamless, welded, high-pressure pipe employed today. Extensive losses due to leaks in early gas pipe lines were accepted as normal. In fact, the facility with which natural gas escaped from most types of joints was largely responsible for the introduction of the welded joint that is now standard for virtually all types of pipe lines.[38] Recent advances have been in the direction of increasing maximum length of line, increasing operating pressures, and paying greater attention to methods for obtaining maximum flow[39] and to the planning and operation of equipment so as to curtail interruptions in the movement of gas.

Gasoline Pipe Lines

In recent years there has been much activity in the construction of pipe lines for transporting gasoline.[40] This commodity, both natural and refinery gasoline, is pumped through lines similar in every respect to the ordinary crude-oil lines, but it must be stored in pressure tanks, as it is extremely volatile. For short distances it frequently is forced through the lines by air at low pressure. This particular commodity has a high solvent quality, hence the pumps must be equipped with special packing to prevent leaks and losses.

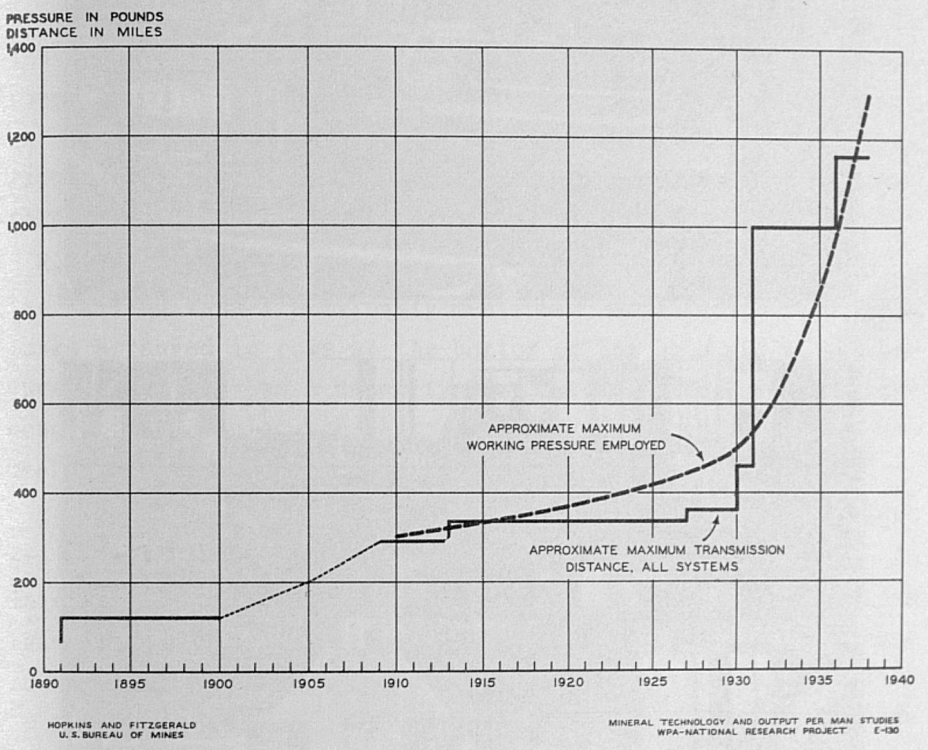
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[38] Hopkins, Kennedy, and Fowler, *loc. cit*; Federal Oil Conservation Board, *Report IV*, p. 13; and E. L. Rawlins and L. D. Wosk, *Leakage From High-Pressure Natural-Gas Transmission Lines* (U. S. Dept. Com., Bur. Mines, Bull. No. 265, 1928), p. 2.

[39] For example, the effect of condensates or rust scale in a pipe line may reduce the delivery capacity as much as 50 percent below the theoretical maximum. See report by T. W. Johnson and W. B. Berwald, *Flow of Natural Gas Through High-Pressure Transmission Lines* (New York: U. S. Dept. Int., Bur. Mines, Monograph 6, prepared in cooperation with the State of Oklahoma and the Natural-Gas Department of the American Gas Association, 1935), p. 84.

[40] For a concise recent discussion of the status of gasoline pipe lines see Splawn, *op. cit.*, pp. 54-5.

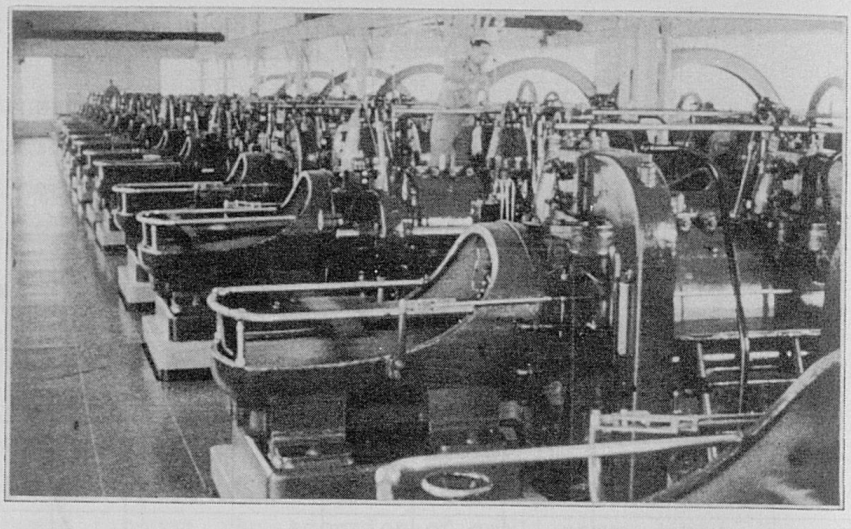
Figure 28.- INDICATORS OF TECHNICAL PROGRESS IN THE PIPE-LINE TRANSPORT OF NATURAL GAS

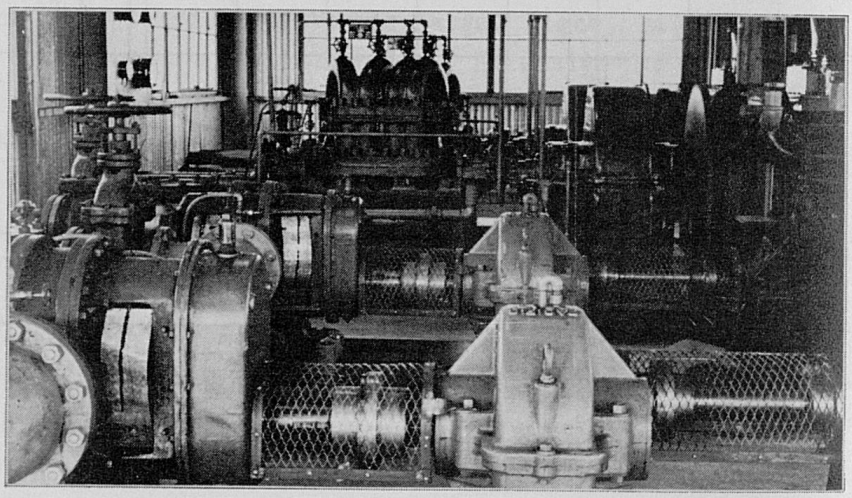


MARINE TRANSPORTATION

Reference has been made to the first attempts at water transportation at Oil Creek, Pennsylvania, in which crude barges were carried down to the Allegheny with some success. This inauspicious beginning, despite the difficulties noted, did prove the possibility of marine transportation. When the export business grew to substantial dimensions, therefore, considerable interest was shown in the movement of petroleum in ships. Export shipments were first made in barrels, but in 1869 the first sailing vessel equipped with tanks for bulk shipment arrived on the Atlantic coast. This ship was loaded successfully, and her cargo was discharged later without mishap in Europe. The success of the first tanker sped the building of others, and oil was moved at much lower freight rates than were formerly demanded by the shipping companies handling barrels. By 1885 the tank steamer had entered the transportation field,[41] representing a great improvement over the sailing vessels that were eventually displaced.

Footnote 41 appears on page 241.





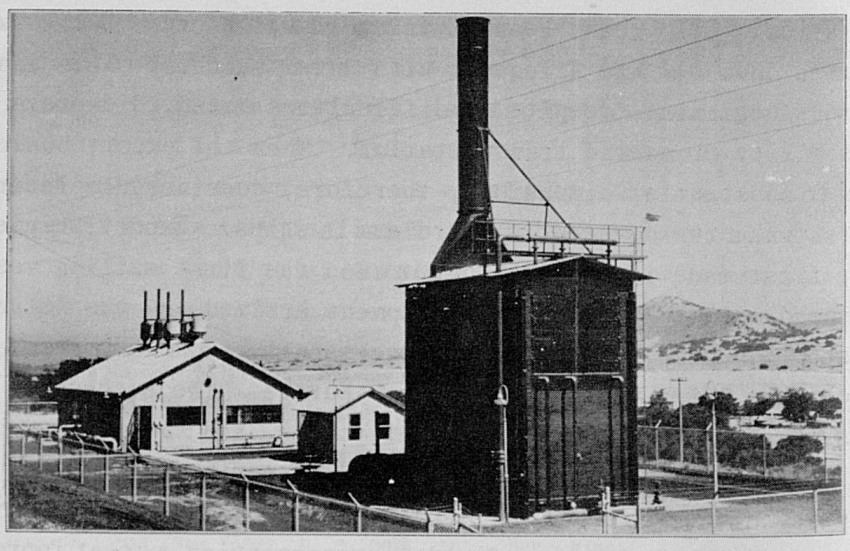


ILLUSTRATION 28.- PUMPING EQUIPMENT USED ON PIPE LINES

The upper view shows a battery of powerful compressors in a booster pumping station on a major, high-pressure, natural-gas pipe line. The middle view shows rotary pumps, driven by gas engines, in a pumping unit on an oil pipe line. This unit is housed in the pump station shown in the bottom view.

Improvements in Tanker Design

As already noted, oil was exported in barrels and wood-encased cans before tankers were available for bulk shipments. Thus, in 1885 the total exports of this type amounted to 5 million barrels compared with 40 thousand barrels shipped in bulk. Less than 12 years later the condition was completely reversed; annual exports in bulk increased to $11\frac{1}{2}$ million barrels, and "package" shipments dropped to 40 thousand barrels.[42]

Early tankers were of comparatively small capacity. The *Charles*, the sailing vessel previously mentioned, was fitted with 59 iron tanks arranged in rows at the bottom of her hold and in the between decks and had a capacity of 794 tons. There were no pipe connections joining the tanks, and leakage during the voyage was replaced by salt water to maintain the requisite balance.[43]

Since the early days many improvements in construction of tankers have meant greater and more efficient carrying of oil. As late as 1915 the average dead weight of bulk-oil steamers was less than 6,000 tons, but the European war stimulated a rapid increase in capacity and by 1924 the average dead-weight tonnage had risen to 10,000 tons.[44] Since that time development has continued; now fast, all-metal tankers, some of 20,000 tons dead weight, carry 50,000 to 170,000 barrels.

Increased speed and economy in tanker operation have come with the fairly recent introduction of welding in the larger vessels.

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[41]Various writers on tanker transportation do not agree as to the date of the first tank steamer used in oil transport, and this date has been variously set at 1866, 1872, 1878, and 1885. See Oscar H. Reinholt, *Oildom: Its Treasures and Tragedies* (Philadelphia, Pa.: David McKay Co., 1924), part I, p. 88; H. Barringer, "Oil, Transport, Storage and Distribution," *The Petroleum Industry* (London: The Institution of Petroleum Technologists, 1921), pp. 132-3, 136; and "Tanker Transportation Began in the Early 60s," *The Oil and Gas Journal*, Vol. 33, No. 14 (Aug. 23, 1934), p. 57.

Although accurate records for the earlier years seem to be lacking, it appears that the steam-tanker trade was under way by 1885, as suggested by the following observer: "The S.S. 'Vaderland,' built in 1872 . . . ., although by no means the first vessel to carry oil, was the first one to be actually built with tanks suitable for carrying oil in bulk, but whether she ever carried any oil appears doubtful. It is said that the owners feared to load her with petroleum lest her passenger bookings became affected. On the other hand, an unofficial and unpublished account stated that she actually carried a cargo of oil, but it seems scarcely possible that she could have done so without leaving some trace of the discharge of her cargo in the records of some port or the books of one of our pioneer companies. . . . . in 1885 the export of American oil was accomplished by over 1000 vessels, mostly foreign sailing ships . . . . . The first tank steamer to run in European waters was the S.S. 'Fergusons' in 1885. Her records included the first trip from England to Batoum for oil, and also the first run across the Atlantic for a cargo of American petroleum. It was about this time that it became recognised that steamers could be fitted up to carry oil in bulk by means of tanks, and the S.S. 'Gluckauf' was built." (M. Mitzakis, "Tank Steamers," *The Oil Encyclopedia* [New York: John Wiley & Sons, Inc., 1922], p. 471.)

[42]Reinholt, *loc. cit.*

[43]J. D. Henry, *Thirty-five Years of Oil Transport* (London: Bradbury Agnew and Co., Ltd., 1907), part I, p. 6.

[44]Reinholt, *op. cit.*, p. 89.

Smoother plates that result from such welding provide less opportunity for surface corrosion and permit easier cleaning of the interior of tanks. Welding further permits a decided reduction in the weight and hence enables greater efficiency and ease of operation.[45]

Just as steam engines replaced sails as a means of propulsion, so Diesel engines and motors with greater efficiency of operation are gradually replacing steam engines; oil fuel has been almost completely substituted for coal.

The old single hold in tankers gradually has changed, through a series of progressive steps, to a new system. Each vessel now has at least two sets of tanks, running fore and aft, and the cargo is divided by the centerboard into two equal quantities, assuring against a possible shift of cargo. All tanks are interconnected, and the load thus may be equalized easily at any time. Some of the tankers carry black oil (crude oil, fuel oil, etc.) exclusively. Some transport only refined products, such as gasoline and kerosene, and others are equipped with special tanks and lines so that they can carry several commodities at the same time. Cargoes are loaded and unloaded in an astonishingly short time, primarily because the carefully planned arrangement of pumps, lines, and receiving tanks facilitates the movement.

Movement by tanker is the cheapest method of transporting oil. Large oil companies own and maintain their own fleets of such tankers, and in 1938 there were 418 oil-tank ships (1,000 tons gross and upward) of American registry in operation, comprising 349 steamers and 69 motorships.[46] This does not include boats and barges operating on inland waterways, smaller ships in coastwise traffic, and tankers owned by Americans flying flags of other countries. In general, tanker rates have been lower than pipe-line tariffs. The principal effect of this situation has been to increase the tanker movement of petroleum and related products.

DEVELOPMENT OF STORAGE TECHNIQUES

In the petroleum industry transportation is closely related to storage. The pipe lines alone represent an enormous storage

[45] H. S. Norman, "Ocean Tankers, Inland Barges, Supplement Pipe Lines," *The Oil and Gas Journal*, Vol. 37, No. 19 (Sept. 22, 1938), p. 60.
[46] *Ibid.*

system, with a capacity of 40 million barrels.[47] There was, however, no especial need for any form of substantial bulk storage in the early days of the industry. Petroleum was produced in small quantities; the accumulation of this primary production occasionally mounted to dimensions that required small, crudely built tanks for storage, but in general, quantities were still low enough to obviate even that necessity.

With rapid development of the industry in the sixties, the era of the small container ended. An industry that a short time before required only an indiscriminate collection of small containers developed a demand for some 500,000 barrels or their equivalent. The need for storage facilities grew so rapidly that very soon even barrels were inadequate. The filling of barrels was, to begin with, expensive, and the demand for them was so great that they were difficult to find at any price. Hence there grew up the practice of storing oil in open pits or "sumps."

When ground storage was first resorted to, large, unknown quantities of oil were lost through seepage, but the ground pits sooner or later became sealed with a coating of asphaltic or paraffinic material that retarded losses from this cause. In addition to the loss through seepage, the method entails substantial dissipation of light constituents by evaporation. Sumps of this type continue to be used in cases of emergency for the salvage of oil from wells out of control or from pipe-line breaks. The practice of open "ground storage" of petroleum, however, is now recognized as wasteful and is rarely necessary. Today, if ample storage and pipe-line facilities are not available, the wells are usually produced at a reduced rate.

Growth of Tank Storage and Tank Farms

About the time the first small tanks were built and utilized by the producers, the petroleum industry was in a particularly favorable position in which the demand for its products greatly exceeded the supply. Succeeding years showed, however, that these conditions were not permanent. Price wars, overproduction, fluctuating demand, and other exigencies pointed to the advisability of creating enough storage to maintain a reserve supply and to hold excess output without undue loss until wanted. To do this

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[47] H. A. Osgood, "Transportation," *Technological Trends and National Policy* (National Resources Committee, June 1937), p. 197.

required large tanks, and such tanks were later grouped into the tank-farm systems that are now found common.

The transition from small to large wood tanks and from wood to metal was prompted by a number of obvious reasons. The metal tanks were made from thin steel or iron sheets that could be comparatively easily shaped, riveted, and caulked, so that they were much more easily manufactured than the prevailing wood variety with their multiple staves and tightly drawn hoops. In the wood tanks also, the staves, when not properly seasoned, tended to swell unevenly, particularly at the seams, or to shrink because of drying, causing leaks. The metal tanks could be moved more easily from one location to another, were better adapted to the connection of fittings for pipe lines, reduced the fire hazard, and in general promised a greater all-around efficiency. However, wood flow-tanks did not corrode, and for that reason many are still used in Texas Panhandle and West Texas fields, where oil is high in sulphur and hydrogen sulphide. In 1936 tanks with steel shells or walls represented 99.5 percent of the total tankage, the remaining storage capacity (3,308,000 barrels) comprising wood, concrete, and earthen types of tanks. (This excludes concrete tanks in California used to store heavy crude oil classed as fuel oil rather than crude, but includes other concrete tanks east of California, with a capacity of 2,535,000 barrels.)

A special type of oil-storage container was developed about 1914-15 and was quite popular for several years, particularly in California. Concrete-lined reservoirs of immense size were used, storing large volumes of heavy or corrosive oil obtained directly from the wells or from refineries. These were usually built in the form of large concrete bowls similar to many water reservoirs. Ordinarily they were covered with wood roofs and were protected against lightning by an ingenious system of lightning arrestors. The need for such protection is suggested by the fact that one California oil company had two such reservoirs, over 200 miles apart, fired by lightning on the same day. A more specific impression of the capacity of this type of container may be obtained by noting that one of them can store approximately 4 million barrels of crude oil or more oil than is produced currently in one day from all wells in the United States. Most of these reservoirs, however, are considerably smaller and hold 750 thousand to 2 million barrels. With a few possible excep-

tions, as in California, where these containers are well adapted for storing surplus low-gravity oils, their use is declining.

Metal tanks were made first with open tops, but like the wood tanks, they later were provided with roofs to prevent evaporation losses. As the industry grew, storage requirements became greater. The technique of tank manufacture was improved, and tank capacities increased rapidly. Iron and steel tanks that could store 5,000 barrels or more began to replace the wood containers, and in a few years changes in construction method brought about the manufacture of large tanks of continually increased capacity. About 1915-20, 55,000-barrel riveted tanks predominated, and later a number of 178,000-barrel steel tanks were erected. After the war the stimulus for storage construction continued, as there seemed to be indications of an impending shortage of oil.[48]

For reasons already indicated in chapter VI (pp. 162-3) the amount of oil produced beyond market needs and requiring storage has dropped following application of an increasing degree of production control in the industry during the past decade. A recent report of the U. S. Bureau of Mines[49] estimates that a minimum working stock requires approximately 105 million barrels and contingent reserves of about 100 million barrels, making a total necessary stock accumulation of about 205 million barrels. This same survey indicated that stocks are stored for a relatively long time, the weighted average age of all stocks, as of June 30, 1936, being about 3 years, although 12.5 percent of all the oil in storage at that time had been stored over 11 years.

Tank storage in the United States reached its peak about 1931, when the total capacity of storage tanks for crude oil was 620,505,000 barrels, exclusive of tanks for producers' (lease) stocks and tanks used in California for storage of heavy crude and fuel oil.[50] By June 30, 1936, the capacity had dropped 6 percent to 583,478,000; over the same period the number of crude-oil tanks dropped from 16,342 to 15,094. Of the total storage capacity reported in 1936, about 10 percent was represented by tankage at pipe-line stations, about 73 percent by tankage at tank farms, and the balance by storage facilities at refineries. Observers

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[48] H. C. Fowler and R. A. Cattell, "Influences of Petroleum Technology Upon Composite Interest in Oil," *Minerals Yearbook, 1935* (U. S. Dept. Int., Bur. Mines, 1935), p. 777.

[49] *Survey of Crude Oil in Storage, 1936-1937.*

[50] *Ibid.*, p. 35.

report that the total capacity of storage has declined still more since 1936, and it is interesting to note that on January 1, 1939, the total amount of domestic crude-oil stocks was about 272,000,000 barrels, indicating that only about one-half of the total tank-storage capacity reported for 1936 was in use. The shrinkage of stocks and the reduction of above-ground storage reflect the effect of forces tending to stabilize production activity in accord with current market requirements.

Reduction of Storage Losses

Important progress has been made in the reduction of losses from seepage, leakage, and evaporation of the lighter constituents (the last results in the reduction of quality as well as quantity of oil). The use of sumps and open-top tanks, for example, had resulted in the dissipation of incalculable quantities of light, easily volatilized constituents of crude petroleum. These losses, however, were not important because early in the industry gasoline was considered a waste product, and it was not desired to send to the refinery a crude oil containing light fractions having no commercial value. But, as the demand for motor fuel increased and gasoline became an important market factor, efforts were directed toward the reduction of storage losses. The staggering character of these losses by evaporation was brought forcibly to the attention of the petroleum industry as a result of a survey made by the U. S. Bureau of Mines after the war.[51]

Although the simple roofing of tanks to keep out rain and dirt and the housing of wood tanks to protect the staves from the drying action of the sun tended indirectly to reduce losses of oil in storage, it was not until the vaportight roof equipped with vacuum-relief and pressure-relief valves was introduced that constructive progress was made toward the reduction of evaporation losses. This was followed by the introduction of the water-sealed and water-sprayed tanks, in which the water was maintained in trays on the roof or sprayed over the tops of tanks. The evaporation of this water by the heat of the sun cooled the tanks and saved at least part of the volatile contents that otherwise would have been dissipated into the atmosphere. Although water-sealed and water-sprayed tanks, as well as insulation and other

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[51] J. H. Wiggins, *Evaporation Loss of Petroleum in the Mid-Continent Field* (U. S. Dept. Int., Bur. Mines, Bull. No. 200, 1922), 115 pp. Cf. also J. H. Wiggins, *Methods of Decreasing Evaporation Losses of Petroleum* (U. S. Dept. Int., Bur. Mines, Tech. Paper No. 319, 1923), 56 pp.

cooling mediums, contributed to the reduction of evaporation losses of crude oil, they have proved most profitable in gasoline storage and for that reason were usually used at refineries. Another effective measure was the maintenance of gastight or vaportight storage tanks at a low vacuum, so that evolved gases were constantly being drawn off to an absorption plant, where they were recovered and either returned to their original source at some convenient stage in the transportation system or sold as gasoline. Still another method for reducing loss and deterioration was the use of the floating-roof tank, in which the roof floats on the oil regardless of its level, thus eliminating the usual vapor-laden top space, from which diffusion of vapors to the atmosphere readily occurs. More recently different types of breather tanks have been evolved, contrived to eliminate or reduce evaporation losses.

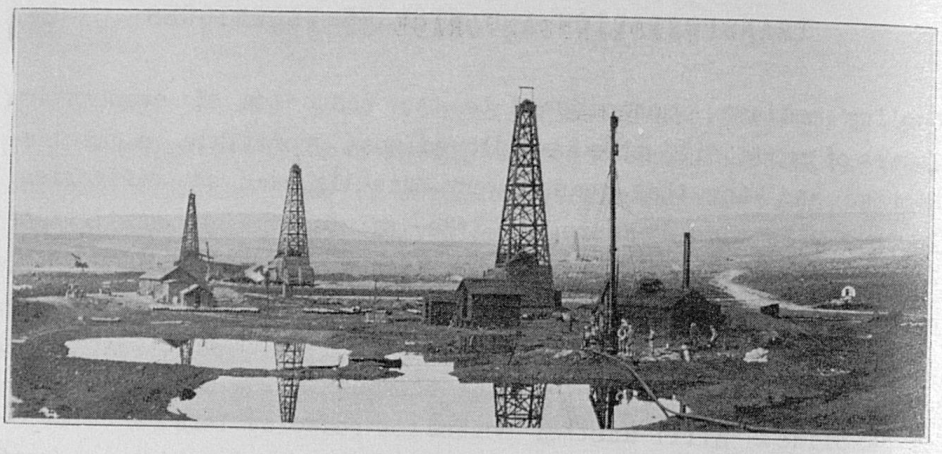
The use of vaportight tanks, painted in light colors, and of vacuum-relief and pressure-relief valves and floating roofs on working tanks in the last 2 decades has reduced evaporation losses appreciably in the gathering, transportation, and storage of petroleum and volatile refinery products. Although conservative estimates based on actual tests indicate that under conditions prevailing in 1931 the average evaporation losses of crude oil from the well to the refinery had been reduced from 6.2 percent in 1920 to 2 percent, losses by evaporation are still enormous.[52] For example, 2 percent of the annual crude-oil production classified as light oil represents an evaporation loss exceeding 19 million barrels. This volume is exclusive of the losses suffered by the evaporation of gasoline and other light refinery products in storage.

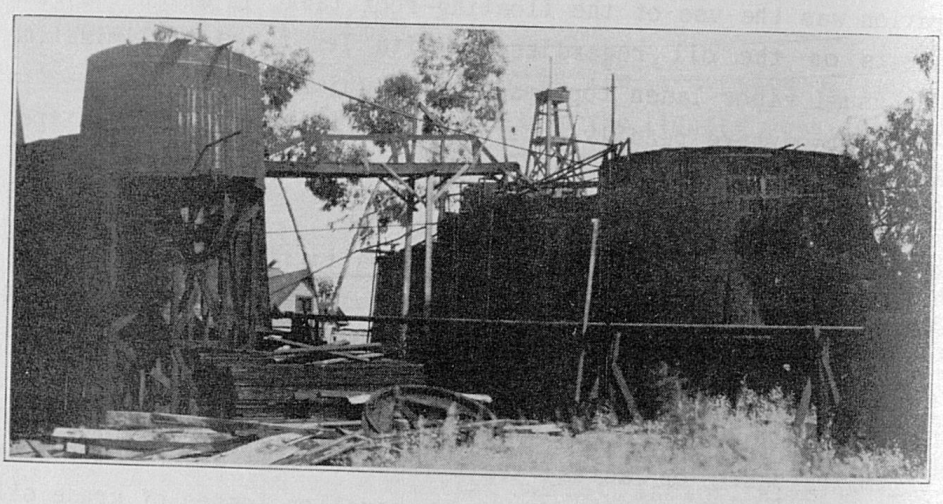
The storage of inflammable oils and of liquid refinery products involves a great fire hazard, and losses from fire have been appreciable in the history of the industry. An ingenious treatment of this particular problem is contrived by cooling exhaust gases - rich in carbon dioxide - from nearby boilers and conducting them to the top of the large storage containers.[53] The gas, being both inert and heavy, not only provides a blanket that acts as a fire preventive but also tends to reduce evaporation.

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[52] L. Schmidt, *Applied Methods and Equipment for Reducing Evaporation Losses of Petroleum and Gasoline* (U. S. Dept. Int., Bur. Mines, Bull. No. 379, 1934), p. 4.

[53] At least two California oil companies have used this system of preventing fires and reducing storage losses. The same system is employed on tankers, the flue gases being cooled and used as a blanket on the oil in the ship's tanks.





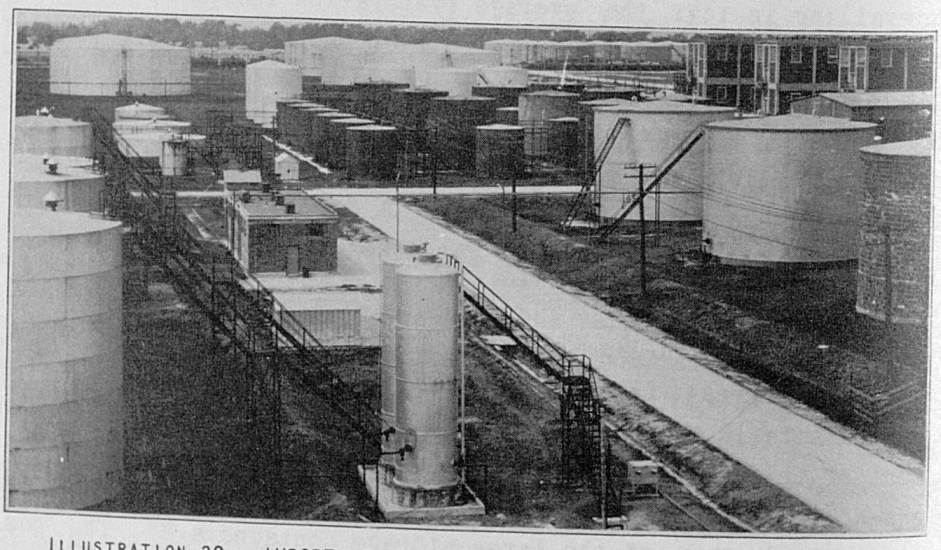


ILLUSTRATION 29.— IMPORTANT PROGRESS HAS BEEN MADE IN THE REDUCTION OF STORAGE LOSSES

In the early days of the industry, ground storage in open pits was widely resorted to and there were large losses because of seepage of oil into the ground and evaporation of the lighter constituents. Such open storage in an earth reservoir, shown in the upper view, is now generally recognized as wasteful and its use today is generally confined to emergencies. The middle view shows wooden storage tanks with open tops. The use of such equipment entailed losses due to leakage and evaporation, and the maintenance of the wood tanks represented considerable expense. The lower view shows modern metal storage tanks that are designed and equipped to keep storage losses at a minimum.

In general, fire losses have been held in check by providing adequate space between large containers and by surrounding them with impounding walls, so that if any of the vessels should be ignited the possibility of spreading fire is minimized. Development of suitable fire-fighting equipment, installation of preventive injectors at all large containers, and education of the industry's personnel as to safe and unsafe practices have also played important roles in reducing fire hazards.

Other Changes in Storage Practices

The corrosion of tanks and other storage equipment has been reduced by four general methods: (1) The development, by research, of anticorrosive surfacing materials; (2) the development and use of construction materials that resist particular corrosive agents encountered in specific situations; (3) the elimination of corrosive agents from the stored materials when possible; and (4) the blending of various raw materials with each other in the proportions requisite to produce noncorroding concentrations, even though corrosive agents are present.

Changing technology has been accompanied by modifications in storage practice. In the oil fields, for example, the necessity of receiving freshly produced oil in tanks at or near the wells - for the purpose of measuring production - is slowly being eliminated by the introduction of pipe-line meters that measure the quantity of oil coming from each well (see pp. 146-7). This permits oil to be pumped directly from the wells to larger centralized storage plants and greatly reduces the work of the oil gauger and the pumper. Another change that is affecting storage procedures is the practice of dewatering crude oil in bulk by electric dehydrators or by the injection of demulsifying agents in the tubing or flow lines at the wells, with subsequent separation of water by automatic means. All flow tanks on leases in which water is produced with the crude oil are equipped with siphons that regulate the height of oil and water in the flow tank, making it unnecessary for the pumper to stand and watch the water draw off. By way of explanation, it should be pointed out that water and oil form a dangerous mixture in a high-temperature still, and consequently it is desirable (and compulsory within limits) to remove as much water as possible from the crude oil before it is pumped into the main lines that lead to the refinery.

Fluctuating or changing demand for various types of crude oil also required some modification of storage arrangements. Progress in automobile design, for example, led to the gathering in some regions of large quantities of crude oil from which an antiknock fuel can be manufactured readily; this required rearrangement of storage plans in many quarters. The sudden discovery of a new and prolific producing field, adjacent to one already established, may also throw the storage system awry. In addition, the task of transporting a new type of crude oil through a pipe line that has been handling some other type presents many problems.

The advances that have been described in connection with the development of major bulk-tank storage facilities have also been adopted at oil-field storage plants, at pipe-line stations, and at refineries. Progress has continuously favored larger, more efficient tanks, sufficient in number to segregate the various types of crude, and large enough to hold adequate auxiliary stocks to satisfy peak demands.

Pumping through trunk lines generally is conducted in stages. The stations are placed at strategic intervals along the line, and each must have its own storage plant. The development of storage facilities in these intermediate stations has been toward larger, stronger, safer, and more economical tankage.

Refinery storage has followed the same trend. The variety of products handled makes the segregation of commodities more complicated than where crude oil only is handled. Meters, automatic gauging devices, and even automatic testers have been responsible for notable reductions in manpower to handle a unit quantity of oil. Closed containers and breather systems keep losses relatively low. In recent years evaporation losses at refineries have been reduced from 2.1 percent of the crude run to stills to approximately 1.5 percent.[54]

The same improvements have been made in marketing-area storage. Usually the storage of refined products requires less bulk capacity than crude-oil storage, but the tendency is toward greater-capacity containers and automatic measuring and delivery systems.

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[54] See statement of L. Schmidt, Petroleum Engineer, U. S. Bureau of Mines, Bartlesville, Oklahoma, *Petroleum Investigation* (U. S. Congress, House of Representatives, Hearings on H. Res. 441, 73d Cong., Recess, 1934), part 3, pp. 1950-4.

ADVANCES IN TRANSPORTATION AND STORAGE TECHNIQUES TO CONTINUE

Although no revolutionary changes are in prospect for the immediate future, past trends toward more efficient transportation and storage techniques appear likely to continue. The present tendency is in the direction of more complete mechanization of equipment and more efficient operation that has been noted since the early days. Van Syckel's three pumps could "work all day and all night" and do the work of 300 teams working 10 hours a day.[55] Writing before 1890, Samuel B. MacDonnell said:

> Like all new inventions, the tank steamships have deprived thousands of men of employment. The gangs of stevedores who for years made good wages loading vessels with cases and barrels are not in it now; the tanker is loaded through a pipe. Coopers are in no demand for the making of barrels; the tanks are iron and are permanent. Dunnage wood dealers cannot sell their cordwood to keep the cargo from shifting; the tanks are built secure. Ballast dealers are not needed, for when unloaded the tanks are filled with water. Ship brokers are useless, the shippers owning their own carriers . . . . . The tank steamship is the greatest invention afloat.[56]

In like manner, the small, open-top wood tub of the early days has changed to the huge tank farm with its automatic valves, gauges, and measuring devices that obviate hundreds of incidental operations and greatly curtail manual effort. Similarly, a single modern tanker with a crew of 10 to 12 men can carry as much oil (100,000 barrels or more) as could an entire fleet in the early days. A train of tank cars with two men aboard can perform the work of thousands of teamsters, and pipe lines are even more efficient. The long-time tendency has been definitely toward reduction of maintenance and operating costs and toward equipment and arrangements that required less human energy - and particularly less physical labor.

Effect of Technical Improvements on Employment

To indicate the possible effect of technical improvements upon employment is difficult because there are many different factors for which quantitative information is incomplete. Nevertheless,

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[55] *The Derrick's Hand-Book of Petroleum*, p. 52.
[56] *Ibid.*, p. 1024.

the data available are enough to show that the influences making for less employment in the transportation and storage phase of the industry seem to outweigh those making for greater employment.

It does not appear probable that in the immediate future employment on pipe lines, for example, will exceed the levels of the late twenties. Pipe-line employment, it should be noted, falls into two classes - workers engaged in the construction of lines and pumping stations and those employed in the actual movement of oil or gas, including the maintenance of equipment. Employment in the first class is intermittent in the sense that the reconditioning of old lines and the construction of new ones may be postponed. Moreover, in times of even ordinary activity this type of employment may involve many times more workers than are required in the regular operating activities.[57] Since the pipe-line system of the Nation is now fairly well completed, no boom in construction activity appears imminent during the next decade.[58] It is true that new gasoline lines will be built, but this development - although interesting - will not make up for the lack of major construction of long-distance, large-diameter oil and gas lines.

Although it seems that construction in the immediate future will be limited largely to moderate extensions, to replacements, and to the addition of gasoline lines, at the same time employment opportunities are not increasing in other branches of the pipe-line service. The net result of more efficient equipment has been to reduce the labor required for maintenance and for operation. As the remaining older stations, moreover, are replaced with the newer automatic and semiautomatic equipment, still fewer workers will be required. Notably larger quantities of oil probably will continue to be moved, with no corresponding increase in labor outlay.

Although employees in oil tankers probably are more correctly classified as maritime workers than as employees related directly to the oil industry, it is interesting to note that tank ships are already efficient pieces of machinery and that future employment

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[57] National Youth Administration of Texas, J. C. Kellam, Director, *Employment Opportunities in the Oil Industry in Texas* (Austin, Tex.: Industrial Study No. 1, mimeo., Sept. 1, 1938), pp. 45, 49.

[58] For example, it is reported that in the important State of Texas, accounting for more than one-third of the Nation's petroleum production, "the present mileage of the Texas trunk pipe line system appears adequate to serve the known and prospective oil producing areas of the State. If a new field should be found, its output soon could be turned into the present system with the addition of some miles of a gathering line. Therefore, pipe line construction employment is not to be anticipated hereafter on a large scale or on more than a temporary basis." (*Ibid.*, p. 43.)

on such ships depends more upon the quantity of oil available for movement by water than upon possible further technical improvements in ship design and operation.

The number of men required for the storage of petroleum and petroleum products probably will not increase and may decline, since the need for storage has decreased with effective production control and since technologic advances in storage practice have tended to reduce the number of men needed in relation to a given volume of oil. The effect of automatic regulating and control devices is illustrated by the relatively large storage capacity of a typical tank farm and the almost complete absence of workers. Where once many men were busy gauging tanks, switching gates, operating pumps, and doing maintenance work, now a few men read some instruments and press some buttons, and the various tasks are performed quickly and without confusion. Even at the less modern farms equipped with steam pumps, one engineer, a fireman, and an assistant on each shift are frequently the entire labor force. The present trend is toward more completely automatic stations requiring even fewer men.

The factors that retard an increase in employment opportunities in pipe-line construction and operation and in storage activities may be offset in part by a further shortening of the workday and the workweek, although the average workweek for operating employees of major companies apparently has been about 40 hours for some time.[59] It should also be noted that when a large number of plants are at least semiautomatic, as they are today, the opportunities for making large relative reductions in employment are not so great as they were 10 years ago. Moreover, although the total number of jobs available may not increase or may even decline, there is urgent need for more highly skilled workers. In addition, mechanical, electrical, and chemical engineers who can still further advance the process of simplification, economy of operation, and more complete mechanization will be required. Although lack of data prevents a more detailed and definite appraisal of future employment opportunities, other future trends that appear likely are increased shipment of gasoline by pipe lines, a continuation of low transportation costs for oil per barrel-mile, and an increase in the quantity of oil, gas, and gasoline moved per man employed.

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[59] Calculated for 1937 from "Progress Continues in Accident Prevention Work; Fatality Rate Far Below U. S. Average," *American Petroleum Institute Quarterly*, Vol. 8, No. 2 (Apr. 1938), p. 27.

CHAPTER X

TECHNICAL ADVANCES IN REFINING*

Matching strides with progress in the production and transportation branches of the oil and gas industry have been the technical advances in refining. It is true that, measured by the volume of crude oil run to stills, the output per man-hour at refineries shows a somewhat less spectacular upward trend than in primary production (see figure 5). But, as indicated in chapter II, throughput per man is an imperfect yardstick for measuring the performance of the refineries because it makes no allowance for the increasing number of refinery products and improvements in their quality.[1] If appropriate weight were given to these factors, the gains would be much more striking, for refinery technology has heaped one improvement upon another during the past quarter-century.

Like the production branch of the industry, petroleum refining started with a generous heritage from an older technology. As early as 1846 Dr. Abraham Gesner laid the groundwork for the industry with the development of a process for distilling an illuminating oil from coal.[2] Because of the growing scarcity and high prices of sperm oil, the process quickly spread and, when the first oil well was drilled in 1859, coal distillation was a flourishing industry in the United States. Since the basic principles of the coal-distillation process were readily adaptable to oil refining, many of the coal-oil refineries were converted into petroleum refineries when abundant petroleum supplies became available.[3] Although records show that petroleum was distilled in Russia as early as 1735, the first commercial refinery designed solely to handle petroleum was constructed and operated

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*By Boyd Guthrie, Associate Chemist, U. S. Bureau of Mines, Bartlesville, Oklahoma; Herbert Schimmel, Research Engineer, and J. C. Albright, Special Consultant, WPA National Research Project; H. O. Rogers; and J. S. Ross.

[1]Besides gasoline, lubricants, and fuel oils, petroleum refineries manufacture, or have processes for the manufacture of, many commodities that enter into our everyday use. These include candles, paints and lacquers, preservatives, solvents, chemicals, medicinal and pharmaceutical supplies, dyestuffs, perfumes, and many other products. A more complete list may be found in the *National Petroleum News*, Vol. 28, No. 6 (Feb. 5, 1936), p. 296.

[2]R. F. Bacon and W. A. Hamor, *The American Petroleum Industry* (1st ed.; New York: McGraw-Hill Book Co., 1916), I, 206; *The Encyclopedia Americana* (New York: Americana Corp., 1938), XII, 626.

[3]Bacon and Hamor, *op. cit.*, p. 211.

by William Barnsdall and William H. Abbott in 1860 at Titusville, Pennsylvania.[4]

THE CRUDE BEGINNINGS

In its most elementary form petroleum refining consists in heating the raw oil to its boiling point in stills and allowing the vapors to pass through condensing tubes, a process that had been used for many hundreds of years in the distillation of other liquids. As demand throughout the early years of the industry's history was primarily for kerosene as an illuminating oil, the primitive process of distillation served well enough, and advances in technology were notably lacking.

During the boom days that followed the discovery of oil most of the refineries were built near the source of supply, along the banks of Oil Creek from Titusville to Oil City, Pennsylvania. In the succeeding 20 years, however, the business spread to larger towns and cities, the largest plants being constructed near Cleveland, Ohio; Pittsburgh and Erie, Pennsylvania; and along the Atlantic seaboard.

The Batch Era

The size and capacity of the early refineries varied over a wide range. Some plants consisted of one small vessel capable of processing only a few barrels of oil a day, but other plants had several small vessels or a large one in which several hundred barrels could be distilled in the same length of time. Regardless of capacity and size of vessels, all refineries of the pioneer era utilized the batch system of operation and the simple distillation methods that had been known for hundreds of years. The stills were of two general types, one using a horizontal cylinder called a "shell" still and the other a short, vertical, large-diameter cylinder having a flat bottom and a cone-shaped top, called a "cheese-box" still.

Both types of stills were supported on brick walls forming an enclosed space beneath the vessels that served as a combustion chamber for the fuel. As the shell stills were laid in a horizontal position on the supporting walls, only one firing space was provided, but the cheese-box stills were set vertically on

[4] W. L. Nelson, *Petroleum Refinery Engineering* (1st ed.; New York: McGraw-Hill Book Co., 1936), p. 5.

segmented walls, each segment forming a separate combustion space for burning fuel. Due to its firing versatility, the cheese-box still was perhaps the more popular, and lubricating oils were distilled almost exclusively in this type of apparatus.

The early refiners used different fuels, including coal, wood, oil, gas, and often the residuum left in the stills after kerosene had been distilled. Gas, which was produced by many of the oil wells, was used for fuel by many plants because firing was controlled more easily.

Under the operating methods that prevailed during the early days a charge of oil was placed in the stills and processed as a batch, requiring 12 to 36 hours to complete the distillation. Heat was applied to the still slowly and the temperature was carried high enough to distill all of the kerosene fractions from the crude oil. The rate of distillation was controlled by the intensity of the fires in the combustion chamber, which was fitted with simple, manual controls and required constant attention of the operators until distillation was completed.

Both types of stills were equipped with suitable vapor draw-off lines, always attached to an opening at the highest point of the vessel. These vapor lines led to a worm (spiral-tube condenser) submerged in a vat of cool water, either flowing through the vessel from a nearby stream or pumped in at a constant rate. It was possible to vary the amount of water flowing through the vessel; this, in turn, controlled the amount of liquefaction into raw kerosene of the vapors that were flowing from the still.

To produce kerosene by this method an attempt was first made to vaporize and condense the lighter and more volatile products. A considerable amount of the latter, however, was condensed with the raw kerosene that required a primary treatment, called weathering, to remove the highly inflammable hydrocarbons before the kerosene could be used as an illuminating oil. In general, the method used to remove the undesirable light material was to place the raw kerosene in open-topped containers and expose it to the air. The time required to evaporate the light fractions varied considerably, but the degree of their removal could be tested roughly by determining the specific gravity of the remaining product.

Because of the lack of engineering and chemical knowledge, coupled with crude refining technique, the kerosene produced was

frequently inconsistent in quality and had an offensive odor. To overcome these disadvantages, A. C. Ferris developed a chemical method of treatment.[5] This method involved agitating the weathered kerosene with sulphuric acid, allowing the mixture to settle, and withdrawing the acid sludge, immediately following with a wash of cold water. The kerosene was then agitated with a hot caustic-soda solution followed with a second water wash after the caustic sludge was drained from the vessel. This treatment, with minor variations, has been used for treating both kerosene and gasoline until the present.

DEVELOPMENTS DURING TRANSITIONAL PERIOD

Although the basic technology of petroleum refining remained virtually unchanged for years, a number of modifications in the manufacturing processes that had an important bearing on labor requirements were effected after the first decade of the industry's history. One significant development was the adoption of larger-capacity stills. Experience gained during the pioneer period had definitely proved that stills of much larger capacity could be operated as efficiently as the smaller vessels with little or no increase in labor requirements. Consequently, from the late seventies onward, the tendency was to increase the size of the stills and to group them in batteries.

Beginning of Continuous Distillation

More important than the increase in still capacities was the change to the system of continuous distillation. Although the principles of continuous operation were known as early as 1860,[6] a completely successful continuous plant was not in operation until 1899[7] and it was not until early in the present century that the system was generally accepted.

The continuous system involved moving the fluid charge in an uninterrupted stream through a series of shell stills where progressively higher temperatures were attained. The lightest hydrocarbons, corresponding to what is known today as gasoline, were distilled from the first still, and the residue oil was run

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[5] *The Derrick's Hand-Book of Petroleum: Petroleum Developments From 1859 to 1898* (Oil City, Pa.: Derrick Publishing Co., 1898), p. 1016.

[6] Nelson, *loc. cit.*

[7] Bacon and Hamor, *op. cit.*, II, 533-5.

to the next still where (due to the increased temperature) the kerosene was removed. As the remaining charge flowed through the next and succeeding stills - where it boiled at progressively higher temperatures - lubricating oils and other heavier fractions were obtained until all the desired products were recovered. To obtain continuous flow by gravity, the stills in the battery were erected in receding elevation or, if built on grade, they were connected by lines that left the stills at regular decreasing levels. In some later practices the first still in the battery was not fired, the crude-oil charge being heated by heat exchange with the residue from the last still in the series. In this way, the first still acted primarily as a dehydrator, distilling light naphtha with the water. Development of the continuous process was the first major improvement in refining technique.

Improvements in Steam Distillation

Distillation by the use of steam was practiced early in the industry[8] to reduce decomposition of the oil and to improve the quality of the oil distillates. Steam distillation was advantageous because introduction of steam into the body of heated oil caused the constituents to vaporize at temperatures below their normal boiling points. In this process, "dry" steam was introduced by means of a coil or branched pipe so perforated that the steam was directed upon the bottom of the still, thus preventing the oil from becoming damaged through overheating from contact with the bottom of the still. Not only could an increase in the quality of the distilled products be obtained, but also finer separation among some of the fractions could be made without destroying their value. Both the steam and hydrocarbon vapors distilled from the charge were condensed in the cooling sections, and the water was separated from the oil by taking advantage of their immiscibility. The accumulation of water in the bottom of the separators was drained periodically by the stillmen and their helpers.

As the capacity of the distilling plants was increased by arranging the stills in batteries and employing continuous distillation, larger volumes of materials requiring chemical treatment were produced. To accommodate this increase, treating vessels were improved in design, with mechanical agitators built larger

[8] Ibid., p. 457.

and with conical bottoms to facilitate collection and withdrawal of acid and caustic sludges. Eventually compressed air replaced other means of agitation, and the time required to process a batch of kerosene or lubricating oil was reduced.

Growing Recognition of Petroleum's Potentialities

During the first 25 years of petroleum refining, there was little or no demand for products other than kerosene.[9] Throughout this period animal and vegetable fats held the market for lubricants in a firm grip. The possibilities of producing good lubricants by further distilling the residual oil left after the removal of the kerosene, however, were recognized almost from the beginning. This potentiality was confirmed by investigation; despite consumer resistance, mineral oils made gradual inroads in the market for lubricants. The paraffin-base lubricating oils from Pennsylvania gained a particularly favorable reputation and they were rapidly adopted after 1885.

Prior to 1900, with few exceptions, all lubricants were made from crude oils produced in the Appalachian districts. After that time, however, the refiners in the Mid-Continent area and California started processing lubricants from crude oils of those fields. Because of the difference in characteristics of the crude oils from the Appalachian, Mid-Continent, and California districts, the processes used by refiners in these different localities varied.

Following the developments in the processing of lubricants, the refiners, especially in the Mid-Continent and California, sought profitable outlets for the residual oils that previously had been wasted or used for fuel. Petroleum coke was found to have commercial possibilities as a fuel, and many refineries in certain localities carried on a business in this product. Road oils and asphalts were commodities of another type derived from distillation; these developed commercial possibilities as road-building materials.

Most important, the internal-combustion engine created a market for the first fraction distilled from the crude oil. As a result, the light hydrocarbon products that had formerly been wasted soon

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[9] E. DeGolyer, N. Robinson, R. Hardwicke, and M. W. Watkins, "Organization of Production, Refining, and Distribution of Petroleum and Petroleum Products," *Transactions of the Third World Power Conference* (Washington, D. C.: 1936), Vol. IV, Sec. II, Paper No. 5 (U. S. A.), p. 168.

became a valuable byproduct. Kerosene, however, remained the principal product of the refineries until well after 1900.

CRACKING AND ACCOMPANIMENTS

During the early years of the present century no major improvements were made in the technical processes of refining. Throughout this period the refiners devoted their efforts mainly to the enlargement of their plants and the erection of new plants to meet the growing demand for petroleum products, while improvements of design and new methods of processing had secondary importance. The shell still, arranged in series suitable for progressive or continuous distillation, continued to be the prevailing unit and process. The use of steam in the production of heavy distillates had become virtually universal, and very few dry distillations were carried on. Residual oils, petroleum coke, and natural gas were fast supplanting coal and wood as fuels for heating stills and boilers, and, wherever possible, firing operations were mechanized. Mechanical firing, the use of larger stills, and the grouping of units into efficient operating batteries, along with the mechanization of certain distilling operations, resulted in substantial labor savings.

Some improvement had been made in condensers, but the equipment found at the majority of refineries early in the century consisted of many coils of pipe, arranged in banks submerged in the condenser boxes. The use of heat exchangers to conserve and reduce costs of cooling vapors and distillate probably was furthest advanced in California topping plants.[10] The exchangers passed the hot residuum from the last still through piping, in which were installed other pipes with smaller diameter which carried the cold crude oil to the first still. This application resulted in a saving in fuel, as it often eliminated the necessity of firing the first still in the battery.

The cheese-box device was still preferred for the production of lubricating oils because the multiple-firing chambers made possible easier control over distillation. When lubricants were manufactured, both in the shell and cheese-box stills, steam was used extensively.

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[10] J. M. Wadsworth, *Removal of the Lighter Hydrocarbons From Petroleum by Continuous Distillation, With Especial Reference to Plants in California* (1st ed.; U. S. Dept. Int., Bur. Mines, Bull. No. 162, Oct. 1919), 162 pp.

Changing Character of Demand

The adaptation of internal-combustion engines to transportation began in the nineties, but it was not until about 1905 that the possibilities of motor transportation were definitely established and the manufacture of automobiles began to be a factor in American industry. With the advent of the automobile, the demand for gasoline and lubricating oils increased by leaps and bounds. At the same time, electricity was fast supplanting kerosene and gas as an illuminant. As a result of these changes, the kind and quantity of major refinery products were materially altered: the manufacture of gasoline became the principal concern of the refiners, and kerosene rapidly dwindled in relative importance.

The increased use of the automobile, moreover, created a demand for improved highways, opening a market for asphalt. Processes were developed to reduce the asphalt in special stills that required blowing with air while heating. In this type of equipment were made oils adaptable for waterproofing roofs as well as those suitable for road building. Many asphalt products, differing in particular specifications, were manufactured from the same basic type of crude oil.

Refining Technology Revolutionized by Cracking

That the heavy hydrocarbon molecules could be broken into lighter fractions by the application of comparatively high temperatures - the basic principle of cracking - was known from the early days of the refinery.[11] Advantage was not taken of this knowledge, however, until just before the outbreak of the World War, when refiners faced the possibility of being unable to keep pace with the rapidly expanding market for motor fuel. Spurred by the prospects of a shortage of motor fuel, numerous investigations were undertaken, and a commercial cracking process was developed by W. M. Burton of the Standard Oil Company of Indiana. Burton's process was introduced about 1913 and remained the principal method until after the World War.

In the early days most cracking stills operated on gas-oil. As the cracking units were improved and became capable of withstanding higher temperatures and pressures and as cracking technique

[11] H. S. Bell, *American Petroleum Refining* (2d ed.; New York: D. Van Nostrand Co., Inc., 1930), p. 249.

became more advanced, more and more kinds of oil were charged. Finally, even crude oil was used in cracking stills in appreciable quantities, and combination units were designed that combined straight distillation and cracking.

At first cracked gasoline was regarded as distinctly inferior in quality to that derived by ordinary distillation.[12] It was not long, however, before it was discovered that the cracking process not only doubled the quantity of gasoline available from a barrel of crude oil but also vastly improved the quality of the product.

Development of Pipe Stills

The appearance of the tube or pipe still in 1911 was the first radical departure from the conventional shell-still distillation process.[13] The design of the tube or pipe still differed sharply from that of the shell still in that the earliest units consisted of large pipe through which the oil circulated before entering a vessel known as an evaporator. The tubes through which the oil passed were enclosed in a furnace where for the first time the radiant as well as the convection heat from the fuel was utilized to heat the charge. The evaporating vessel was heated by the flue gases. Even though the tube or pipe stills offered great possibilities in distillation processes, their general development and adoption in the industry did not come until a decade later, when improvements in metallurgy provided pipe and fittings better able to withstand the severe conditions of service.

In the early pipe stills the tubes were large in diameter and the oil was pumped through them slowly. The action of heat at local points in these tubes caused deposition of foreign matter, such as sand, silt, dust, and salt, as well as coke from decomposition of the oil, which caused rapid deterioration of the pipe and shortened its life. Cleaning was necessarily frequent and, as the tubes were joined to each other at the ends to form a compact bundle when surrounded by the combustion chamber, it was necessary to remove the tubes completely each time a still was closed for cleaning.

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[12] G. Egloff and E. F. Nelson, *The Modern Cracking Process* (Chicago: Universal Oil Products Co., Booklet No. 186, 1936), p. 6.

[13] F. H. Garner, "Distillation," *Petroleum - Twenty-Five Years Retrospect, 1910-1935* (London: Institution of Petroleum Technologists, 1935), pp. 80-2.

It was soon discovered, however, that greater velocity of the oil through the pipes of a tube still would reduce the formation of deposits of coke, crystalline salt, and other foreign matter. Thereafter the stills were constructed with pipes of an inside diameter as small as 4 inches. Contemporary investigators devised a type of connection for joining the ends of the pipes in the still that facilitated cleaning by the removal of plugs fitted to openings in these connections. As this type of tube still came into general use, it was built as a more permanent unit and could be operated longer without dismantling.

With the introduction of cracking, the pipe still became the principal unit for heating the oil being processed, and alloys that would withstand long exposure to high pressures and temperatures without breaking down were produced for tube manufacture. Furnaces were continually redesigned until they were built so that an even input of heat could be obtained over the full length of the tubes with a minimum of firing. Refractories were developed to line these furnaces so that heat losses by radiation from outside walls were reduced and the heat was more effectively centered on the tubes.

Because of the continuity of processing and the greater volumes of oil that could be refined, pipe stills began to press shell stills for leadership. As pipe stills became more flexible, due to added improvements in tube length and diameter and in distribution of the tubes in the furnace, they were used for the primary or first distillation of the crude oil as well as in cracking plants. The amount of oil that could be processed with the aid of tube stills was many times greater than for any battery of shell stills in operation at this time.

Introduction of the Fractionating Tower

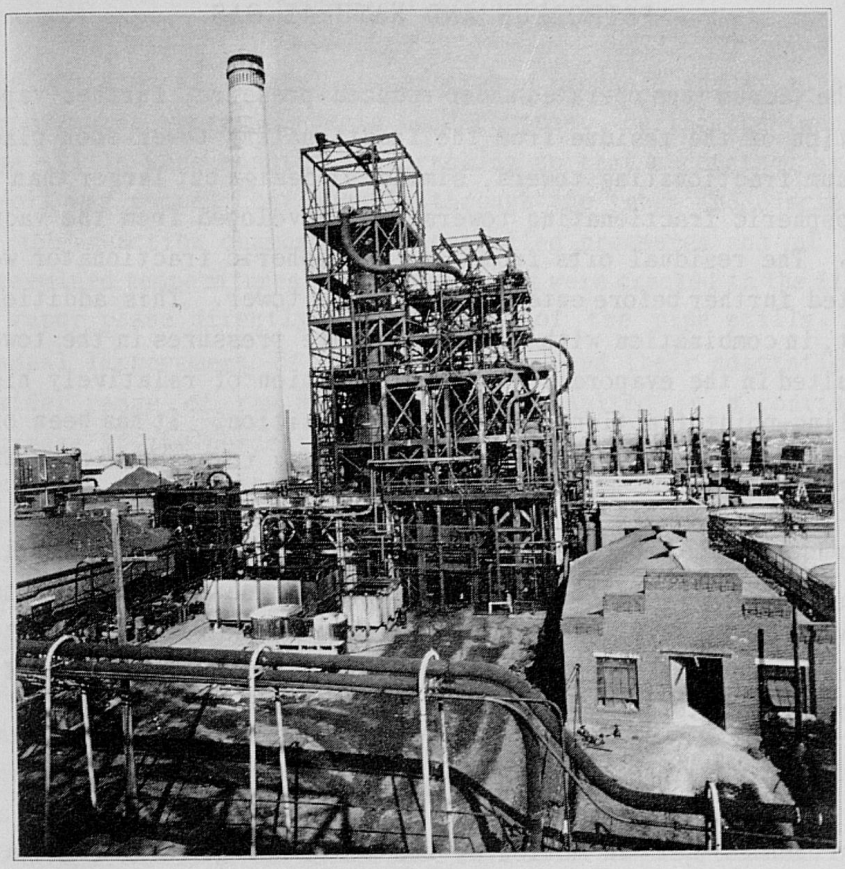
About the same time the pipe still was being developed the petroleum-refining industry adapted the fractionating tower, which was eventually to serve in conjunction with the pipe still as the predominant type of equipment employed for continuous distillation. These fractionating towers, already known to the chemical industry, were introduced to meet the demand for more accurate separation of one product of distillation from another. Prior to their use the products that were condensed directly from the stills included a wide range of hydrocarbons and had to be

redistilled several times or weathered to meet the increasingly stringent specifications of consumers. With the fractionating tower it was possible to make these accurate separations in a single step.

In the process of fractionation the heated fluid from the still enters the tower, where ascending vapors are scrubbed by a descending flow of liquid. The lowest-boiling-point material is drawn off at the top of the tower, while the heaviest material is removed at the bottom. A number of additional fractions are drawn off at intermediate points. The success of this method of operation depends on the intimate mixing of the ascending vapors and the descending liquids. At first, columns packed with stones or any other material that would break the flow of vapors were used. From the beginning, however, the most popular type of equipment was the bubble tower. This type of fractionating tower was fitted internally with many trays placed one above the other. Each tray held a layer of liquid oil and the rising vapors bubbled through this liquid. From the outset the use of the fractionating tower proved a tremendous advantage in the processing of petroleum, as it eliminated the need for numerous distillations or the even more undesirable method of weathering products to meet trade requirements.

To achieve the potential precision of separation made possible by the fractionating tower, operating temperatures and pressures had to be carefully controlled. Regulation of the temperature at the top of the tower was particularly important, and instruments were employed for this purpose; when temperature changes were required the material was either refluxed by the use of internal condensers or liquid from the side streams was pumped in at the top of the tower.

It was found that, in the operation of the fractionating tower, the number of trays had a direct relationship to the degree of fractionation and the quality of the products. Moreover, as the number of trays was increased there was an increase in the pressure difference between the bottom and top of the tower. This pressure differential controlled the amount of product recoverable from the charging stock for any given degree of heat. To overcome the pressure drop and to vaporize still more from the residue of these towers, so-called vacuum jugs were developed into which the hot residue from the fractionating tower was flashed. Inasmuch



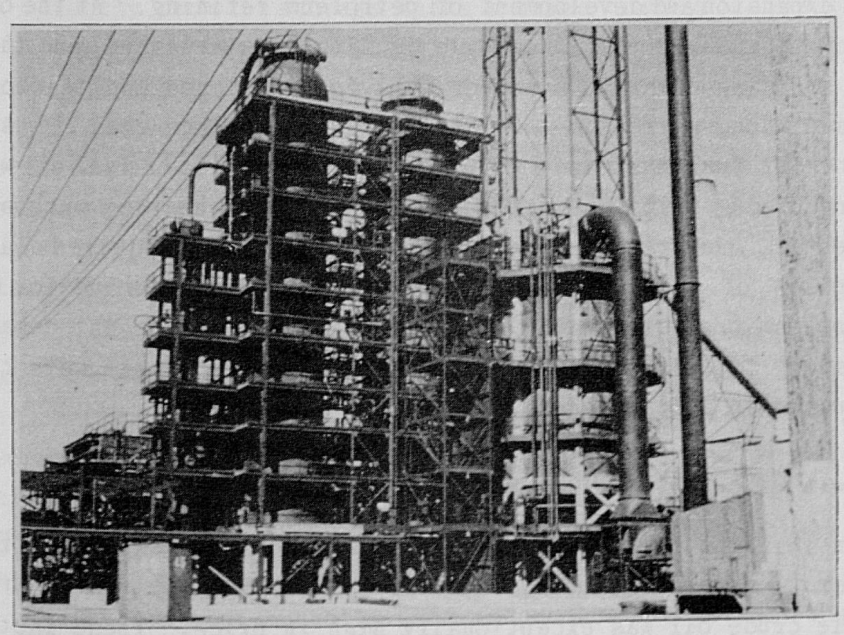


ILLUSTRATION 30.- FRACTIONATING ("BUBBLE") TOWERS IN USE AT LARGE REFINERIES

Fractionating towers are essential equipment at modern refineries and are used to obtain an accurate separation of one product of distillation from another. They are comparatively tall structures equipped to treat ascending vapors so as to obtain the different products of distillation at various intervals. The upper view shows a continuous-distillation unit with a fractionating tower. The lower view shows a number of fractionating towers at a large refinery.

as the vacuum jugs operated under reduced pressure, further vaporization of the residue from the fractionating tower took place. Vacuum fractionating towers, similar in design but larger than the atmospheric fractionating towers, were developed from the vacuum pot. The residual oils from the atmospheric fractionator were heated further before entering the vacuum tower. This additional heat, in combination with the low absolute pressures in the tower, resulted in the evaporation and fractionation of relatively high-boiling-point fractions without decomposition. It has been only within the past 15 years that fractionating towers have come into general use.

The development of two-stage fractionating towers and pipe stills and their combination into one unit represented an important advance. This development has permitted precise technical control over the manufacture of high-quality distillates ranging from light naphthas to heavy lubricating oils.

MODERN REFINING TECHNOLOGY

Influences set in motion by the World War greatly stimulated the expansion and development of petroleum refining. At the outbreak of the war the automobile was firmly established, and there was a rising demand for motor fuel for airplanes and tractors. In addition, petroleum was beginning to replace coal in some important fuel markets, and increasing quantities of fuel oil were being used by ships and railroads and for many heating purposes. Moreover, the rapid mechanization of industry required large supplies of lubricants. The war stimulated the demand for all petroleum products and, to supply the huge and urgent demand, existing facilities were enlarged and many new plants were constructed in all parts of the country.

Growth of Cracking and Its Economic Significance

In 1914 the cracking process was used in only a few refineries. Under the stress of war needs the demand for gasoline rose sharply while crude oil was exceptionally high in price. These factors were an incentive to the growth of cracking which was continued until the present.

The cracking units in use about 1915 were of the semibatch type, built similar to shell stills but containing recirculating tubes so that heating could be accelerated. These cracking units

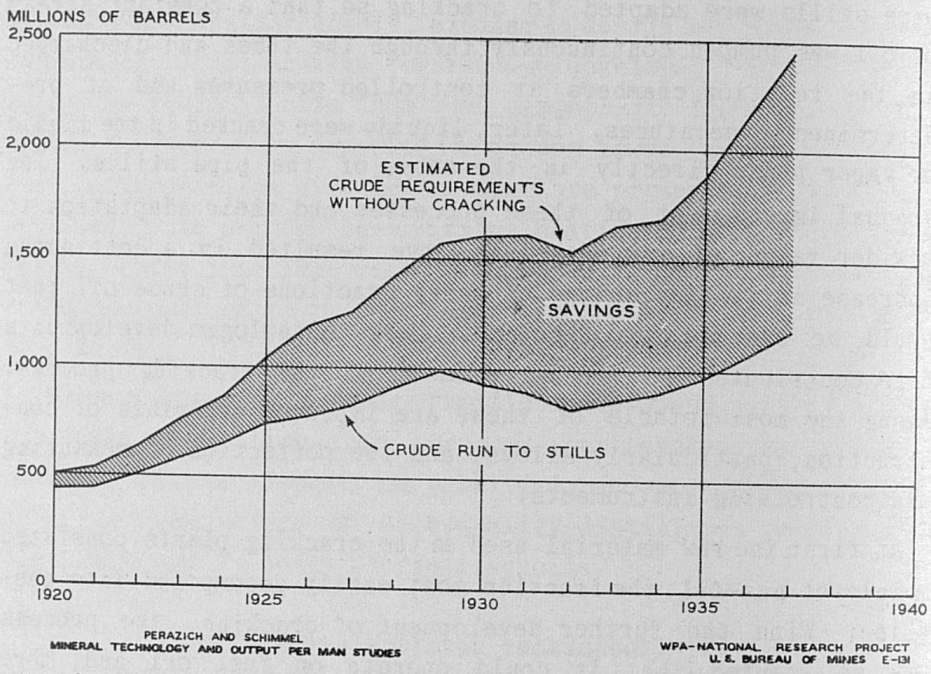
were operated at several atmospheres of pressure and at advanced temperatures where oils begin to decompose. During the twenties pipe stills were adapted to cracking so that a constant stream of oil was pumped continuously through the tubes and discharged in the reaction chambers at controlled pressures and at predetermined temperatures. Later, liquids were cracked in the liquid or vapor phase directly in the tubes of the pipe stills. The gradual improvement of these processes and their adaptation to a wider range of raw materials have resulted in a continuous increase in the percentage of heavy fractions of crude oil that could be cracked into gasoline. Many technologic developments have contributed to the improvement of the cracking process. Among the most notable of these are improved materials of construction, particularly alloys, and the perfection of measuring and controlling instruments.

At first the raw material used in the cracking plants consisted mainly of gas-oil, the fraction most easily decomposed into gasoline. With the further development of cracking, the process was so adapted that it could operate on fuel oil and, more recently, combination units have been built that processed crude oil directly from the storage tanks and then cracked the resulting fractions in continuous operations. In the earlier stages of cracking, many units were required to produce the desired volume of light products and each unit required several operators. Since the introduction of combination units, one crew of operators can process three times as much oil and obtain an even greater yield of gasoline than was possible a decade ago with several units and a large force of men.[14]

Development of the cracking process is probably the most significant contribution of petroleum-refining technologists. In 1914, when cracking was being introduced, the yield of gasoline from crude oil was only 18 percent (see figure 27), whereas the present yield is 45 percent, or approximately double the maximum yield obtainable by straight-distillation methods. Had it not been for the cracking process, more than twice as much crude oil would be required as that actually used to produce the present supply of gasoline. Estimates of the amount of crude conserved during the period 1920-35 by virtue of the cracking process are shown in figure 24. In one sense the data in the figure represent only

[14]This development is discussed in greater detail on p. 286 and is illustrated in figure 29.

Figure 24.- CRUDE PETROLEUM CONSERVED BY THE CRACKING PROCESS, 1920-37



Were it not for the increased yield of motor fuel made possible by cracking, nearly twice as much crude oil would be needed today as is actually processed to supply the demands of our motorized civilization. That the savings in crude oil are due to an approximate doubling of the yield of gasoline obtained per barrel of crude oil in the decade and a half following the World War is shown in figure 27. The extension and refinement of cracking and related processes has also improved the quality of gasoline.

Besides lengthening the life of our petroleum reserves, the conversion of the heavy fractions of petroleum to gasoline by cracking has tended to retard the extent to which coal has been replaced by oil as an industrial fuel. This is because cracking made possible the breaking down of fuel and residual oils - that would have been available in constantly larger quantities from ordinary straight-distillation processes that would have been used had not cracking been employed - into gasoline, and has thus reduced the quantity of such oils placed on the market at prices in competition with coal. Data are from table A-26.

minimum savings, since gasoline produced by cracking has superior antiknock qualities that make it a more effective motor fuel. As a result of this progress in refinery efficiency, it is estimated that in 1935 alone 300 million barrels of crude were conserved by the cracking process.[15]

The development of cracking has resulted in substantial reductions in unit labor requirements represented by the labor that would otherwise have been required to produce and refine large additional amounts of crude oil. Furthermore, it has resulted in the conservation of an important natural resource of which the available supply may be definitely limited. On the other hand,

[15] G. Egloff, *Cracking and Its Economic Significance* (Chicago: Universal Oil Products Co., Booklet No. 197), p. 7.

it is doubtful whether the petroleum industry would have undergone its rapid growth during the past 25 years had not cracking or some similar technological innovation been introduced. To the extent that the economies of cracking have resulted in lower-priced gasoline, they have widened the market for motor fuel and contributed to the rapid growth of both the petroleum and automobile industry after 1914.

Manufacture of Lubricants

The demand of industry for lubricants capable of withstanding the rigors of high-speed machinery and extremes of temperature has imposed upon the petroleum refiner the task of manufacturing a wide variety of lubricating oils and greases, each capable of meeting certain exact specifications. To meet the new requirements, the manufacture of lubricants has undergone many technical changes within recent years. An outstanding change has been the development of solvent treating processes for the extraction of desirable lubricants from unrefined lubricating stocks or from stocks formerly unsuitable for treatment. These processes, almost universally used in the refining industry, depend on the solvent action of certain chemicals and require relatively large plants. The plants may vary in daily capacity from 500 to several thousand barrels, and the operating crews may consist of 10 to 30 men per shift. In this division of refining, advances in the technique of lubricant manufacture have been accompanied by an increase in employment.

Furthermore, the practice of "packaging" lubricating oils also has added substantially to employment. Where once lubricants were shipped only in bulk or in barrels, today there has arisen a demand for individual containers for small amounts of oils. The manufacture and packaging of wax candles, fly sprays, insecticides, solvents, and a large variety of other special products of petroleum refining also have added to employment despite the fact that mechanical aids, such as filling and labeling machines, conveyors, and small power trucks, have been added to packaging and shipping departments.

Improvements in Treating Processes

Although treating has improved greatly during recent years and new processes have been developed, sulphuric acid still is

the major chemical utilized for treating distillates. Lighter distillates relatively free of sulphur, however, are treated for sweetening with an aqueous solution of sodium hydroxide (caustic soda) and litharge (lead oxide). The solution is used in direct contact with the distillate in a continuous process through a battery of vertical or horizontal tanks, with the gasoline emerging finished and in many cases ready for market.

Technical advances have proceeded with rapidity in other forms of treating as, for example, in cold-treating processes for cracked gasoline. Treatment at low temperatures diminishes the loss of desirable hydrocarbons, the formation of deleterious substances such as polymers and sulphonated compounds, and the amount of caustic soda required for subsequent neutralization, whereas the selective action of sulphuric acid in removing sulphur compounds is not affected adversely. Modern cold-treating processes require equipment with a refrigerative capacity of about 100 tons[16] per 1,000 barrels of cracked gasoline treated daily.

Another low-temperature process utilizes refrigeration and the mixing of gasoline to be treated with predetermined proportions of sulphuric acid in specially designed centrifuges and mixers where the time of contact is reduced to seconds. As in the cold-treating process, the gasoline is not subjected to deleterious influences, but in some instances additional treatment with a solution of caustic soda and litharge is required to sweeten the product after some of the sulphur compounds have been eliminated

Rates of throughput in these treating processes are governed by automatic instruments regulating the operation of pumps that handle the chemicals and gasolines and, after initial adjustment, require little supervision or attention to maintain thorough treating. The thoroughness of the reactions between the compounds in the gasoline and the chemicals, however, is determined by laboratory inspection, with plant checks made hourly or oftener by the operators of the units in the plant.

Development of Complete Plants

Complete refineries are those that process crude petroleum for recovery of nearly all available products. These plants

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[16]The American unit of refrigeration (ton) is the abstraction of an amount of heat equal to the latent heat of fusion of 1 ton of ice (usually taken as 288,000 B. t. u.), and the unit of refrigerative capacity (ton) is the capacity to abstract 288,000 B. t. u. per 24 hours or 200 B. t. u. per minute. See Bell, *op. cit.*, p. 311.

necessarily utilize complicated processes that permit the separation and segregation of products for many industries and uses.

Gasoline, kerosene, fuel oils, lubricants, domestic heating oils, waxes, medicinal supplies and pharmaceutical ingredients, and a variety of chemical raw materials are manufactured from crude petroleum. Some of these products are derived by simple distillation methods and others by cracking; still others require intricate manufacturing methods that involve physical and chemical processes. Technical knowledge and skilled employees are required to operate these involved processes.

Vapor-Recovery and Stabilization Plants

In the early operation of atmospheric- and vacuum-distillation plants varying amounts of light, frequently unstable, hydrocarbon gases containing products of commercial value were not recovered but were burned under boilers or vented to the atmosphere. With the increased number of cracking units in operation, still larger volumes of gas were produced that could not be condensed under normal operating conditions. To recover the gasoline and other valuable components of these waste refinery gases, refiners adopted the processes and methods developed in the natural-gasoline industry.[17] Consequently, today the vapor-recovery plant and its adjunct, the gasoline-stabilization plant, are integral parts of most complete refineries. Gathering systems collect the vapors from condensers, storage tanks, and other sources and carry them to the vapor-recovery plant where, either by compression and subsequent cooling, or by absorption, or both, the valuable constituents are extracted. By the use of stabilizers or fractionating towers, the gasoline, butane, and propane are segregated without the losses of gasoline that characterized the early weathering processes. Butane and propane, formerly waste products, are being used extensively, not only as fuels but also in the manufacture of high-octane gasoline by the polymerization process.[18] Moreover, refinery operations have been benefited by the general adoption of gasoline-storage and run-down tanks fitted with pressure-tight or vapor-tight tops or with special roofs that float on the liquid. These have substantially reduced the losses of gasoline by evaporation.[19]

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[17] See pp. 182-4.

[18] See pp. 281-2.

[19] L. Schmidt, *Evaporation Losses of Gasoline in the Refinery* (U. S. Dept. Com., Bur. Mines, Report of Investigations 2721, mimeo., Nov. 1925), 16 pp.

The operation of vapor-recovery plants in refineries, although increasing employment, has been the means of economically reducing product losses in refining petroleum.

Development of Automatic Control

The technical developments of the refining industry since the war can be attributed mainly to the efforts of refinery technicians. The research, development, and control departments of the larger refining organizations have in reality become indispensable, and refiners have steadily developed and enlarged these departments. Out of the research laboratories have come new products and new operating practices for improving the quality and yield. Coupled with the accomplishments of the refinery technicians have been the contributions of the instrument manufacturers who made possible the adaptation of automatic control devices.

Soon after widespread adoption of continuous processes it was found that their successful application hinged largely upon accurate control of temperature, pressure, rates of flow, and liquid levels. Although refiners were leaning more and more heavily on the measures provided by indicating and recording devices, almost all operations were still controlled by the manual operation of valves. Through the use of instruments, operation gradually became standardized during the post-war decade, and it became necessary to specify distillations quantitatively in terms of temperature, pressure, rate of flow, and liquid level.

Once it had become standard practice to specify the operation of a petroleum refinery in quantitative terms, an advanced form of instrumentation was developed. Indicators and recorders had been used during the period of manual operation, and operators were guided by these instruments in their manual adjustment of valves and other control devices. Control instruments, direct combinations of indicating or recording instruments with regulatory devices, made possible automatic control of various processing conditions. In this way refiners were able either to eliminate certain operating labor or to control additional processing conditions whose regulation would otherwise have required an increase in the labor force.

At first the control instruments employed were not particularly suited to oil refining, as they had been borrowed from other industries whose control problems were different. These early

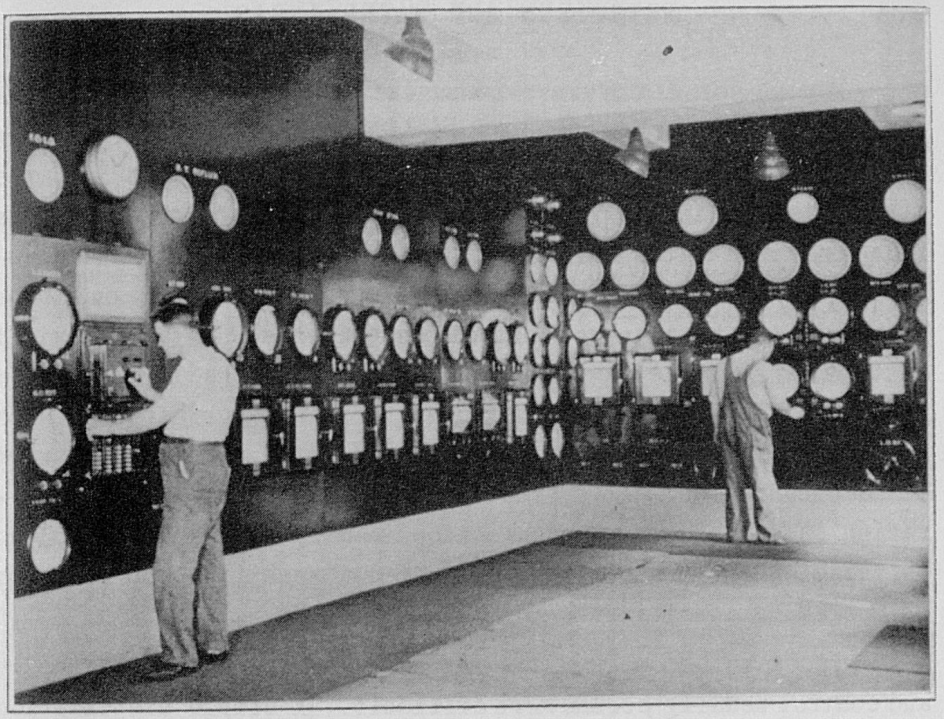




ILLUSTRATION 31.- CONTROL BOARD IN A PETROLEUM REFINERY AND A REFINERY LABORATORY

The upper view shows a control panel that comprises chiefly indicating and recording instruments. Many large modern refining units are operated by small labor crews from such centralized instrument panels.

The lower view shows a refinery laboratory where tests of material being treated are made and where research, seeking improvements in processes and products, is conducted. Research activity in petroleum refining has increased more rapidly in the period since the World War than in any other major industry except automobile manufacturing.

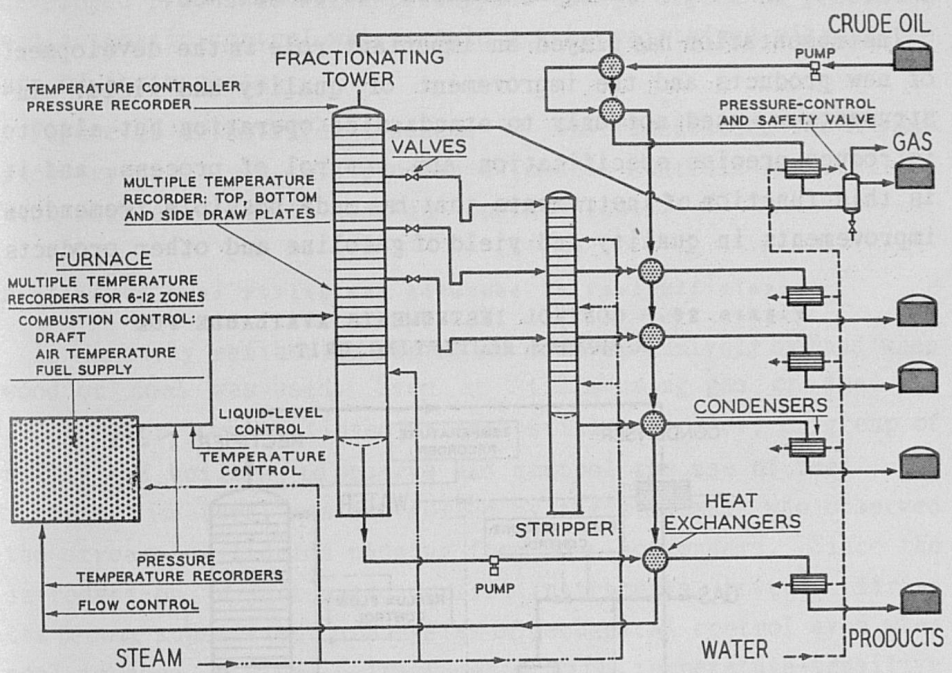
controls were for the most part the simple "on-and-off" type that would either open or close a valve completely. This form of regulation was not suitable to a continuous process, as the control devices themselves were constantly causing irregularities that were transmitted throughout the equipment. Instrument manufacturers and petroleum technologists worked jointly on these problems, and by 1933-34 control instruments had been devised that were suitable for the peculiar conditions of petroleum refining. They had a smoother operation that corresponded with and even improved upon the gradual adjustments possible under manual regulation. At present automatic control by instrumentation has become standard practice in many phases of petroleum refining, where it provides a reliable and sensitive coordination of operating conditions.

As processes become more complex and more refined, coordination and control usually become more difficult. A simple distillation unit (topping plant), for example, can be readily controlled manually, but even in plants of this kind automatic control now is used customarily, as the process has become complicated to a degree where manual regulation no longer provides the desired level of precision. For this reason complete manual operation of topping plants is now the exception rather than the rule.

More complicated processes, such as those employed at continuous cracking plants, require a high degree of precise control. Units of this kind, in their earlier simple forms when precision requirements were less exacting, were operated manually. During this stage the plants were of small capacity and had relatively low efficiencies. In their present form measuring and controlling devices are equipment essential to successful operation, not only because they provide greater precision but also because they safeguard the huge investments involved in modern refining equipment.

To indicate the extent to which instrumentation is being utilized in modern refining, figure 25 shows a typical scheme of instrumentation for a topping plant, which has equipment that ordinarily depends less on automatic control than the more advanced and recently developed processes. Of the instruments indicated in the diagram, not all are standard practice. As a matter of fact, there is a great deal of variation among the different refineries. Some of the instruments indicated are not used in some plants, but at other plants much more elaborate schemes of instrumentation

Figure 25.- CONTROL INSTRUMENTS AVAILABLE FOR MODERN STRAIGHT-DISTILLATION UNIT (TOPPING PLANT)



PERAZICH AND SCHIMMEL
MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES

WPA-NATIONAL RESEARCH PROJECT
U.S. BUREAU OF MINES E-132

An indication of the extent to which instrumentation is being utilized in modern refining is given above in the typical scheme of instrumentation for a topping plant. Even in this simple straight-distillation unit, which can be readily controlled manually, the process has become complicated to a degree where manual regulation no longer provides the desired degree of precision. Not all the instruments indicated in the diagram are standard practice, for there is a wide degree of variation among different plants. Some refineries, however, employ even more instruments than those shown. The diagram is based largely on figure 117 in W. L. Nelson, *Petroleum Refinery Engineering* (1st ed.; New York: McGraw-Hill Book Co., 1936), p. 365, but the scheme of instrumentation has been modified in several respects on the basis of data obtained from a leading oil company.

have been adopted. The diagram shows only four automatic controls; namely, top temperature of the tower, liquid level, control of temperature at furnace output, and rate of feed of the crude oil. A survey by the *National Petroleum News*[20] suggests that more extensive automatic control than this is in use at most modern refineries.

A further indication of the extent of instrumentation in modern refineries is given by the statement of Proctor and Egloff:[21]

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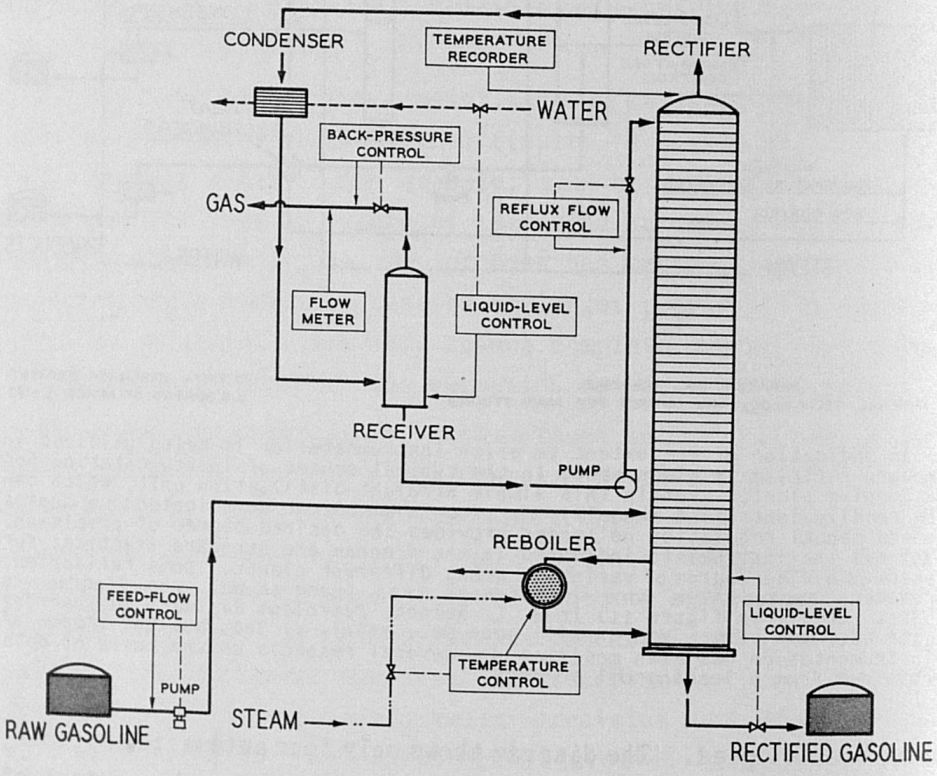
[20] J. W. Thompson, "Automatic Control Applications Increase as Refiners Find Operating Economies," *National Petroleum News*, Vol. 27, No. 13 (Mar. 27, 1935), pp. 28-30.

[21] A. C. Proctor and G. Egloff, "Instrumentation in Oil Refining," *Proceedings of the American Petroleum Institute - Section III - Refining* (sixth midyear meeting, Tulsa, Okla., May 12-15, 1936), p. 47.

"At the present time [1936] some refining units are equipped with more than 300 control or indicating points for accurate control, which are serviced by highly skilled instrument men."

Instrumentation has played an important role in the development of new products and the improvement of quality and yield. Instruments are used not only to standardize operation but also to introduce precise specification and control of process, and it is this function of instruments that has made possible tremendous improvements in quality and yield of gasoline and other products

Figure 26.– CONTROL INSTRUMENTS AVAILABLE FOR A MODERN RECTIFYING UNIT



PERAZICH AND SCHIMMEL
MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES

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U.S. BUREAU OF MINES E-133

Not only has instrumentation in petroleum refining played an important role in the development of new products but it has also made possible tremendous improvements in quality and yield of gasoline and other products manufactured from crude oil. Gasoline rectification, in which the raw refinery product is rectified to market specifications, as well as polymerization, hydrogenation, and solvent recovery are illustrations of more recently employed processes that require a high degree of precision and automatic control that could not be maintained without the use of instruments. Automatic controls are used more extensively in the scheme of instrumentation for a modern rectifying unit, as shown above, than in the topping plant illustrated in figure 25. Adapted with modifications from figure 4034, *Foxboro Co. Bull. 175* (Foxboro, Mass.), p. 27.

manufactured from petroleum. Polymerization, hydrogenation, gas rectification, and solvent recovery each illustrates more recently developed processes which presuppose a high degree of precision and automatic control which could not be maintained without the use of instruments.

Figure 26 illustrates a scheme of instrumentation for a gas-recovery unit. In this process automatic controls are utilized much more extensively than in topping plants.

Decline of Hand Firing and Advances in Fuel Efficiency

In the early refineries firing was done exclusively by hand when wood or coal was used. Even at stills using gas or fuel oil an operator was stationed at each still or boiler, or group of stills and boilers, to observe and control the use of fuel. The fireman, in turn, was controlled by the stillman, who observed the streams of liquids passing from the condensers. Since the introduction of automatic control instruments, however, firing has become subservient to a system of mechanical control even when coal is used as fuel. Instruments with temperature-sensitive elements inserted at strategic points in the refinery regulate the volume of fuel required to bring the liquids to a desired operating temperature and to maintain this condition. In addition, flow and electric meters provide continual checks on the economical consumption of steam and electricity.

The improvements in firing methods have been attended by notable increases in fuel efficiency (see figure 27). Between 1925 and 1937 fuel requirements per barrel of crude oil run to stills were reduced by a third.[22] Even this does not represent all the improvements that have been made because, during the period since the war, the introduction of additional processing methods would normally have necessitated an increase in fuel requirements per barrel of crude oil refined. The trend toward the manufacture of an increasing variety and volume of products from the crude petroleum has tended to obscure, in part, the striking economies made in fuel utilization.

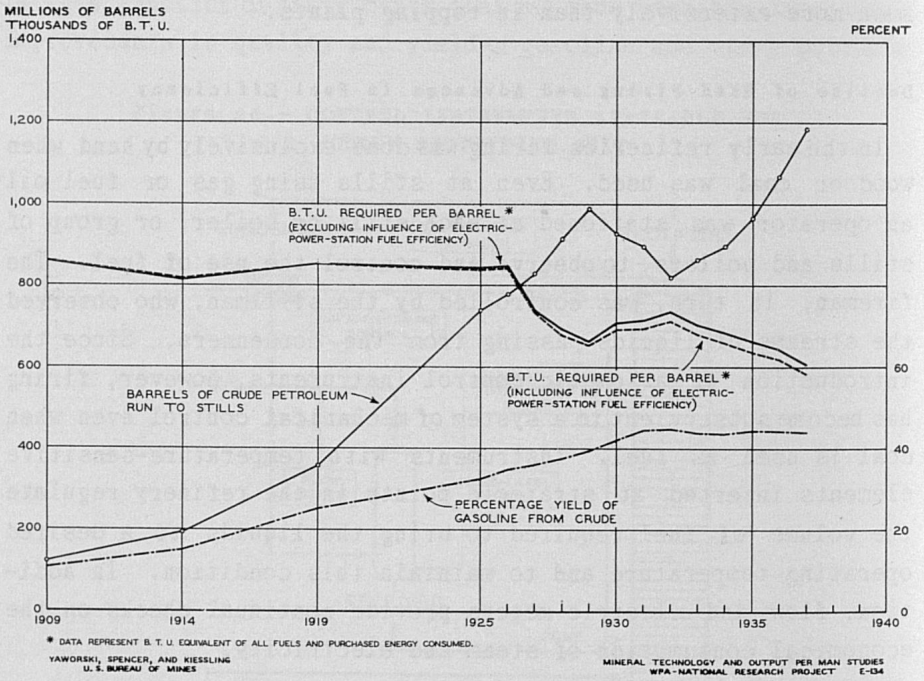
Additional economies in fuel utilization are indicated by the changes in the kinds of fuel that are now being used by the refineries. In recent years gas has become an important refinery fuel, and the consumption of coal has dropped sharply. This shift

[22] G. R. Hopkins, *Survey of Fuel Consumption at Refineries in 1937* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3430, mimeo., Dec. 1938), fig. 1.

is due to marked progress in the utilization of refinery gases formerly wasted (see figure 28).

The widespread shift from batch to pipe stills has been the primary factor responsible for the advances in fuel efficiency.

Figure 27.- INCREASING FUEL EFFICIENCY IN PETROLEUM REFINING, 1909-37

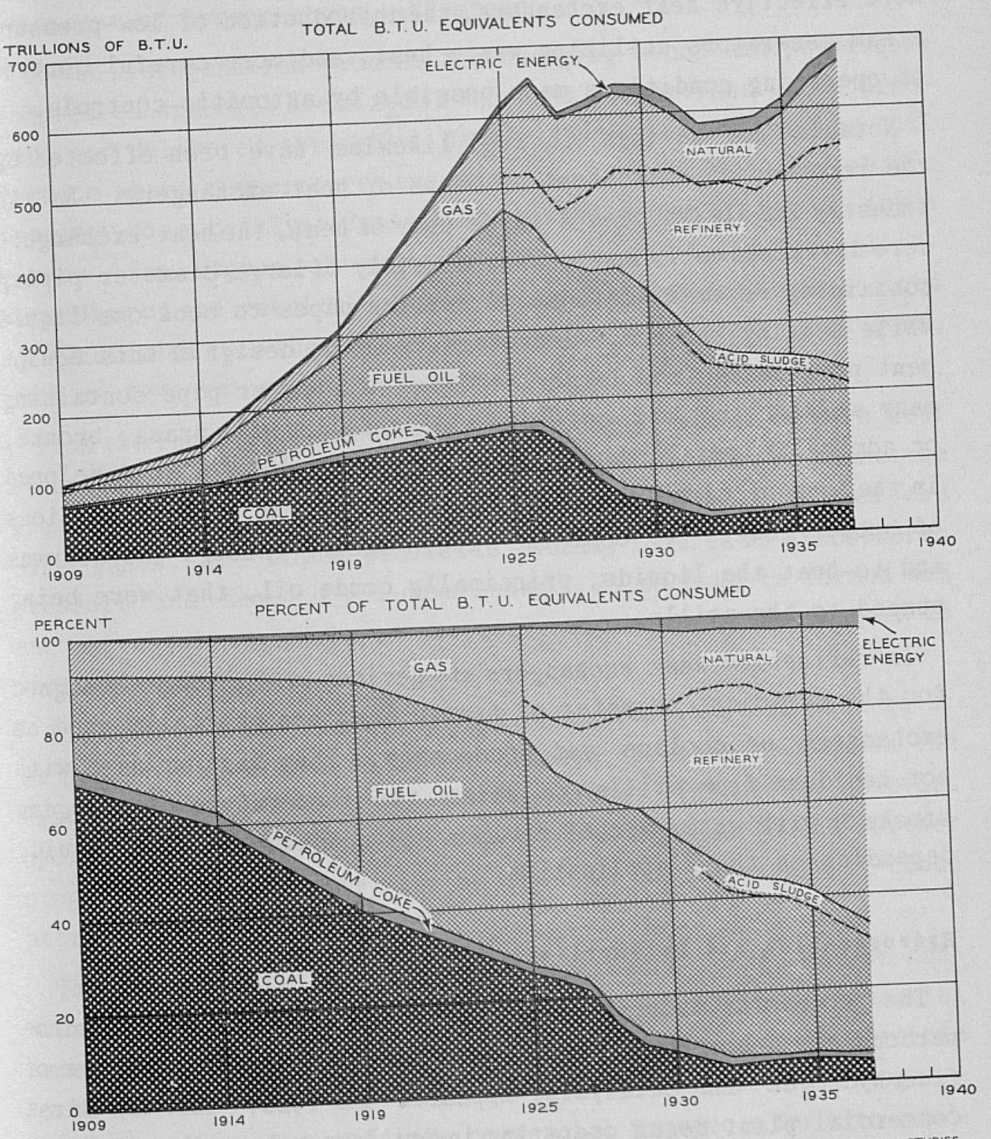


Unit heat requirements for petroleum refining were reduced by rapid improvements in refining techniques and by the introduction of new and more efficient equipment. An important technical advance was the greater use of the pipe or tube still and widespread substitutions of the continuous-refining process for the old, inefficient batch methods. Modern pipe stills, constructed to take greater advantage of radiant heat, have a thermal efficiency as high as 80 percent, compared with less than 40 percent for shell stills. Another important technical advance was the greater use of heat exchangers, in which the heat from hot vapors to be condensed is employed to heat the incoming cold oil. Other improvements include greater use of heat from hot gases to preheat air for combustion, greater use of exhaust steam formerly wasted, improved techniques in generating and using steam (by more efficient boilers and by higher steam pressures and temperatures), substitution of electric-driven for steam-driven equipment, adoption of automatic temperature control and periodic checking of firing conditions of units, and a reduction of heat losses through better insulation.

The consumption of energy per barrel of crude oil run to stills increased in 1930, 1931, and 1932, principally because of a decline in the proportion of petroleum-refining capacity utilized. Much of the fuel consumed at refineries is used for other purposes than under stills and is, in the main, required regardless of the number of barrels of crude oil refined. Consequently a reduction in the volume of crude runs to stills is accompanied by an increase in fuel consumption per barrel.

An influence that has retarded reduction in average heat requirements has been the growth of cracking and re-forming in the production of a higher gasoline yield than was obtainable by "skimming" and "topping" methods. The additional cracking and re-forming entail relatively high temperatures and the heating of additional stills. As shown from the trend, however, a more than fourfold improvement of gasoline yield has been achieved with lower unit fuel requirements. Data are from tables A-27 and A-29.

Figure 28.- ENERGY CONSUMED IN PETROLEUM REFINING, BY TYPES, 1909-87



YAWORSKI, SPENCER, AND KIESSLING
U. S. BUREAU OF MINES

MINERAL TECHNOLOGY AND OUTPUT PER MAN STUDIES
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The energy requirements of petroleum refineries increased rapidly from 1909 to 1926, coincident with the rapid growth of petroleum refining. After 1926 the growth in energy consumption ceased and in some years declined. This failure of petroleum refineries to increase their consumption of fuel after 1926 (although the amount of petroleum refined continued to increase except during the depression years) is explained by rapid advances in fuel efficiency. The period since 1926 is marked especially by the greatly increased use of refinery gas made available by the extensive use of the "cracking" process of refining and by utilization of other fuel byproducts, which, until recently, were commonly allowed to go to waste. From 1926 to 1936 the consumption of refinery gas increased about 300 percent, much of it replacing the consumption of fuels obtained outside the oil and gas industry - particularly coal, which fell 78 percent. Data are from table A-28.

Other contributing factors have been the use of improved firing facilities, better firing chambers, the general adoption of more effective heat exchangers, the introduction of low-pressure steam generators utilizing waste heat, and more careful control of operating conditions made possible by automatic controls.

Notable net savings in fuel likewise have been effected by the recovery of waste heat by means of heat exchangers. As the industry has always been a large user of heat, the heat exchangers were developed early and consisted mainly of large-diameter piping containing several sections of smaller pipes to cool one liquid while heating another. Improvements in the design of this equipment progressed from larger sections of shorter pipe containing many smaller tubes to cast-iron shells filled with brass, bronze, or admiralty metal tubes. Heat exchangers were also developed in the form of circular coils of pipes placed in certain sections of bubble towers to cool the vapors rising through the columns and to heat the liquids, principally crude oil, that were being pumped to the stills.

In refineries heat exchangers are devices or equipment designed for the efficient transfer of heat. They are generally used as exchangers or coolers and condensers. They may be used with hot residuum from stills to raise the temperature of charging stocks or with water to cool a vapor and condense it to a liquid, depending on their application.

Hydrogenation and Polymerisation

The process of hydrogenation, by means of which heavy hydrocarbons are decomposed by heat and pressure in the presence of free hydrogen and catalysts, appeared in 1928, and the first commercial plant began operating in New Jersey in 1930. Although the possibilities of hydrogenation are considered great, both because of the flexibility of the process and because of the amount and degree of the important changes that can be effected in the chemical properties of the hydrocarbons present in petroleum, only a few hydrogenation plants are now being operated in the United States.

The hydrogen used in the process may be produced by any of the usual methods, and since the hydrogen need not be free from sulphur, its production from coal or coke by the water-gas process is somewhat simpler than when the hydrogen is to be used for the

production of ammonia. For the oil industry, with its generous supply of refinery and natural gas, hydrogen may be made by the treatment of hydrocarbons with steam.

In the hydrogenation process the charging stock and previously compressed hydrogen are mixed in required proportions under pressure and delivered through a heat exchanger to a pipe or coil furnace where temperatures are maintained as required, the charge passing to a catalyst-containing vessel where reaction takes place. The degree of hydrogenation is carefully controlled, depending on the results desired; control in general is maintained by alteration of the catalyst or other operating conditions, such as temperature and pressure.

From the reaction chamber the final products pass through heat exchangers and coolers to a high-pressure separator, where the liquid product is separated from the unconsumed hydrogen and other gases. The liquid product is finally reduced to atmospheric pressure and sent to run-down tanks. As no coke is formed and as the catalysts employed are extremely rugged, the process is virtually continuous.

The economic importance of hydrogenation is still uncertain. At present the expansion of the process has been checked in the United States by the high cost of operation. In Europe, however, hydrogenation has reached substantial proportions,[23] and further progress in this country may be expected if our supply of crude petroleum should dwindle.[24]

The process of polymerization, in the broad sense, may be considered as the reverse of cracking and has assumed commercial importance only in the last few years. Although it is possible by polymerization to form numerous chemical compounds and reagents from petroleum, the immediate commercial prospects for such products are not too encouraging, and polymerization has been confined to the manufacture of products suitable for combining with motor fuels. In both straight-run distillation and cracking processes, mainly the latter, large quantities of highly unsaturated hydrocarbon gases are formed that are too volatile for use in gasoline. To synthesize products suitable for motor fuel or for addition to motor fuel the light, unsaturated gases are subjected in reaction

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[23] G. Egloff, "Motor Fuel Economy of Europe," *Industrial and Engineering Chemistry*, Vol. 30, No. 10 (Oct. 1938), pp. 1091-5, 1103.

[24] H. E. Howe, "The Chemical Industries," *Technological Trends and National Policy* (National Resources Committee, June 1937), p. 297.

vessels to high temperatures and pressures for long enough periods to cause the formation of less volatile liquid compounds. Such processes of polymerization are often conducted in the presence of catalysts.

Butane and propane, usually discarded from the natural-gasoline plant stabilizers, can also be utilized in the polymerization process. Both compounds are more or less inert chemically and require preliminary processing, similar to petroleum cracking, to convert them to other compounds that contain more carbon, relative to hydrogen, than the original materials. The compounds so produced can then be made to combine with each other to form heavier fractions or compounds, either by continuation of the heat-and-pressure method or by the use of catalysts. The finished gasoline produced by either of the polymerization processes has an exceptionally high antiknock value and is used principally for blending with ordinary gasoline to improve this characteristic.

The development and operation of polymerization plants for the conversion of waste hydrocarbon gases have been other steps toward conservation and have resulted in an increase in employment in the industry. The number of workers employed is not large, but as plants are being constructed in many parts of the country to operate either on refinery gases or on butane and propane from natural-gasoline plants, more workers are constantly being required. These may be indirectly employed as operators of stabilizer plants producing the raw butane and propane or in refineries where the refinery gases are processed so that they may be converted by polymerization into gasoline.

INFLUENCE OF TECHNOLOGIC CHANGE ON LABOR REQUIREMENTS

The changes in the technical process of petroleum refining have been attended by important economies in unit labor requirements (see pp. 27-8). Judged by the volume of crude oil run to stills, the throughput per man-hour has increased more than threefold since the end of the World War. Despite such labor saving, employment has shown a general long-time growth, and in 1937 - the latest year for which statistics are available - it was above the previous all-time high of 1929. The constantly increasing demand for petroleum products apparently has more than offset the decrease in labor requirements per barrel of crude oil charged.

The increases in output and employment were accompanied by changes in the length of the working day. At the beginning of the industry the number of hours each employee worked varied to some extent, but the length of the working day was generally long and in some instances men were kept at their tasks 18 to 20 hours a day. About 1890 more regular and definite hours were established, and refinery employees worked 12 hours a day and 7 days a week. Later this working schedule was changed to a 12-hour day and a 6-day week. Following the World War the majority of refineries established an 8-hour day and a 6- or 7-day week. Under the NRA an 8-hour day and a 5-day week were established, and this schedule is still generally followed.

Displacement Caused by Continuous Process, Improvement of Equipment, and Increased Capacity

Continuous processes have resulted in a substantial saving in labor per unit of product. In this type of operation complete mechanization is usually achieved except for the workers needed to control operations through the regulation of valves, switches, and other devices. Measuring and controlling devices make possible the success of such processes by providing means for achieving the necessary precision in synchronizing the operation. Careful analyses of all the various phases of a continuous process make it possible to increase the speed of operation gradually so that the capacity and hence the output per unit of time are greatly increased without increasing the number of workers employed. This form of labor saving, together with the method of placing several units under the supervision of a single operator, is probably the most significant factor in increasing the productivity of operating labor.

Another significant development has been the marked increase in capacity of the stills. During the 30-year period from 1889 to 1919 the average daily production per still more than doubled. Moreover, since the tendency throughout the period was to increase the number of stills operated by each labor crew, it is evident that output per worker increased even more rapidly than the production per still. One observer has noted, however, that when the continuous process was first introduced the reduction in labor requirements was not so great as might have been expected, because considerable savings had already been realized by having

single crews operate up to a dozen batch stills. Although a fair comparison cannot be made between the capacity of the modern stills and the capacity of the stills in use during the batch era because of the revolutionary improvement in still design, it is interesting to note the U. S. Bureau of Mines reported that in 1935 the 709 tube stills in operation had a daily charging capacity of approximately 3 million barrels. This indicates that the average daily capacity of tube stills is about 4,000 barrels, but there are well-designed units capable of processing over 30,000 barrels per day. The number of workers needed to operate a unit of this type has been greatly reduced, and some plants are now being operated with as few as two men per shift.[25] For this reason the shift from shell to tube stills, together with the grouping of stills into batteries, probably was one of the most important of all factors contributing to the rising output per worker employed in refining.

The influence of increasing capacity on productivity in refining is likewise shown in the expanding capacity of the cracking equipment. During the period 1925-32 the average daily capacity of the individual cracking units increased more than 300 percent. Abandoning of the small skimming plants that had been hastily constructed in response to the high prices of 1920[26] was a factor that contributed toward increasing average capacity of all types of equipment.

The rising use of instruments during the past decade has played a particularly prominent part in encouraging the tendency to increase plant capacity and simultaneously to increase the number of units operated by a single crew. At simple distillation plants, for example, it is not at all uncommon for one crew to operate two or three units from a single control panel. Thus, while a labor force of three workers might be required for operating a single distillation unit, four men are capable of operating two or three units. In this way output per man is more than doubled.

Changes Effected by Adoption of Automatic Control

Coincidental with the development of continuous processes, increases in capacity of equipment, improvements in design and

[25] Includes workers required in actual operation of the plant, but does not include workers employed in maintenance work, pumping the crude oil from storage to working tanks, treating the products, loading, and in many other necessary tasks.

[26] E. G. Nourse and Associates, *America's Capacity to Produce* (Washington, D. C.: The Brookings Institution, 1934), p. 88.

materials, and other advancements that have contributed heavily to the rising output per worker in petroleum refining has been the shift from manual to automatic control, as already noted. With the introduction of automatic control and central instrument panels, not only has it been possible to eliminate considerable operating labor as a result of concentrating regulatory function at a single station, but also manual control has frequently been eliminated by the introduction of extensive automatic devices. Developments of both types have been taking place simultaneously in the refining industry in recent years. At present central panels, which involve considerable automatic control, have become standard practice.

Some of the typical savings in labor requirements effected by the adoption of automatic control devices are suggested by numerous articles published in the technical press. A recent survey, for example, reported that the use of a certain type of automatic control unit on a cracking still eliminated one man from a 3-man crew, thus cutting the labor cost by a third.[27] An automatic water-level alarm displaced one man, and the installation of a temperature control of tower-overhead vapors enabled one refinery to reduce the operating crew from four to three, effecting a substantial saving in wages. Finally, an automatic fuel control for pipe stills cut the manpower requirements in half.

When it is considered that control instruments have comprised more than one-third of the new industrial instruments appearing annually on the market from 1931 to 1937 and that the petroleum-refining industry has adopted automatic control instruments more extensively than most other industries,[28] it appears that considerable reduction in labor requirements has been effected through their introduction.

In recent years the possibility of increasing greatly the capacity of operation without materially increasing the labor force has depended largely on additional facilities and the precision of operation provided by instruments. Increases in capacity usually are accomplished by advancing the speed of flow of materials or by increasing the actual size of equipment, factors that make technical regulation more complex. But these inherent difficulties are overcome in large part by the concentration

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[27] Thompson, *op. cit.*, p. 30.

[28] G. Perazich, H. Schimmel, and B. Rosenberg, *Industrial Instruments and Changing Technology* (WPA National Research Project, Report No. M-1, Oct. 1938), pp. 46, 63-7.

of measuring and controlling devices on a single panel and by the use of alarm devices that afford protection to the huge investment in refinery equipment.

Net Effect of Technologic Advances

Although an appraisal of changes in employment and output per man in refining should carefully consider the influence of increasing capacity, continuous operation, improved equipment, and central control, it is extremely difficult to measure quantitatively the net effect of each factor in terms of employment. An indication of the over-all effect of these converging factors, however, can be obtained from an illustration furnished by a leading designer and constructor of refineries.

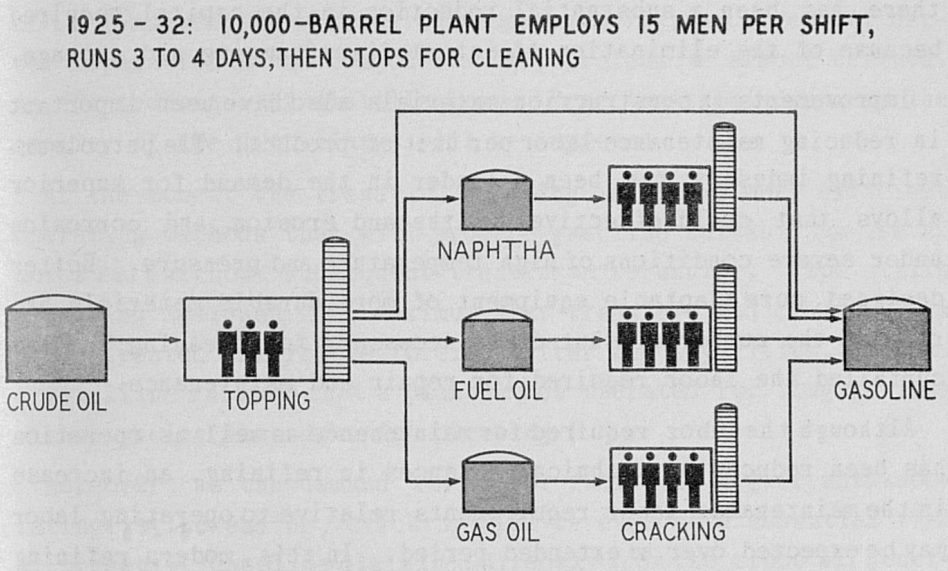
In the period 1925-32 the best practice among refineries operating primarily for the production of gasoline could be found in plants with an approximate daily capacity of 10,000 barrels. These plants usually included a topping unit employing three workers per shift and three cracking units, each of which employed four men per shift. The total direct-operating labor force was thus 15 men per shift. During the past 5 years a method was devised to interconnect the operation of the topping and cracking units in such a way that a single combination unit with a daily capacity of 30,000 barrels of crude oil can be operated with a labor force of only five men per shift. This represents approximately a ninefold increase in the productivity of the operating labor.[29]

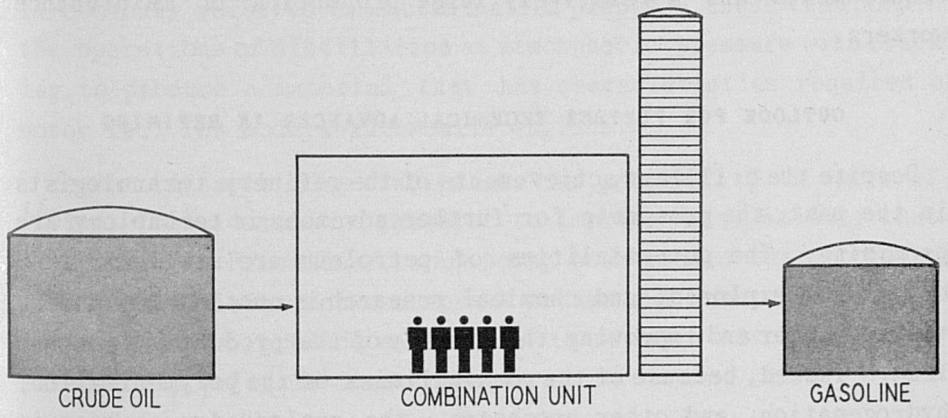
The striking contrasts between the two methods of production are illustrated by figure 29. It should be remembered that this is simply an illustration of the prevailing general tendency. Neither type of plant should be considered representative of the prevailing technique of the particular years, but rather should be regarded as representing the most efficient method developed. Thus, if a best-practice plant of the later type were to be substituted for an average-practice plant of the 1925-32 type, the improvement would be greater than the figure suggests because of a substantial lag between best and average practice.

In the technologic change represented by the combination unit, not only has the output per worker been greatly increased, but also

[29] In the 10,000-barrel plant of the 1925-32 era, the 15 men per shift undoubtedly worked at least 48 and probably 56 hours per week, whereas in the modern 30,000-barrel plant, each man works approximately 40 hours per week.

Figure 29.- EFFECT OF INCREASING CAPACITY AND CONTINUOUS PROCESS ON LABOR REQUIREMENTS IN PETROLEUM REFINING





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A development in petroleum refining during the past 5 years has been the replacement of individual topping and cracking units with a single, continuous combination unit. This change increased the capacity of the plant and reduced the operating labor requirements. In the period 1925-32 the best practice among refineries operated primarily for the production of gasoline could be found in plants with an approximate daily capacity of 10,000 barrels. These plants usually included a topping unit and three cracking units and required a total direct-operating labor force of 15 men per shift. On the other hand, a single modern combination unit with a daily capacity of 30,000 barrels can be operated with a labor force of only 5 men per shift. This represents a ninefold increase in the productivity of operating labor over a relatively short period.

there has been a substantial reduction in the capital required because of the elimination of intermediary pumping and storage.

Improvements in construction materials also have been important in reducing maintenance labor per unit of product. The petroleum-refining industry has been a leader in the demand for superior alloys that could effectively withstand erosion and corrosion under severe conditions of high temperature and pressure. Better designed, more adaptable equipment of more durable materials has reduced the number of shut-downs necessary for cleaning and has curtailed the labor required for repair and maintenance.

Although the labor required for maintenance as well as operation has been reduced by technical advances in refining, an increase in the maintenance-labor requirements relative to operating labor may be expected over an extended period. In this, modern refining technique follows a characteristic of virtually all highly automatic processes that tend toward small direct-operating labor requirements and a relatively large proportion of maintenance workers.

OUTLOOK FOR FURTHER TECHNICAL ADVANCES IN REFINING

Despite the brilliant achievements of the refinery technologists in the past, the prospects for further advances in technology are promising. The potentialities of petroleum are still far from being fully explored, and chemical research is continually adding to the number and improving the quality of the products of petroleum. Indeed, because of the possibilities of the polymerization, hydrogenation, and other processes, the outlook for changes in the technology of the refining industry today is much the same as it was in 1915, when the cracking process was just beginning to be applied. The lines of progress, however, hinge upon two factors of critical importance. The first is the adequacy of the crude-petroleum reserves and the second is the probable trend of demand. Because of these uncertainties, forecasting the future of refining is extremely hazardous.

Impending Changes in Techniques

Assuming an adequate supply of crude oil, the efficiency of present-day operations appears likely to be increased as a result of the engineering and chemical research that has recently been carried on in connection with the distillation process. Knowledge

of the fundamentals of fractionation is growing; as a result, better separation of the components of petroleum is almost certain. As the technique of distillation and fractionation advances, the quality of the distillates will be improved.

At the moment the trend of refining is toward more efficient operating methods that will produce gasoline suitable for use as motor fuel without subsequent treating or rerunning. Pipe stills are being designed for maximum heat transfer, and crude oil is being treated to remove foreign matter and impurities, such as crystalline salt, so that a plant may be operated for long periods without being shut down for cleaning.

Moreover, as the demand for motor fuel with higher antiknock rating is increasing, cracking will be even more essential than at present. Gasoline distilled directly from the crude oil generally has an octane rating too low for satisfactory use in modern automobiles; as a result, most plants now being erected are what is commonly referred to as combination plants - those that combine the operations of distillation at atmospheric pressure with cracking to produce a material that has characteristics required of motor fuel for modern automobile engines.

Recent research also indicates the possibility of more efficient fractionation of gasoline to improve the volatility characteristics. Fractionators are being constructed that provide a clean-cut division between normal butane and isobutane, and make it possible to produce a gasoline to a large extent free from exceedingly volatile constituents.

A characteristic feature of petroleum refining is a high rate of obsolescence. In order that they may be kept abreast of the ever-advancing technology, plants are almost continually being dismantled, reconditioned, rebuilt, or replaced. In complete refineries that manufacture a large variety of petroleum products, the motives for remodeling to take advantage of some new improvement are as powerful as those behind the rebuilding of strictly motor-fuel plants, and these changes involve considerable construction and maintenance labor.

Hydrogenation and polymerization as processes in the petroleum-refining industry are still in their infancy, but notable technical progress in both fields can be expected within the next 10 years. These developments will undoubtedly result in the manufacture of many new products, as well as an increase in the volume of current production. These processes may supplant older methods

of manufacture and reduce the labor required, but the manufacture of new products may open new fields of employment in the industry.

Within the past 2 years the polymerization process has been established on a commercial basis; enough data have been accumulated in the United States and abroad to indicate definitely that hydrogenation of coal and crude oil can be utilized to manufacture motor fuel on a large scale. The production of motor fuel by catalytic synthesis of water gas may be one of the many processes employed in the future when the supply of crude oil becomes less than the requirements of internal-combustion engines.

Both hydrogenation and polymerization employ high pressures and temperatures - factors that tend to make for high costs. Thus it may be that technologists will draw upon these processes in the future, but under somewhat different operating conditions than have been generally expected. A hint that this may be at least part of the nature of future technologic progress is suggested by a recent discussion of methods for transforming petroleum hydrocarbons into motor fuel at moderate temperatures and relatively low pressures.[30] A report that lends weight to this development is that two companies "were building ten new . . . . plants [that] . . . . will process approximately 150,000 barrels of residual oil from 300,000 barrels of crude oil a day, or some 10 per cent of the total U. S. crude refining capacity in use."[31]

Another reason why some close observers believe that hydrogenation and polymerization, in themselves, may not be the most important techniques that are being developed and introduced is that they are likely to be used on only a relatively small percentage of the total crude oil refined. The trend in the petroleum-refining industry has been toward more accurate specification and control of the properties of the finished product and toward increase in the yield of the most desirable ones. Particular emphasis has been placed on the development of high-octane gasoline[32] and the manufacture of numerous products represented by narrow boiling-point fractions. Although progress along these

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[30] E. Houdry, W. F. Burt, A. E. Pew, Jr., and W. A. Peters, Jr., "Catalytic Processing of Petroleum Hydrocarbons by the Houdry Process," *Proceedings, Nineteenth Annual Meeting, American Petroleum Institute* (Chicago, Nov. 14-18, 1938), Vol. XIX, Sec. 3, pp. 133-48; with reference to the low temperatures and pressures employed see particularly U. S. Patent No. 2,136,382 (application Mar. 27, 1936, Serial No. 71,341) granted Eugene J. Houdry, Nov. 15, 1938, p. 1.

[31] "Monsieur Houdry's Invention," *Fortune*, Vol. XIX, No. 2 (Feb. 1939), p. 57.

Footnote 32 appears on following page.

lines has been achieved thus far through close control of temperature, pressure, and other process variables, and has depended on instrumentation and improved materials and design, some technologists now think that precise control of process variables is no longer sufficient by itself. In ordinary distillation processes some 50 or more different hydrocarbons usually are present, and regardless of how closely processing conditions are controlled, the processes are not selective enough to yield the desired definition of final product. There is a growing belief that the extensive use of catalytic agents will overcome this limitation.

Certain polymerization and hydrogenation processes already utilize catalysis, and effort is being made to extend its use further to the accepted distillation and cracking processes. A handful of small pilot plants for this purpose are said to be either in the process of development or already in operation. The perfection of these methods is conceived as an important impending change in refining technique, since they will affect processes that operate on a major fraction of crude oil. As has been mentioned, the impetus for their development is the desire to manufacture finished products of narrow boiling-point ranges having accurate, predetermined, desirable properties. What effect they will have on labor requirements cannot be predicted.

Finally, further advances in liquid- and vapor-phase cracking are likely. Progress in this direction, however, depends on the better design and construction of equipment as well as on additional fundamental research by the chemists and engineers. The processes will be simplified, the quality of the products increased, and a wider variety of charging stocks handled. Improvements in operating technique, design, and construction will be devised to increase the capacity and the "on stream time" of the units. In the future, cracking processes and equipment may be improved to such an extent that by proper control and by catalysis narrow boiling-point fractions can be made as required.

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[32]The production of high-octane gasoline has received great attention during the past decade and much progress has been made. The octane number (a standard of measurement of the ability of fuels to resist detonation) has been improved by the addition of small quantities of tetraethyl lead and approximately 75 percent of the gasoline sold currently contains this antiknock agent. Other methods involve blending high-octane with low-octane gasolines and improved methods of extraction in regular production processes. Reflecting the advances that have been made, refiners have been able to raise the average octane number of regular-brand gasoline from approximately 61 in 1928 to an average of 71 in 1938. Data are estimated by W. W. Scheumann, "Automobile Engine Design Governs Modern Refinery Methods," *The Oil and Gas Journal*, Vol. 37, No. 25 (Nov. 3, 1938), p. 43.

Prospective Changes in Labor Requirements

Any change in the technical process of manufacture is sure to have an important effect upon labor requirements. In the aggregate, such changes are likely to cause a drop in the demand for manpower per unit of product. Direct-operating labor, for example, is particularly vulnerable to the onslaught of advancing technology and is the first to be affected by the further spreading of automatic control devices. Confirmation of this tendency is to be found in any modern large-scale plant where, without exception, operations are conducted by small labor forces of three or four men. The decline in unit labor requirements, however, may be expected to be more than offset by the expanding markets for an increasing variety of petroleum products, and total employment in the industry probably will increase. Indeed, the character of this trend is foreshadowed by recent preliminary figures showing a substantial increase in employment in petroleum refineries between 1935 and 1937.[33]

Although increased aggregate labor requirements may be expected to accompany impending changes in technique, there will also be important qualitative effects on the type of workers required. In general, the use of instruments and control devices, by transforming the manufacturing process so that quantitative measures replace accurate perception and experienced judgment, has eliminated many of the skills formerly required. Nevertheless the cumulative effect of these innovations has tended to raise the responsibility and training requirements of the operating labor. This apparent paradox results from the fact that it is usually easier to displace the most routine control operations by automatic devices, so that the workers who are left after the routine operations have been transferred to automatic control have additional responsibilities and require knowledge of the operation of at least a large portion of the whole plant. This change may be expected to continue in the future and finally may result in almost complete elimination of operating helpers who were formerly numerous in the refining industry.

Advancing technology has resulted, likewise, in significant qualitative and quantitative changes in other departments of the refining industry. In both the research and development departments employment opportunities have increased rapidly in

[33] *Census of Manufactures: 1937*, "Petroleum Refining" (U. S. Dept. Com., Bur. Census, mimeo., Dec. 28, 1938), p. 1.

recent years, more rapidly, in fact, than in almost any other industry.[34] The demand, however, is almost exclusively for skilled technicians and research workers. Although the number of workers in all occupations of the professional class has increased in recent years, the employment of laboratory assistants and other technicians has increased more rapidly than that of professional scientists.

Employment opportunities in petroleum refining for men without technical training are becoming more and more restricted to the "bull gang" - workers who perform the heavy manual labor incident to cleaning the stills and who handle equipment that cannot be moved by cranes and other devices.

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[34] G. Perazich, report on "Growth of Industrial Research" (WPA National Research Project, in preparation).

CHAPTER XI

EMPLOYMENT PROSPECTS IN THE PETROLEUM AND NATURAL-GAS INDUSTRY*

Employment opportunities in the oil and gas industry over the long run will be governed largely by answers that the future provides to three questions of critical importance. First, will it be physically possible for our oil and gas reserves to continue to supply the growing demand of a motor-minded society? Second, what will be the probable trend of future demand? Third, how much further can mechanization be carried with declining unit labor requirements?

The ultimate extent of oil and gas reserves is highly uncertain. The technical arts of discovery and production, moreover, stubbornly refuse to halt in their progress, and it is not possible to discount with reasonable precision the probable economic effects of advances that will be made at some distant date. It is feasible, nevertheless, to look forward 10 to 20 years and indicate developments already under way that will affect the trend of employment in oil and gas production insofar as this can be done simply by assembling the threads of evidence that have been uncovered in earlier chapters and generally accepted information on proved reserves and published estimates of probable demand. Although judgments are limited mainly to the short-term outlook, in some instances a long-time view is also possible.

THE BOUNTY OF NATURE

A decade and a half ago the first question, regarding the potentialities of our oil and gas reserves, would have been answered with little hesitation. Indeed, during the middle twenties, particularly, estimates of the probable life of our reserves were volunteered in many quarters. However, one by one these calculations were speedily relegated to the scrap heap by some untoward development; a Seminole or East Texas pool was discovered, advances in drilling techniques enabled producers to reach the great pay sands of a Kettleman Hills, or means were devised for

*By O. E. Kiessling, H. O. Rogers, Lew Suverkrop, G. R. Hopkins, and J. S. Ross.

recovering a larger percentage of the oil and gas from the underground reservoirs. If these lessons did nothing more, they at least suggested that wholesome respect for the complexity of the problem was in order, as the task of estimating petroleum and gas reserves is one of major magnitude. With better understanding of the meaning and importance of data on reserves, the rather numerous confident pronouncements of a decade ago have given place to more infrequent but more authoritative statements. These now usually bear the added weight of expressing the opinion of a representative industry committee, of an official Government agency or inquiry, or of an outstanding individual authority.

Petroleum Reserves

The most recent estimate of the Nation's proved petroleum reserves was made by the American Petroleum Institute Committee on Petroleum Reserves. According to this estimate the proved reserves of oil recoverable by prevailing practice totaled 17,348 million barrels on January 1, 1939.[1] This figure exceeds by nearly 2 billion barrels the estimate of reserves made by the same committee for January 1, 1938, and it is roughly $3\frac{3}{4}$ billion barrels above an estimate as of September 1, 1938, prepared for the Governor of Oklahoma.[2] Thus this 1939 estimate, used in this discussion, represents the most optimistic view taken in recent years of the size of proved reserves. It should be noted, however, that the proved reserve is quite a different matter from the volume of oil yet to be produced, since it makes no allowance for fields that may be discovered in the future.

By far the largest of the known reserves at the beginning of 1939 were those of Texas, California, Oklahoma, Louisiana, and New Mexico, which comprised 54.5, 18.4, 6.7, 6.0, and 4.1 percent, respectively, of the total. The remaining 11 percent was divided among 13 other commercially productive States. At production rates that prevailed in 1938 in the several States, moreover, the proved reserve has a calculated life ranging from 2.2 years for Michigan to 21.3 years for Montana.

At the rate of output that prevailed in 1938, total estimated proved reserves were ample to last 14.3 years. Actually it would

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[1] "Petroleum Reserves Are Estimated by Institute Committee at New Record Total," *American Petroleum Institute Quarterly*, Vol. 9, No. 2 (Apr. 1939), p. 7.

[2] A. W. McCoy, *Estimate of Petroleum Reserves From Known Fields in the United States, Sept. 1, 1938 - Including Estimated Costs - Past and Future* (Ponca City, Okla.: mimeo., Sept. 6, 1938), p. 2.

be impossible to produce the last fraction of the obtainable oil in existing fields in less than 20 or 30 years;[3] although output tends to decline rapidly in most fields after the early high-production period, it also continues for many years at a relatively low rate. Therefore, even before the period calculated as the life of present known reserves is ended, important new discoveries must be made if supplies are to be adequate.[4]

The recent upward trend in estimates of total proved reserves is apt to be misleading unless two other factors are considered as well. Although notable success in exploration explains a large part of the increase, "one of the prime causes of the recent increases in the indicated reserve is the revision brought about by the increased efficiencies of improved technique and delayed production."[5] Thus part of the larger figure on proved reserves represents a statistical refraction owing to inadequate discounting of progress toward efficient production in preparing earlier estimates. There is a definite limit to which such bonuses of potential production can bolster future estimates. A second point is that although estimates of total proved reserves increased roughly 4 billion barrels from the end of 1936[6] to January 1, 1939, the calculated life of such reserves at prevailing market requirements has shortened somewhat. This has been caused by a steady growth in demand, a trend that can be illustrated by noting that average yearly output for the five years 1934-38 was 23 percent greater than the average for the five years 1926-30. Should demand continue to grow, reserves must be increased at a still faster rate in the future than in the past if the relative size of the "working stock in advance of production"[7] is to be maintained.

Natural-Gas Reserves

Although careful estimates of natural-gas reserves have been made for individual fields from time to time, no comprehensive

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[3]National Resources Board, *A Report on National Planning and Public Works in Relation to Natural Resources and Including Land Use and Water Resources, With Findings and Recommendations* (Dec. 1, 1934), p. 405.

[4]A. W. McCoy, *op. cit.*, chart (d), "Estimated Producing Ability of Known Drilled Reserves" and chart (e), "Necessary Production From Discoveries After 1941 . . . ."

[5]J. E. Pogue, *Economics of the Petroleum Industry* (New York: Chase National Bank, 1939), p. 15.

[6]The figure used in this calculation is an estimate of 13,360,000,000 barrels made as of December 31, 1933, by Hale B. Soyster of the U. S. Geological Survey. See "Geology and Occurrence of Petroleum in the United States," *Petroleum Investigation* (U. S. Congress, House of Representatives, Hearings on H. Res. 441, 73d Cong., Recess, 1934), part 2, p. 1081.

[7]Dr. Pogue (*loc. cit.*) has used this phrase to describe the concept of the proved reserve.

survey has been attempted for the country as a whole. The most recent official estimate, made early in 1939 by the National Resources Committee, placed the proved reserves of natural gas at "from 60 to 100 trillion cubic feet."[8] Ralph W. Richards, who supplied the data upon which the National Resources Committee based its figure, believes the upper limit of this estimate to be conservative. He states: "The discovery of important gas reservoirs . . . . notably by deeper drilling in California, the Rocky Mountain area, and in the North Central States, warrants the opinion that the known natural gas reserves of the Nation are at least of the order of a hundred trillion cubic feet, or in excess of 30 years supply in terms of the present high rate of utilization."[9] Drafts on our natural-gas reserves, however, are being made at a much more rapid rate than the marketed consumption (approximately at the annual rate of $2\frac{1}{3}$ trillion cubic feet in 1937) indicates, since a large part of the gas produced is still being wasted outright[10] or is being discharged into the atmosphere after being stripped of its gasoline content. For this reason the actual life of present known reserves probably will be less than the theoretical life calculated on the basis of quantities of gas marketed currently. Neither information on natural-gas reserves nor on quantities of gas wasted is accurate and detailed enough to permit anything more than rough approximate conclusions.

Prospects for the Future

The inventory of proved reserves, reviewed in preceding paragraphs, indicates that supplies of both oil and natural gas are adequate for at least the next 10 years at the current - or even an expanding - rate of withdrawal. From chapter IV (pp. 69-73), moreover, it appears likely that new discoveries will continue to provide ample supplies for at least an additional decade. This opinion is based upon the view that (1) there remain large areas underlain with sedimentary rocks that have never been ade-

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[8]National Resources Committee, *Energy Resources and National Policy* (preliminary summary, mimeo., Jan. 1939), p. 83.

[9]R. W. Richards, "Natural Gas Reserves of the United States," *Energy Resources and National Policy* (National Resources Committee, 1939, in press), part II, sec. I. Richards' discussion suggests the following approximate percentage distribution of the proved natural-gas reserves: Mid-Continent and Gulf Coast, 52.2; California, 37.7; Appalachian, 7.8; Rocky Mountain States, 2.2; and North Central States, 0.1 percent.

[10]In 1935, according to F. S. Lott and G. R. Hopkins, losses and wastage of natural gas amounted to 479,826 million cubic feet. This was nearly a fifth of the total estimated production of natural gas during the year. See *Minerals Yearbook, 1937* (U. S. Dept. Int., Bur. Mines, 1937), p. 1060.

quately explored, (2) there are deep productive formations to be discovered in present producing fields and in areas prospected only to shallow depths or never prospected at all, (3) knowledge of the occurrence of petroleum will continue to expand and further increases in the technical efficiency of exploration are very likely, and (4) there are no recent signs that the technologist's ability to find new oil fields is waning. Certainly, over the relatively short-time outlook of 2 decades there appear no physical barriers to additional expansion of the industry.

Nevertheless the long-time prospect is one of growing difficulties. It appears doubtful that the constantly rising rate of discovery required by growing demand could be projected indefinitely into the future. Most of the discoveries to date have been made in new localities or at deeper horizons in some of the older areas, but each year the potential areas in which discoveries of major importance are possible are being reduced as a result of exploration. First, huge strips of the country have been discredited by geologists as possible sources of discovery because of the known character of the underlying rock.[11] In addition, large blocks of the areas that the geologists have regarded as favorable for the discovery of oil have been explored to the basement rocks that mark the end of possible producing strata. There remain other areas where there are deep-lying beds that are oil-bearing at shallower depths and have yet to be penetrated by the drill. Past experience, however, seems to indicate that for certain areas the gravity of the oil becomes lighter and lighter as pay horizons are topped at deeper levels until the oil in some instances exists as distillate; thus it appears that at still greater depths the hydrocarbons may exist only in the gaseous state. Just how these and other developments may affect the status of the industry in the more distant future is uncertain.

PROBABLE FUTURE DEMAND

Assuming that reserves are ample for the next 2 decades, employment opportunities in the oil and gas industry throughout this period will then depend primarily on demand. The present and potential applications of gas and liquid fuel are so inviting, moreover, that we can be sure that in the calculable future there

[11] *Petroleum Investigation*, part 2, pp. 910-2.

will be no return to the horse-and-buggy days. If our oil and gas resources cannot satisfy demand, the latter will be supplied by other raw materials.[12] But the precise level of future demand will be governed largely by a number of important variables.

Trend of Population

An important factor affecting future demand will be the trend of population. Since the war the slowing down of population growth has been quite marked, and it is certain to be still slower in the future. In fact, it appears likely that the population will attain its maximum early in the closing quarter of the present century and will subsequently decline.[13] A sharp contraction of immigration and a lower birth rate have more than offset the fall in death rates and are the principal factors responsible for the changing trend of population.

The prospects for the next 3 decades, however, are that the population will continue to increase, though at a gradually slackening rate. Assuming medium fertility and mortality and no net migration to or from foreign countries, Thompson and Whelpton of the Scripps Foundation for Research in Population Problems have published the following estimates of the future population of the United States:[14]

Year	Total population (thousands)
1940	132,630
1950	141,213
1960	147,612
1970	151,783

The consequences of this slackening of population growth on the demand for petroleum and natural-gas products probably will be less marked than might be expected because the age composition of the country will change materially. As a people we will live to a higher average age; during the next 20 years there will

[12] For a discussion of substitute motor fuels for gasoline obtained from crude oil from wells, see K. C. Heald, "Petroleum and Natural Gas," *Technology and the Mineral Industries* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-1, Apr. 1937), pp. 27-31.

[13] W. S. Thompson and P. K. Whelpton, "The Population of the Nation," *Recent Social Trends in the United States* (New York: McGraw-Hill Book Co., 1933), I, 48.

[14] National Resources Committee, *Population Statistics*, Vol. 1, "National Data" (Oct. 1937), p. 9.

be a large increase in the proportion of persons 45 and over and a somewhat smaller increase in the proportion in the most productive ages.[15] At the same time there will be a sharp decline in the proportion of minors and particularly of children under 5 years of age. For this reason a larger proportion of the total population will be potential customers for mechanical energy.

Probable Increase in Number of Motor Vehicles

As the oil and gas industry is geared primarily to supplying the requirements of the automobile, the next most important factor affecting demand is the number of motor vehicles likely to be in use in the future. Here again the task of anticipating the changes that lie ahead is complicated by great uncertainties. Although much depends on the purchasing power of future consumers, there are also other factors that have an important effect on the course of demand. How far-reaching will be the continued spread of compulsory drivers' liability insurance? In view of the mounting motor-accident rates, is it not likely that tests for drivers will be much more stringent and the number of licensed drivers greatly reduced? For the same reason, might not mechanical governors of maximum speed become standard equipment, at least in certain areas? As a new car costing approximately $750 delivered is by no means low-priced for the great bulk of car owners whose incomes are $1,500 a year or less,[16] what would be the effect of introducing a car costing $400 delivered?

In spite of the hazards posed by these questions, most observers think that an increase in the number of both passenger cars and trucks is to be expected in the future. In 1936 there were 28 million registered motor vehicles in the United States - 24,200,000 passenger cars and 3,800,000 trucks.[17] By 1937 the number of registered motor vehicles had increased to 29,705,220, excluding 336,072 Government-owned automobiles.[18] Although this was an all-time high, there have been no indications that a saturation point has been reached. An analysis of car ownership made when the depression was at its worst indicated that there was a motor

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[15] *Ibid.*

[16] D. H. Palmer, "Automobiles of 1938," *The New Republic*, Vol. LXXXXIII, No. 1205 (Jan. 5, 1938), p. 242.

[17] H. A. Osgood, "Transportation," *Technological Trends and National Policy*, (Washington, D. C.: National Resources Committee, June 1937), p. 182.

[18] *State Motor Vehicle Registrations - 1937* (U. S. Dept. Agr., Bur. Public Roads, mimeo., May 1938), table MV-1.

vehicle for every 2.77 people in California and one for every 3.46 people in Washington.[19] The survey showed that the ratio of car ownership was lowest in Arkansas, Mississippi, Alabama, and Georgia. Thus an important factor in expanding the use of motor vehicles appears to be the definitely limited ability of consumers to buy, particularly in what have been heretofore low-income areas of the country.

Recognizing the facts that there are many uncertainties and that ". . . . the problem of stabilizing the demand for automobiles lies in the . . . . future",[20] Breakey and Carmichael believe that the saturation point is one passenger car for four persons and assume that this density will be reached in 1950, when it is estimated there will be a maximum of 35,725,000 registered passenger cars.[21] At the same time, it is concluded that the number of motor trucks in operation in 1955 will be approximately twice the number 20 years earlier. After expansion has reached a certain level it appears probable that the trend of the number of vehicles will flatten after the middle of the present century and subsequently will parallel more closely the trend of population.

Prospective Course of Motor-Fuel Consumption

The average consumption per motor vehicle has increased more or less steadily in recent years[22] as the gain in average mileage driven and more powerful motors have more than counterbalanced the economies resulting from improvements in engine design. In 1937 the average vehicle used 18.8 barrels of motor fuel, an increase of 25 percent over 1928. Although the average mileage per car may continue to gain, even with increased traffic congestion, indications point to eventual stabilization in the average consumption of fuel per vehicle as results of the trend toward smaller, more economical cars[23] and of the probable development of more efficient motor fuels[24] and motors. It would be hasty,

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[19] Osgood, *loc. cit.*; see also statement of H. A. Breakey and F. L. Carmichael, "Consumption Aspects of the Petroleum Industry," *Petroleum Investigation*, part 1, p. 124.

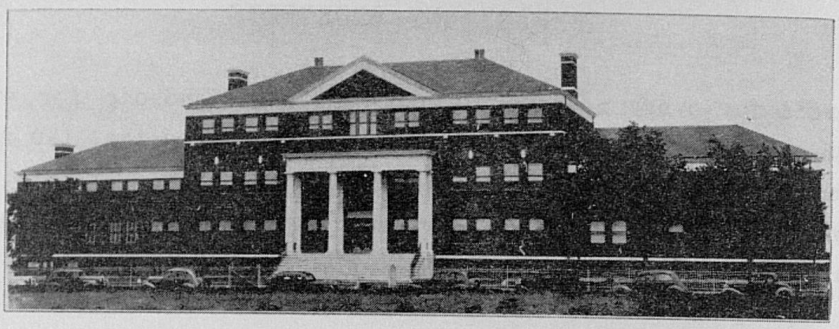
[20] S. M. Dubrul, "Significance of the Findings," *The Dynamics of Automobile Demand* (New York: General Motors Corp., 1939), p. 139.

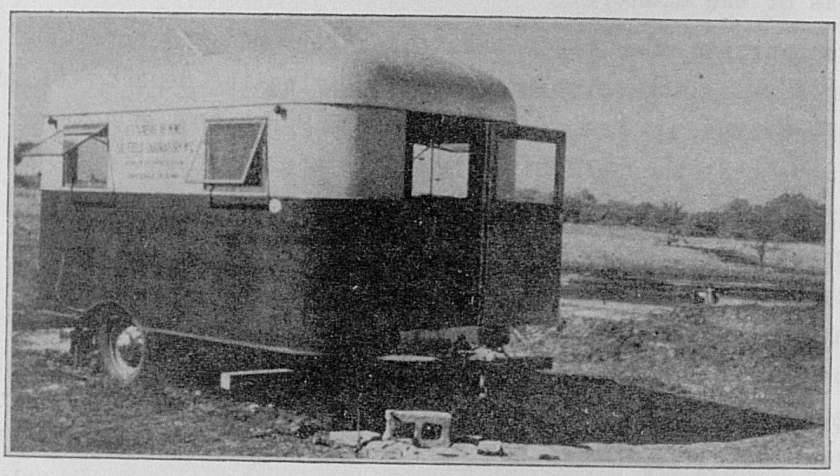
[21] Breakey and Carmichael, *loc. cit.*

[22] A. G. White, G. R. Hopkins, and H. A. Breakey, "Crude Petroleum and Petroleum Products," *Minerals Yearbook, 1937*, p. 1029.

[23] Palmer, *loc. cit.*

[24] H. E. Howe, "The Chemical Industries," *Technological Trends and National Policy*, pp. 295-6.





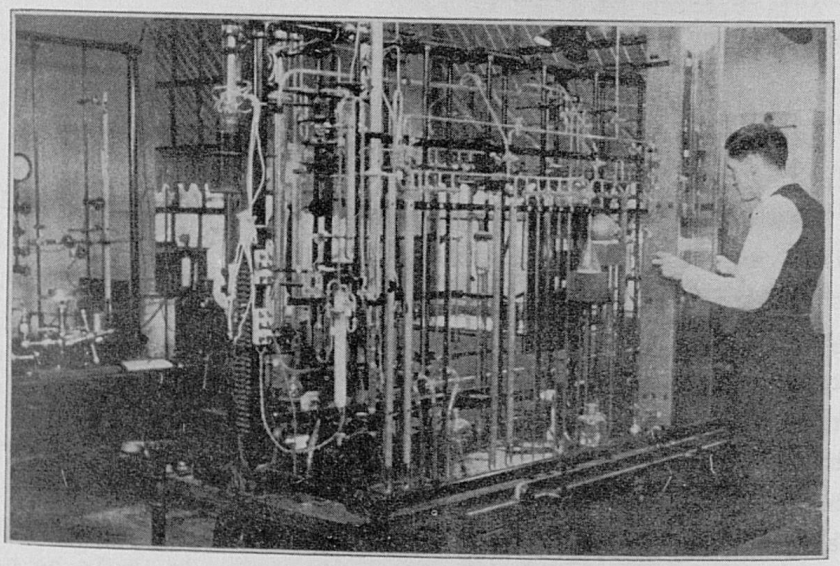


ILLUSTRATION 32.- FURTHER TECHNOLOGIC PROGRESS IN OIL AND GAS PRODUCTION ASSURED BY ACTIVE RESEARCH PROGRAMS

The growth of oil and gas production has been accompanied by a rapidly developing technology that has drawn extensively upon research conducted in many fields. State and Federal agencies, as well as operating companies, have sponsored such research work and have made important contributions.

The upper view shows the petroleum experiment station of the U. S. Bureau of Mines at Bartlesville, Oklahoma, where a research staff works upon the technical problems of the oil and gas industry; these studies sometimes require the use of a field laboratory, shown in the second view, that provides needed facilities for technical work at the well site. The bottom view shows laboratory equipment used in conducting investigations regarding the characteristics of petroleum at the pressures and temperatures in producing formations.

however, to assume that the trend will be toward the European-type small car in the near future. As one observer has noted, the present American car is based on the size of human beings, and the small English and Continental cars are products of enormous taxes on large motors, of high prices of fuels and lubricants, and of other conditions peculiar to the countries where they are used.[25]

A current development that confuses somewhat the outlook for motor-fuel demand has been the increasing use of Diesel motors. Although the first cost of Diesel-powered cars is relatively high, operators of trucks, busses, and tractors have turned to Diesel engines because fuel costs are notably smaller than those for equivalent power with gasoline. Comparisons between Diesel fuel-oil and gasoline costs are misleading, however, as a large part of the difference is explained by the fact that gasoline carries a heavy tax and fuel oil generally does not.[26] A broad shift from gasoline to fuel oil would almost certainly be followed by a tax on the latter. While it is true that Diesel engines already have definite application where relatively large power units are required, they have not yet been proved practicable for general use in the lighter cars. In some quarters, moreover, it is believed that the extra cost of efficient Diesel units for small cars will more than offset the fuel savings that they achieve.[27] Should these difficulties be overcome, it still appears that the oil industry's managers would adjust the refining process to increase the output of fuel oil and reduce the output of gasoline; the net effect upon total crude-oil demand would be the same whether the rate of increase in the average consumption of motor vehicles slowed because of the more efficient use of gasoline in regular motors or because of the increased use of Diesel engines.

Aside from increased consumption by passenger automobiles and trucks, additional expansion of the demand for motor fuel and for other petroleum products is to be expected from other sources during the next decade. Especially large increases in requirements are to be anticipated as a result of the continued growth of air transport. The increase in consumption may not be so spectacular as in the past dozen years, when the number of pas-

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[25] Osgood, *loc. cit.*
[26] Osgood, *op. cit.*, p. 183.
[27] *Ibid.*

sengers carried in the course of regularly scheduled air-transport operations rose from 5,782 in 1926 to 1,102,707 in 1937,[28] but it is likely to exceed the growth of consumption by automobile and truck by a substantial margin. Similarly, definite limits of consumption of motor fuel and related products by tractors and other agricultural equipment,[29] by railroads for Diesel-powered streamlined trains, and for domestic heating by an increasing number of families[30] are not yet in sight.

The demand for motor fuel is not a precise indicator of the demand for crude oil because of changes in the ratio of motor fuel obtained per barrel of crude oil refined. Since 1929 the average yield of gasoline has been more than 40 percent of the crude run to stills (see figure 27), but new knowledge concerning the possibilities of intensive cracking, polymerization, and other advanced refining processes promises substantially higher yields of gasoline in the future (see pp. 288-92). In a few installations today, yields as high as 70 percent are already being obtained. With more intensive processing, gasoline yields as high as 80 percent or more of the crude charged probably are possible. Such yields have not yet been obtained on a commercial basis because plants are not equipped to obtain them, because there has been no real need to cut that far into the crude to satisfy motor-fuel demand, because of the demand for other petroleum products, and for other reasons. In general, however, a gradual increase in the ratio of motor fuel to crude run to stills can be expected, and such an average ratio might well reach 75 percent should prices increase enough to make crude petroleum too valuable for other purposes than gasoline and lubricating oils.

Outlook for Future Requirements

A number of observers have appraised the long-time market tendencies already noted and have developed estimates of future crude-oil requirements. Such estimates, prepared by Parsons and St. Clair, by Breakey, and by the American Petroleum Institute,

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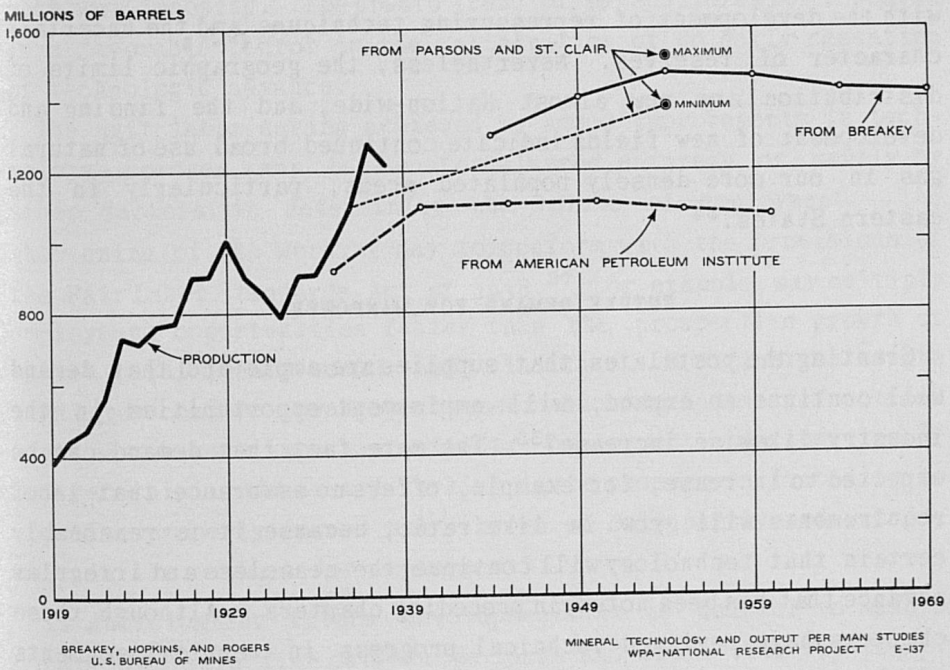
[28] *Progress of Civil Aeronautics in the United States* (U. S. Dept. Com., Bur. Air Com., mimeo., May 21, 1938), p. 3.

[29] E. G. McKibben and R. A. Griffin, *Changes in Farm Power and Equipment: Tractors, Trucks, and Automobiles* (WPA National Research Project, Report No. A-9, Dec. 1938), pp. 72-4; S. H. McCrory, R. F. Hendrickson, and Committee, "Agriculture," *Technological Trends and National Policy*, p. 101.

[30] L. J. Chawner, *Residential Building* (National Resources Committee, Housing Monograph Series No. 1, 1939), p. 17. It is noteworthy that the consumption of light fuel oil for domestic heating increased from 8,905,000 barrels in 1926 to 60,178,000 in 1936. See American Petroleum Institute, *Petroleum Facts and Figures* (5th ed.; New York: 1937), p. 39.

have been selected for presentation here. These figures range from a possible high of 1,520,000,000 barrels for 1954, predicted as a maximum by A. B. Parsons and Stuart St. Clair,[31] to a low of 1,088,000,000 barrels for 1955, predicted by the American Petroleum Institute.[32] The differences are explained by variations in weighting the factors that are expected to influence demand.

Figure 30.- ESTIMATED TRENDS OF CRUDE-PETROLEUM PRODUCTION TO 1969



As is shown in figure 30, estimates prepared by H. A. Breakey of the U. S. Bureau of Mines[33] are somewhat below the possible maximum suggested by Parsons and St. Clair and also are considerably above the figures of the American Petroleum Institute. Breakey concludes that the demand for crude oil will reach its peak about 1954, when demand will be approximately 1,500,000,000

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[31] "Outlook for World Consumption of Metals and Fuels," *Mining and Metallurgy*, Vol. 18, No. 364 (Apr. 1937), p. 195.

[32] American Petroleum Institute, Committee on Future Demand, F. Van Covern, chmn., "Demand: The Probable Future Demand for Crude Oil and Motor Fuel in the United States in Intervals of Five Years From 1940-1960," *American Petroleum Industry* (New York: 1935), p. 32.

[33] From an unpublished study by H. A. Breakey, "The Measurement and Forecasting of Domestic Motor Fuel Demand."

barrels (see table A-30). Thereafter the trend is expected to be moderately downward, and the crude-oil requirements for 1969 are estimated at 1,418,000,000 barrels. For the purposes of this survey it suffices to note that the estimates of Breakey and of Parsons and St. Clair anticipate continuation of the upward trend of crude-oil demand for about the next 2 decades.

Although inadequate information precludes an estimate of the future demand for natural gas, here, too, the evidence points toward expansion of markets over at least the short-time outlook. There are, it is true, influences regarded as retarding by some observers, such as the increased use of gas in oil production with the development of repressuring techniques amd the uncertain character of reserves. Nevertheless, the geographic limits of distribution are now almost Nation-wide, and the finding and development of new fields indicate continued broad use of natural gas in our more densely populated areas, particularly in the eastern States.[34]

FUTURE DEMAND FOR MANPOWER

Granting the postulates that supplies are ample and that demand will continue to expand, will employment opportunities in the industry likewise increase?[35] The mere fact that demand can be expected to increase, for example, offers no assurance that labor requirements will grow in like ratio, because it is reasonably certain that technology will continue the ceaseless and irregular advance that has been noted in preceding chapters. Although these chapters have reviewed technical progress in vertical segments of the industry, it should be noted that technology cuts across the industry as a whole in broad, horizontal sweeps. Evidence that technical progress will continue in the future, moreover, is to be found in the continued growth of scientific research in the industry.

According to a study now in preparation,[36] research activity (for which data are available) in petroleum refining has increased more rapidly in the period since the World War than in any other

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[34] E. B. Swanson, "The Natural-Gas Invasion: An Example of the Sudden Expansion of Transport," *Mineral Economics: Lectures Under the Auspices of the Brookings Institution* (1st ed.; New York: McGraw-Hill Book Co., 1932), p. 103.

[35] The term "employment opportunities" is used in this discussion to mean both the total man-hours of labor and the number of workers.

[36] WPA National Research Project report on "Growth of Industrial Research", in preparation by George Perazich, who has kindly supplied the statistics used in this paragraph.

major industry except automobile manufacturing. Between 1920 and 1933 the number of oil companies maintaining research laboratories increased from 7 to 53, and the number of employees engaged in this kind of research rose from 160 to 2,808. The period since 1933, moreover, has been marked by further expansion in organized research, and at the beginning of 1938 the total research personnel connected with petroleum refining probably was between 5,000 and 6,000. If figures were available on the number of persons engaged in research in other branches of the industry - particularly in the geological and production-engineering departments - the over-all total of number of research workers employed would be much more imposing. The upward trend of expenditures for research is a favorable factor in the anticipation of no early cessation of technologic advance.

The unit labor saving achieved by added improvements in technology, however, may be counterbalanced entirely or partly by other factors in determining the volume of employment. The shortening of the working day to conform with the provisions of the Fair Labor Standards Act of 1938,[37] for example, may multiply employment opportunities faster than the prospective growth of market requirements would tend to indicate. Modification of the legal and economic arrangements under which the industry functions might also have an important effect on employment opportunities.[38] But recognizing the hazard lurking in the observer's inability to appraise properly forces now unknown or only partly understood, what is the outlook for employment?

In anticipating future developments it is helpful to make a clear-cut distinction between the long- and short-time viewpoint. It is also essential to distinguish the several segments of the industry for, though all are closely related, each has special problems and characteristics.

Oil and Gas Wells

If attention is focused on the near future - say for the next 10 years - it appears reasonably certain that the forces that

[37] Under this law the standard full-time workweek for all workers in industries engaged in interstate commerce or in the manufacture of goods shipped in interstate commerce, with some exceptions, is defined as 44 hours during the first year of the law's operation (Oct. 24, 1938, to Oct. 24, 1939), 42 hours during the second year, and 40 hours after the law has been in effect 2 years. The law does not forbid employment in excess of the standard workweek hours provided the employee is compensated for such excess at one and a half times the regular rate at which he is employed.

[38] See pp. 210-3.



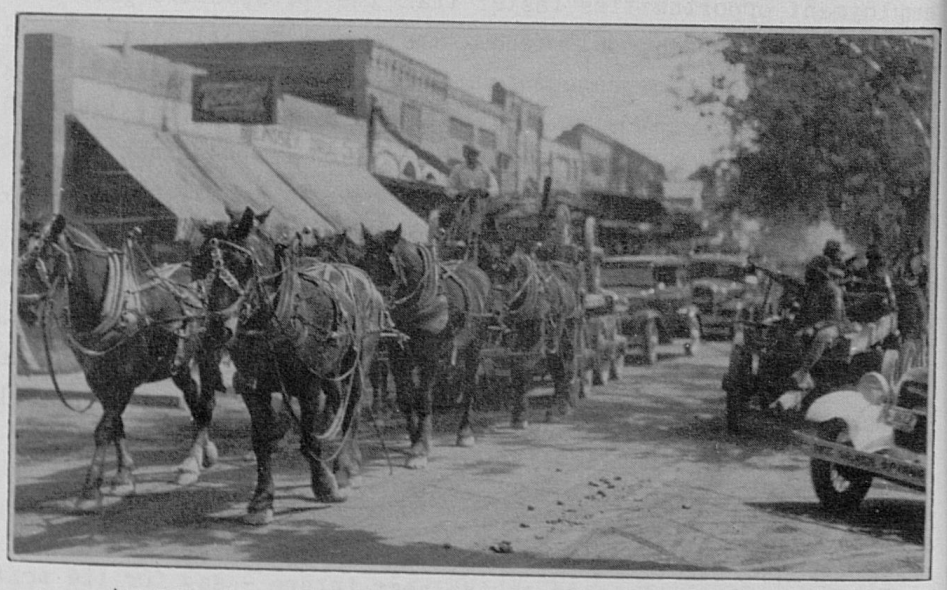


ILLUSTRATION 33.— FEVERISH ACTIVITY FREQUENTLY ACCOMPANIES OIL-FIELD DEVELOPMENT

Oil is not usually found in handy places, and the development of an oil field in rural or sparsely settled areas usually taxes the resources of adjoining villages and is characterized by feverish activity. Such development, moreover, is usually accompanied by an influx of migrant workers.

The upper view shows a street at Seminole, Oklahoma, in 1927, during an oil boom. The lower view shows activity in Overton, Texas, during boom development in East Texas.

operated to increase manpower requirements in oil and gas production before 1929 will again become active and the demand for labor will expand. The setback that employment received during the depression was not due to any epoch-making advance in technology but to the drastic curtailment of drilling and its rigid restriction to proved areas.[39] As a large part of the labor embodied in oil and gas production is utilized in the process of drilling, the sharp reduction in the number of wells drilled reacted immediately to reduce the volume of employment. With rising prices and expanding consumption, however, drilling has been resumed on a more extensive scale. Moreover, the chances favor continued expansion because growing demand requires a large number of new wells and because increasing average depths of wells will probably offset greater technical efficiency in drilling.[40] Finally, changing techniques of exploration indicate that more labor will be required in exploration and test drilling.[41]

Employment in the immediate future at oil and gas wells will also be stimulated by the maximum-hour provisions of the Fair Labor Standards Act of 1938. Before October 24, 1938, drilling operations by a large number of producing companies as well as by contractors were operating on a working schedule of 8 hours a day and 7 days a week, a total of 56 hours.[42] To conform with the 44-hour maximum prescribed by the new law, some of these companies have employed additional crews, resulting in an increase of about a third in the number of men employed.[43] Many other companies, however, were not materially affected, as their working schedules met the requirements of the law. But by 1940, when the full-time week will be limited to 40 hours, virtually all operators will be forced to make some readjustments of their working schedules that will involve the employment of additional workers.

The long-term outlook for employment is obscured by many uncertainties. Although it is reasonably certain that oil and natural gas will continue to be produced in appreciable quantities for several decades more, if additions to reserves fail to equal withdrawals sharp price increases would cause a shift to other

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[39] Between 1929 and 1931 the number of wells drilled (including oil and gas wells and dry holes) decreased more than 50 percent, and even in 1935 the number was nearly 20 percent less than in 1929.

[40] See pp. 122-3.

[41] See p. 73.

[42] L. J. Logan, "Readjustments of Working Schedules Are Necessary Under New Law," *The Oil Weekly*, Vol. 91, No. 9 (Nov. 7, 1938), p. 14.

[43] *Ibid.*, p. 15.

sources of motor fuel and lubricants. At the same time, the higher level of prices would permit greater expenditures for labor in finding and producing oil and gas from wells as long as such efforts were attended with reasonable success. The long-range outlook is for the expenditure of a greatly increased amount of labor in the production of coal and oil shale, the most promising substitute sources of motor fuel and lubricants.

Refining

In refining, also, both short- and long-time prospects seem to favor increased employment opportunities, but the demand will be increasingly for skilled and semiskilled workers and for technicians. It is true that large savings of labor are possible at the modern combination plants that both skim and crack; likewise, in lubricating-oil production the trend is toward manufacture in solvent plants where both the operating steps and labor requirements are reduced. Nevertheless, expanding polymerization capacity[44] and the trend toward the manufacture of an increasing variety and volume of chemical products from petroleum gases probably will more than counterbalance these influences. A beginning has also been made in utilizing crude oil as a raw material in the manufacture of important chemicals; the commodities produced from petroleum include amyl alcohol, acetone, ethylene glycol, and a synthetic plastic.[45] This development already has created many jobs for skilled and technically trained workers and undoubtedly will be the source of more employment in the future. Furthermore, although the polymerization process at present overshadows the possibilities of hydrogenation, the general procedure of adding hydrogen molecules from one source to carbon molecules from another promises to become increasingly important as our oil resources become leaner. For these and other reasons, noted at the end of chapter X,[46] employment in refineries is expected to increase, and there will be further qualitative changes in the character of the labor force.

Natural Gasoline

The need for manpower at natural-gasoline extraction plants also appears likely to increase for some years to come, principally because of the steadily growing demand not only for motor

[44] See pp. 289-90.
[45] Howe, *op. cit.*, p. 296.
[46] See pp. 288-91.

fuel but also for propane, butane, and pentane - the lighter constituents of raw natural gasoline that until a few years ago were allowed to go to waste. The potential applications of liquefied petroleum gases are so inviting, particularly for use in rural areas, that increased effort unquestionably will be required to meet the demand. The wide use of polymerization at natural-gasoline plants seems imminent,[47] moreover, and would stimulate employment. It cannot be overlooked, however, that future trends will depend on developments at oil and gas wells that are the sole source of the raw material required by the natural-gasoline plants.

Transportation

No outstanding changes are in sight that are likely to have an important effect on employment opportunities in the transportation of petroleum and natural gas. In the East the probabilities are that the gas pipe-line network will be extended moderately during the next few years. On the West Coast also the prospects favor gradual extension of the gas lines; deposits of gas have recently been proved in new fields in California, and natural gas eventually may be piped north to Oregon and Washington. There is, however, no immediate prospect of a rapid expansion of gas pipe-line construction comparable with that of the late twenties.

Extension of crude-oil lines appears to be checked at present by the fact that tanker rates are generally lower than pipe-line tariffs. The principal effect of this difference in transportation changes has been to increase the tanker movement to the East Coast and to eliminate through pipe-line movements from the Mid-Continent. The center of production in recent years has been moving southward, thus reducing the average length of pipe-line movement incident to consumption at Gulf Coast and East Coast refineries, but this is balanced by the increase in the distance to the many large plants in the Great Lakes area. Gasoline pipe-line construction, on the other hand, has increased notably[48] and probably will continue to expand for some time.

For pipe lines in general, operation is almost completely mechanized. Greater technical efficiency is possible, of course, but the opportunities for labor saving are not so good as they were

[47] See p. 189.
[48] See p. 238.

a decade ago. Even though the tendency toward greater mechanical efficiency continues, particularly as old stations are replaced,[49] factors inducing less employment probably will be offset by a larger volume of products moved. Thus, barring an unforeseen expansion of large-scale pipe-line construction, the prospect is that employment opportunities in the transportation segment of the industry probably will fluctuate within a narrow range, at least for some time to come.

Summary of Short- and Long-Time Outlook

To summarize, both short- and long-time outlooks indicate that additional workers will be required in the petroleum and natural-gas industry. The increase will follow in part the expected continued growth of demand for motor fuel and lubricants and in part other factors, such as the shortening of the standard workweek, tending to counterbalance a continued increase in output per man-hour owing to improved technology. For the next decade and a half the prospects appear fairly clear. Our proved reserves assure ample supplies for such a period and employment opportunities may be expected to increase, possibly at a somewhat slower rate than demand. The long-time outlook is clouded by uncertainties regarding reserves and the probable success of future efforts in exploration. This prospect, nevertheless, is one of growing difficulties in which technology finds it harder to overcome the handicaps of nature. The arrival of a stage of increasing cost and of greater human effort in production is forecast by experience in older producing fields. Finally, when output from wells undergoes major contraction and it becomes necessary to supply at least a part of the motor-fuel demand from alternative sources such as coal and shale, society must expect to devote an increasing proportion of its labor force to the task of mining the minerals from which the motor fuel is extracted. Although the developments that probably would accompany a scarcity of oil and gas from wells can be visualized to a certain extent, just when the period of diminishing abundance will emerge only the future can disclose.

Although the outlook is for increasing employment opportunities, the influence of technology in modifying the composition of the working force is expected to continue. The demand for unskilled

[9] See p. 252.

labor in most branches of the industry - notably exploration, refining, and pipe-line transportation - is disappearing rapidly. The trend is now toward trained technicians and skilled and semi-skilled workers and away from the floating crew of roustabouts that formerly comprised most of the industry's working force. In drilling there is still heavy work for the laborer, but even here increasing proportions of skilled workers are required. For the bulk of the industry's labor force youths with high-school education or its equivalent are preferred by oil companies as new employees.[50] Most of those accepted for employment, moreover, usually are put through an additional schedule of training at company expense. There is little hope for reemployment of older, untrained workers who have lost their jobs in the industry.

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[50] National Youth Administration of Texas, J. C. Kellam, Director, *Employment Opportunities in the Oil Industry in Texas* (Austin, Tex.: Industrial Study No. 1, mimeo., Sept. 1, 1938), p. 80.

STATISTICAL APPENDIX

Table A-1.- NUMBER OF WAGE EARNERS EMPLOYED IN PETROLEUM, NATURAL-GAS, AND NATURAL-GASOLINE PRODUCTION AND THE NUMBER EMPLOYED IN OTHER MINERAL INDUSTRIES, 1909-35[a]

Mineral industry	1909	1919	1929	1935
Number, total	953,369	999,529	967,356[b]	804,883[b]
Mineral fuels, total	703,924	804,375	780,533	664,599
Bituminous coal	488,000[c]	545,798	458,732	435,426
Anthracite coal	169,175[d]	147,372	142,801	92,438
Petroleum, natural gas, and natural gasoline[e]	46,749[f]	111,205[f]	179,000[g]	136,735
Metal ores, total	149,905	131,186	110,076	76,293
Iron ore[h]	47,305	46,650	28,870	14,873
Nonferrous metal ore	102,600	84,536	81,206	61,420
Industrial nonmetals other than fuels	99,540	63,988	76,747[b]	63,991[b,i]
Percent, total	100.0	100.0	100.0	100.0
Mineral fuels, total	73.8	80.5	80.7	82.6
Bituminous coal	51.2[c]	54.6	47.4	54.1
Anthracite coal	17.7[d]	14.8	14.8	11.5
Petroleum, natural gas, and natural gasoline[e]	4.9[f]	11.1[f]	18.5[g]	17.0
Metal ores, total	15.8	13.1	11.4	9.4
Iron ore[h]	5.0	4.7	3.0	1.8
Nonferrous metal ore	10.8	8.4	8.4	7.6
Industrial nonmetals other than fuels	10.4	6.4	7.9[b]	8.0[b,i]

[a] Except as noted, data for 1909-29 are from *Fifteenth Census of the United States: 1930*, "Mines and Quarries: 1929" (U. S. Dept. Com., Bur. Census, 1933), pp. 33-5; data for 1935 are from *Census of Business: 1935* (U. S. Dept. Com., Bur. Census in cooperation with U. S. Dept. Int., Bur. Mines, mimeo. releases for each mineral industry).

[b] For comparability with data for previous years the totals for 1929 and 1935 exclude the sand and gravel industry. Data for 1935 indicated 8,566 wage earners in this industry.

[c] Wage earners employed in coke manufacture at mines are excluded, partly by estimate. See *Fourteenth Census of the United States: 1920*, Vol. XI, "Mines and Quarries: 1919" (U. S. Dept. Com., Bur. Census, 1922), p. 257.

[d] *Ibid.*

[e] Includes estimates of the number of wage earners employed by contractors. See table A-11.

[f] Data on number of wage earners employed by regular producers from *Thirteenth Census of the United States: 1910*, Vol. XI, "Mines and Quarries: 1909" (U. S. Dept. Com., Bur. Census, 1913), pp. 271, 289.

[g] Estimated by subtracting from the number of wage earners attached to the industry (*Fifteenth Census of the United States: 1930*, "Population" [1933], V, 422, 424) the number of unemployed wage earners (as derived from the number of unemployed persons reported in the *Fifteenth Census of the United States: 1930*, "Unemployment," I, 53-4). The result was first corrected to represent 1929 by the use of the U. S. Bureau of Labor Statistics indexes of crude-petroleum employment and then corrected for the estimated amount of understatement by the Bureau of the Census.

[h] Includes manganiferous ore and, except for 1935, manganese. The incomparability resulting from the exclusion of manganese in 1935 appears to be negligible, as only about 1 percent of the total number of wage earners employed in iron ore and manganese extraction in 1929 were employed in the extraction of manganese.

[i] Excludes sulphur and pyrites which were included in previous years. In 1929, 2,199 wage earners were employed in producing sulphur and pyrites.

Data for marble include a revision that had been made subsequent to the published release for that industry. The revised figure for the number of wage earners is 2,105.

Table A-2.- EMPLOYMENT IN THE OIL AND GAS INDUSTRY, BY MAJOR DIVISION, 1935

Table A-2.- EMPLOYMENT IN THE OIL AND GAS INDUSTRY, BY MAJOR DIVISION, 1935

Major division	Number of producing units or establishments	Average number of wage earners[a]	Number of salaried employees[b]	Total employees		Number of active proprietors and firm members	Total number of persons engaged
				Number	Percent of total		
Total	-	n.a.	n.a.	693,611	100.0	n.a.	n.a.
General administrative offices (for all divisions)	n.a.	n.a.	n.a.	62,000[c]	8.9	n.a.	n.a.
Production of -							
Crude petroleum[d]	340,990 wells	119,305	9,903	129,208	18.6	n.a.	n.a.
Natural gas[d]	53,790 wells	9,673	2,961	12,634	1.8	n.a.	n.a.
Natural gasoline[d]	715 plants	7,997	1,052	9,049	1.3	n.a.	n.a.
Transportation[e] by -							
Gathering and trunk oil-pipe lines[f]	114,690 miles of line	22,000	2,000	24,000	3.5	n.a.	n.a.
Gathering and trunk gas-pipe lines[g]	79,200 miles of line	15,000	2,000	17,000	2.5	n.a.	n.a.
Petroleum refining[h]	395 refineries	77,402	14,709	92,111	13.3	37	92,148
Marketing of -							
Petroleum products							
At bulk-tank stations and other wholesale outlets[i]	27,333 bulk-tank stations, 864 other establishments	n.a.	n.a.	114,856	16.6	3,999	118,855
At filling stations[j]	197,588 filling stations	n.a.	n.a.	203,753	29.4	179,870	383,623
Natural gas	94,800 miles of distributing mains[k]	n.a.	n.a.	29,000[l]	4.2	n.a.	n.a.

[a] The average was computed by totaling the number reported employed on or near the 15th of each month and dividing the sum by 12.

[b] Includes field salaried employees only; central-administrative-office employees for all major divisions are combined and shown separately.

[c] Partly estimated from data reported by oil companies to the U. S. Bureau of Mines cooperating with the U. S. Bureau of the Census, from data specially compiled by the U. S. Bureau of Mines from reports of oil pipe-line companies to the Interstate Commerce Commission, and from other general information.

[d] Data include employment in drilling 15,108 oil wells, 1,401 gas wells, and 4,911 dry holes. Data on number of producing units and employees of regular producers from *Census of Business: 1935*. "Petroleum Industry in 1935" (U. S. Dept. Com., Bur. Census in cooperation with U. S. Dept. Int., Bur. Mines, mimeo., June 21, 1937); "Natural Gas Industry in 1935" (Mar. 30, 1937); and "Natural Gasoline Industry in 1935" (Mar. 3, 1937). Data on number of workmen employed by contractors partly estimated on the basis of partial reports to the U. S. Bureau of Mines on employment, labor cost of drilling wells, number of wells drilled by contractors, and other data. See table A-3.

[e] Excludes tanker ships, motor transport, and all forms of transportation other than by pipe line.

[f] Data on miles of crude-oil pipe line derived from data for May 1, 1931, and June 30, 1936, from *Survey of Crude Oil in Storage, 1936-1937* (U. S. Dept. Int., Bur. Mines, Report of Investigations 3417, mimeo., Sept. 1938), p. 43; data on miles of gasoline pipe line from U. S. Bureau of Mines statistics as published in *Statistics of Oil Pipe Lines, 1921-1937* (Interstate Commerce Commission, Bur. Statistics, Statement No. 398, mimeo., Feb. 1939), p. 13; data on employment of pipe-line companies reporting to the Interstate Commerce Commission was specially compiled by the Bureau of Mines from reports of oil pipe-line companies to the Interstate Commerce Commission; and data for all other companies were estimated on the basis of their pipe-line mileage and miles of pipe line per employee of those carriers reporting to the Interstate Commerce Commission.

[g] Mileage of natural-gas pipe lines received from Paul Ryan, Chief Statistician, Statistical Department, American Gas Association, on May 3, 1939. Employment data were estimated from natural-gas pipe-line mileage and miles of pipe line per employee of oil pipe-line companies reporting to the Interstate Commerce Commission.

[h] Data from *Census of Manufactures: 1935* (U. S. Dept. Com., Bur. Census, 1938), pp. 7-8, 749.

[i] Data from *Census of Business: 1935*, "Wholesale Distribution" (U. S. Dept. Com., Bur. Census, 1937), vol. II, pp. XVII-XVII. For a more detailed analysis of this item see table A-4.

[j] Includes only retail stations primarily engaged in the sale of gasoline and oil and does not include garages, stores, and other enterprises that retail petroleum products as a supplementary activity. Data from *Census of Business: 1935*, "Retail Distribution" (U. S. Dept. Com., Bur. Census, 1937), vol. IV, p. 13. For a more detailed analysis of this item see table A-5.

[k] Data received from Paul Ryan on May 3, 1939.

[l] Partly estimated by subtracting from the total number of employees in all branches of the natural-gas division (obtained from Paul Ryan on March 10, 1937) the number engaged in drilling and operating gas wells, exclusive of contractors' employees, and the estimated number engaged in maintaining and operating natural-gas pipe lines.

n.a. Data not available.

Table A-8.- NUMBER OF WAGE EARNERS AND SALARIED EMPLOYEES EMPLOYED BY REGULAR PRODUCERS AND BY CONTRACTORS, IN PETROLEUM, NATURAL-GAS, AND NATURAL-GASOLINE PRODUCTION, 1935

Type of employee	Total	Crude-petroleum production	Natural-gas production	Natural-gasoline production
Wage earners	136,975	119,305	9,673	7,997
Employed by producers[a]	108,735	93,450	7,288	7,997
Employed by contractors[b]	28,240[c]	25,855	2,385	0
Salaried employees[d]	13,916	9,903	2,961	1,052
Employed by producers[a]	11,770	7,938	2,780	1,052
Employed by contractors[e]	2,146	1,965	181	0
Wage earners and salaried employees	150,891	129,208	12,634	9,049
Employed by producers	120,505	101,388	10,068	9,049
Employed by contractors	30,386	27,820	2,566	0

[a]Data from *Census of Business: 1935*, "Petroleum Industry in 1935" (U. S. Dept. Com., Bur. Census in cooperation with U. S. Dept. Int., Bur. Mines, mimeo., June 21, 1937); "Natural Gas Industry in 1935" (Mar. 30, 1937); and "Natural Gasoline in 1935" (Mar. 3, 1937).

[b]Derived from reports of a sample of contractors to the U. S. Bureau of Mines, from wage costs of drilling wells, from the estimated number of wells drilled by contractors, from average hourly earnings of contractors' employees, and from the estimated number of man-hours worked per wage earner.

[c]Does not agree with figure shown in table A-11 because of rounding off on the latter table.

[d]Represents administrative, supervisory, technical, and clerical employees on a salary basis at field offices; excludes central-administrative-office employees.

[e]Estimated on the basis of the ratio of salaried employees to wage earners as reported to the U. S. Bureau of Mines by a sample of drilling contractors.

Table A-4.- EMPLOYMENT IN WHOLESALE DISTRIBUTION OF PETROLEUM AND ITS PRODUCTS, 1935[a]

Type of operation	Number of establishments	Average number of full-time and part-time paid employees[b]	Number of active proprietors and firm members	Total number of persons engaged
Total	28,197	114,856	3,999	118,855
Bulk-tank stations[c]	27,333	108,323	3,546	111,869
Independent stations[d]	3,880	12,901	3,075	15,976
Chain-operated stations[e]	17,017	78,258	471	78,729
Commission stations[f]	6,436	17,164[g]	0	17,164
Full-service and limited-function wholesalers[h]	674	4,437	389	4,826
Manufacturers' sales branches[i] (with stocks)	56	814	0	814
Manufacturers' sales offices[j] (without stocks)	25	955	1	956
Agents and brokers[k]	109	327	63	390

[a] Data from *Census of Business: 1935*, "Wholesale Distribution" (U. S. Dept. Com., Bur. Census, 1937), vol. II, pp. XVII-XXVII. Data exclude central-administrative-office employees.

[b] Includes salaried corporation officers and executives as well as wage earners. The average was computed by totaling the number reported monthly (for the pay period ending nearest the 15th of each month) and dividing the sum by 12. "For the purposes of this inquiry, respondents were requested to report persons regularly working four or more hours per day, or more than three full days per week, as full-time employees, and all others as part-time employees." Part-time employees accounted for about 4 percent of the total for bulk-tank stations. (*Ibid.*, vol. V, pp. 14-5, 21.)

[c] Represents "wholesale establishments storing and distributing gasoline, oil and other petroleum products. This classification includes stations servicing filling stations owned by the same organization as well as stations selling to independent retailers or to industrial users." (*Ibid.*, vol. II, p. V.)

[d] These stations "are independently owned and not operated in conjunction with others of their kind nor with filling stations under the same ownership. The term carries no implication as to whether the products sold are those of the so-called major oil companies or of independent refiners." (*Ibid.*)

[e] These stations "are operated with others of their kind and/or with filling stations under the same ownership, either by an oil producer or by a multi-unit operator independent of any producer. This classification includes only those stations of multi-unit organizations which are operated on a salary basis." (*Ibid.*)

[f] These stations "are owned by multi-unit concerns but operated by managers with a proprietary interest. The operators of these stations are paid commissions which include indeterminate amounts for overhead and delivery costs as well as pay roll." (*Ibid.*)

[g] As estimated in *ibid.*, p. XVII, ftn. 1. (The estimate was derived by dividing the net sales of commission stations in each State by the sales per employee of noncommission stations in the same State.)

[h] "This functional type-group includes wholesale establishments which are engaged in the buying and selling of goods on their own account, and which are largely independent in ownership." (*Ibid.*, p. III.)

[i] "Wholesale outlets owned and operated by manufacturers apart from their plants primarily for the purposes of carrying stocks of, selling, and delivering their own products. Sales of manufacturers' sales branches include bookings (sales for direct delivery from plant) as well as sales from stocks at the branches. Subsidiary sales corporations of manufacturers have been classified as full-service and limited-function wholesalers rather than manufacturers' sales branches." (*Ibid.*, p. V.)

[j] "Establishments maintained by manufacturers apart from their plants for the purpose of selling their products. Sales offices are distinguished from sales branches by the fact that they do not include facilities for the physical storage, handling and delivery of merchandise." (*Ibid.*)

[k] "This type-group includes middlemen who negotiate purchases and/or sales in domestic or foreign trade, but who do not as a rule take title to the goods. A chief additional function is to furnish marketing information. They commonly receive their remuneration in the form of commissions or fees." (*Ibid.*, p. VI.)

Table A-5.- EMPLOYMENT IN RETAIL DISTRIBUTION OF PETROLEUM PRODUCTS AT FILLING STATIONS, 1935[a]

Type of filling station	Number of stations	Average number of full-time and part-time paid employees[b]	Number of active proprietors and firm members	Total number of persons engaged
Total	197,568	203,753	179,870	383,623
Independents[c]	177,529	145,527	179,381	324,908
Chains[d]	19,575	57,130	282	57,392
All other types[e]	464	1,096	227	1,323

[a]Data are from *Census of Business: 1935*, "Retail Distribution" (U. S. Dept. Com., Bur. Census, 1937), vol. IV, p. 13. Filling stations include "retail stations primarily engaged in the sale of gasoline and oil. The majority of such places are typical drive-in filling stations along the road or street. Included also are cooperative oil companies whose sales in most instances are largely to farmers. This classification also includes super-service stations whose principal sales are gasoline and oil, and establishments operating under the name 'Garage' but which derive the largest part of their receipts from gasoline and oil sales.

"All filling stations sell gasoline and oil and usually maintain lubricating facilities; some also sell tires and provide emergency tire repair service. Some stations sell in addition other merchandise such as lunches and refreshments, candy, tobacco, and groceries. Where filling stations are operated in conjunction with a tourist camp the establishment is included in the Retail Census provided the income from the rental of cabins or other lodging does not exceed one-half of the total receipts." (*Ibid.*, vol. I, p. 4-08.)

[b]Includes salaried corporation officers and executives as well as wage earners. The average was computed by totaling the number reported monthly (for the pay period ending nearest the 15th of each month) and dividing the sum by 12. For the purpose of the inquiry, respondents were requested to report persons regularly working 4 or more hours per day, or more than 3 full days per week, as full-time employees, and all others as part-time employees. Part-time employees accounted for about 21 percent of the total employment at filling stations for the week ending Oct. 26, 1935. (*Ibid.*, vol. I, pp. 1-12, 4-10.)

[c]Independents are local, individual enterprises, usually operating a single filling station but sometimes including two or three filling stations.

[d]Chains are groups of four or more filling stations owned and operated jointly, with central buying, usually supplied from one or more central warehouses. The count of units does not include the warehouses nor buying offices maintained apart from the filling stations.

[e]Includes leased departments of stores, utility-operated filling stations, consumer cooperatives, etc.

Table A-6.- NUMBER OF OIL WELLS, PRODUCTION, AND VALUE OF OUTPUT, 1859-1937

Year	Number of producing wells		Production[c] (thousands of 42-gallon barrels)	Value at wells[c]	
	Drilled during year[a]	Operating December 31[b]		Thousands of dollars	Average per barrel
1859	1	1	2	32	$16.00
1869	986	3,737	4,215	23,730	5.64
1880	4,072	18,634	26,286	24,601	0.94
1889	5,445	21,833	35,164	26,963	0.77
1899	11,630	69,673	57,071	64,604	1.13
1900	13,671	78,745	63,621	75,989	1.19
1901	11,811	85,111	69,389	66,417	0.96
1902	13,019	92,371	88,767	71,179	0.80
1903	15,177	101,182	100,461	94,694	0.94
1904	16,008	110,928	117,081	101,175	0.86
1905	12,601	115,943	134,717	84,157	0.62
1906	14,550	122,590	126,494	92,445	0.73
1907	15,534	133,040	166,095	120,107	0.72
1908	13,210	141,453	178,527	129,079	0.72
1909	13,875	146,736	183,171	128,329	0.70
1910	11,018	148,619	209,557	127,900	0.61
1911	9,825	150,793	220,449	134,045	0.61
1912	12,514	155,046	222,935	164,213	0.74
1913	19,101	170,774	248,446	237,121	0.95
1914	16,668	180,177	265,763	214,125	0.81
1915	9,154	181,317	281,104	179,463	0.64
1916	18,777	192,108	300,767	330,900	1.10
1917	16,590	199,319	335,316	522,635	1.56
1918	17,845	207,815	355,928	703,944	1.98
1919	21,052	228,084	378,367	760,266	2.01
1920	24,273	268,247	442,929	1,360,745	3.07
1921	14,666	274,500	472,183	814,745	1.73
1922	17,333	284,880	557,531	895,111	1.61
1923	16,206	290,100	732,407	978,430	1.34
1924	14,587	299,100	713,940	1,022,683	1.43
1925	16,559	306,100	763,743	1,284,960	1.68
1926	19,013	318,600	770,874	1,447,760	1.89
1927	14,442	323,300	901,129	1,172,830	1.30
1928	12,526	327,800	901,474	1,054,880	1.17
1929	15,572	328,200	1,007,323	1,280,417	1.27
1930	11,640	331,070	898,011	1,070,200	1.19
1931	6,788	315,850	851,081	550,630	0.65
1932	10,444	321,500	785,159	680,460	0.87
1933	8,068	326,850	905,656	608,000	0.67
1934	12,512	333,070	908,065	904,825	1.00
1935	15,108	340,990	996,596	961,440	0.96
1936	17,800	349,450	1,099,687	1,199,820	1.09
1937	22,143	363,030	1,279,160	1,513,340	1.18

[a] Data for 1859-1907 from R. Arnold and W. J. Kemnitzer, *Petroleum in the United States and Possessions* (1st ed.; New York: Harper & Bros., 1931), p. 42; for 1908-30 from *Mineral Resources of the United States, 1930* (U. S. Dept. Com., Bur. Mines, 1932), part II, p. 861; for 1931-32 from *Statistical Appendix to Minerals Yearbook, 1932-33* (U. S. Dept. Int., Bur. Mines, 1934), p. 299; and for 1933-37 from *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), p. 815.

[b] Represents producing wells on December 31. Data for 1859-1920 from Arnold and Kemnitzer, *loc. cit.*; for 1921-29 from *Mineral Resources of the United States, 1929* (U. S. Dept. Com., Bur. Mines, 1932), part II, p. 425; for 1930-32 from *Statistical Appendix to Minerals Yearbook, 1932-33*, p. 299; for 1933-36 from *Minerals Yearbook, 1938*, p. 815, and for 1937 from *Crude Petroleum and Petroleum Products, 1937 - Final Summary* (U. S. Dept. Int., Bur. Mines, Annual Petroleum Statement No. P. 177, mimeo., Nov. 10, 1938), p. 1.

[c] Data for 1859 and 1869 from *Mineral Resources of the United States, 1917* (U. S. Dept. Int., Geol. Survey, 1920), part II, p. 704; for 1880-1935 from *Minerals Yearbook, 1937*, p. 1009; for 1936 from same, *1938*, p. 815; and for 1937 from *Crude Petroleum and Petroleum Products, 1937 - Final Summary*, pp. 1, 8.

Table A-7.- NUMBER OF NATURAL-GAS WELLS, PRODUCTION, AND VALUE OF OUTPUT, 1889-1937

Year	Number of producing wells[a]		Marketed production[d] (millions of cubic feet)	Value (thousands of dollars)	
	Drilled during year[b]	Operating December 31[c]		At points of consumption[d]	At wells[e]
1889	799	2,247	250,000	n.a.	n.a
1902	2,749	14,370	281,000	n.a.	n.a.
1906	1,928	17,226	388,843	46,874	n.a.
1907	2,484	20,468	406,622	54,222	n.a.
1908	2,148	22,709	402,141	54,640	n.a.
1909	2,927	24,734	480,706	63,207	n.a.
1910	3,049	27,305	509,155	70,756	n.a.
1911	3,226	28,978	512,993	74,622	n.a.
1912	3,755	30,905	562,203	84,564	n.a.
1913	3,861	33,345	581,898	87,847	n.a.
1914	3,836	35,291	591,867	94,116	n.a.
1915	3,563	36,546	628,579	101,312	n.a.
1916	3,889	37,997	753,170	120,227	n.a.
1917	3,984	39,283	795,110	142,089	n.a.
1918	3,808	40,369	721,001	153,554	n.a.
1919	2,135	n.a.	745,916	160,888	n.a.
1920	2,274	n.a.	798,210	196,194	n.a.
1921	2,111	n.a.	662,052	174,617	n.a.
1922	2,024	n.a.	762,546	221,535	84,873
1923	2,349	n.a.	1,006,976	240,001	100,849
1924	2,257	n.a.	1,141,521	253,856	105,779
1925	2,330	n.a.	1,188,571	265,271	112,047
1926	2,341	n.a.	1,313,019	300,168	124,693
1927	2,491	n.a.	1,445,428	317,930	127,468
1928	2,727	n.a.	1,568,139	363,726	139,898
1929	2,870	53,545	1,917,693	413,276	157,596
1930	2,866	55,020	1,943,421	416,090	147,048
1931	1,985	55,756	1,686,436	392,816	117,505
1932	1,027	54,160	1,555,990	384,632	98,985
1933	932	53,660	1,555,474	368,540	97,096
1934	1,373	54,130	1,770,721	395,378	106,438
1935	1,401	53,790	1,916,595	429,374	110,402
1936	2,255	53,960	2,167,802	475,439	119,193
1937	2,834	54,440	2,447,620[f]	528,354[f]	123,457[f]

[a] Oil wells that also produced natural gas are excluded. Data are from *Eleventh Census of the United States: 1890*, "Mineral Industries" (U. S. Dept. Int., Census Office, 1892), p. 523; *Mineral Resources of the United States, 1902* (U. S. Dept. Int., Geol. Survey, 1904), p. 639; same, *1906* (1907), p. 817; same (U. S. Dept. Int., Geol. Survey and U. S. Dept. Com., Bur. Mines) part II, *1907*, p. 330; *1908*, p. 324; *1909*, p. 276; *1910*, p. 308; *1911*, p. 289; *1912*, p. 310; *1913*, p. 1420; *1914*, p. 757; *1915*, p. 940; *1916*, p. 596; *1917*, p. 1063; *1918*, pp. 1393, 1401; *1929*, p. 336; *1930*, pp. 477, 861; *1931*, pp. 369, 371; *Statistical Appendix to Minerals Yearbook, 1932-33* (U. S. Dept. Int., Bur. Mines, 1934), pp. 112, 114; same, *1935* (1936), p. 44; *Minerals Yearbook, 1937* (U. S. Dept. Int., Bur. Mines, 1937), pp. 1056, 1064; same, *1938* (1938), pp. 908, 913; and *Natural Gas Consumption Sets New Record in 1937* (U. S. Dept. Int., Bur. Mines, Mineral Market Reports No. M. M. S. 682, mimeo., Dec. 13, 1938), p. 1.

[b] California "dry"-gas wells excluded, 1919-34.

[c] For 1930-33, represents number of wells operating during year.

[d] For 1889 and 1902 see table A-10, ftn. u. For other years see *Minerals Yearbook, 1937*, p. 1062 and same, *1938*, p. 908.

[e] Data from *Mineral Resources of the United States, 1928* (U. S. Dept. Com., Bur. Mines, 1929), part II, p. 176; same, *1930*, p. 458; *Minerals Yearbook, 1937*, p. 1056; and same, *1938*, p. 908.

[f] Preliminary; subject to revision.

n.a. Data not available.

Table A-8.- NUMBER OF NATURAL-GASOLINE PLANTS, PRODUCTION, AND VALUE OF OUTPUT, 1911-37

Year	Number of plants operating during year[a]	Estimated quantity of natural gas treated[a] (millions of cubic feet)	Production[b] (thousands of gallons)	Value at plant[b] (thousands of dollars)
1911	176	2,476	7,426	532
1912	250	4,688	12,081	1,157
1913	341	9,889	24,061	2,458
1914	386	16,895	42,653	3,106
1915	414	24,064	65,365	5,151
1916	596	208,705	103,493	14,331
1917	886	429,288	217,884	40,189
1918	1,004	449,109	282,536	50,364
1919	1,191	480,404	351,535	64,197
1920	1,154	496,431	384,744	71,788
1921	1,058	465,097	449,934	61,815
1922	917	545,139	505,832	72,711
1923	1,067	875,711	816,226	77,268
1924	1,096	1,016,276	933,861	82,233
1925	1,081	1,040,390	1,127,470	120,383
1926	1,102	1,206,300	1,363,090	136,412
1927	1,119	1,341,248	1,641,144	118,688
1928	1,078	1,473,434	1,814,034	138,944
1929	1,087	1,959,294	2,233,688	158,410
1930	1,035	2,088,778	2,210,494	128,160
1931	937	1,790,119	1,831,918	63,732
1932	830	1,499,756	1,523,800	49,244
1933	779	1,551,464	1,420,000	54,368
1934	766	1,776,172	1,535,360	60,523
1935	715	1,822,000	1,651,986	70,940
1936	700	1,815,000	1,796,340	84,572
1937	696	2,108,800	2,065,434	97,125

[a]Data for 1911-17 from *Mineral Resources of the United States, 1918* (U. S. Dept. Int., Geol. Survey, 1921), part II, p. 1408; for 1918-22 from same, *1922* (1925), part II, p. 347; for 1923-24 from same, *1924* (U. S. Dept. Com., Bur. Mines, 1927), part II, p. 334; for 1925-30 from same, *1930* (1932), part II, p. 435; for 1931-34 from *Statistical Appendix to Minerals Yearbook, 1935* (U. S. Dept. Int., Bur. Mines, 1936), p. 21; for 1935-36 from *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), p. 951; and for 1937 from same, *1939* (in press).

[b]Data for 1911-34 from *Minerals Yearbook, 1937* (1937), p. 1097; for 1935-36 from same, *1938* (1938), p. 951; and for 1937 from same, *1939* (in press).

Table A-9.- NUMBER OF PETROLEUM-REFINING ESTABLISHMENTS, QUANTITY OF CRUDE OIL RUN TO STILLS, AND VALUE OF PRODUCTS, 1880-1937[a]

Year	Number of plants[b]	Crude oil run to stills[c] (thousands of 42-gallon barrels)	Value of products[d] (thousands of dollars)
1880[e]	86	17,417	43,705
1889	94	30,663	85,001
1899	67	52,011	123,929
1904	98	66,983	175,005
1909	147	120,775	236,998
1914	176	191,263	396,361
1919	320	365,272	1,632,533
1921	366	443,363	1,727,440
1923	382	581,238	1,793,700
1925	359	739,920	2,376,657
1927	354	828,835	2,142,649
1929	390	987,708	2,639,665
1931	376	894,608	1,524,285
1933	389	861,254	1,378,637
1935	395	966,243	1,838,622
1937	365	1,183,440	2,546,746

[a] Data for 1880-1919 from *Fourteenth Census of the United States: 1920*, Vol. X, "Manufactures: 1919" (U. S. Dept. Com., Bur. Census, 1923), p. 757; for 1921-29 from *Fifteenth Census of the United States: 1930*, "Manufactures: 1929" (1933), II, 770; for 1931-35 from *Census of Manufactures: 1935* (U. S. Dept. Com., Bur. Census, 1938), p. 749; and for 1937 from same, *1937*, "Petroleum Refining" (mimeo., Dec. 28, 1938), p. 1.

[b] Data for establishments with products valued at less than $5,000 are included for 1919 and prior years but not for 1921 and subsequent years. Census data are limited to those establishments which refine crude petroleum by the process of distillation; therefore establishments that compound refined or partly refined petroleum products and those that produce gasoline from natural gas at the wells are excluded. Statistics of the industry as so defined were first collected in 1880 (see *Census of Manufactures: 1905* [U. S. Dept. Com. and Labor, Bur. Census, 1908], part IV, p. 567).

[c] Table A-13.

[d] Represents selling value f. o. b. plant of all products manufactured whether sold or in stock, and includes payments received for contract work. The figure for 1929 represents "value" as so defined but includes only manufactured products shipped or delivered.

[e] Census year ending May 31, 1880.

Table A-10.- COMPARATIVE SUMMARY OF SALIENT CENSUS STATISTICS FOR PRODUCING ENTERPRISES, EXCLUDING CONTRACTORS, IN CRUDE-PETROLEUM, NATURAL-GAS, AND NATURAL-GASOLINE PRODUCTION, 1880-1935[a]

Table A-10.- COMPARATIVE SUMMARY OF SALIENT CENSUS STATISTICS FOR PRODUCING ENTERPRISES, EXCLUDING CONTRACTORS, IN CRUDE-PETROLEUM, NATURAL-GAS, AND NATURAL-GASOLINE PRODUCTION, 1880-1935[a]

	Item	1880	1889	1902	1909	1919	1935
	Number of producing units						
(1)	Petroleum wells (on Dec. 31)[b]	n.a.	35,163	108,644	148,049	243,416	340,990
(2)	Natural-gas wells (on Dec. 31)	0	2,247	14,556	18,271	14,257	53,790
(3)	Natural-gasoline plants	0	0	0	n.a.	1,115	715
(4)	Number of persons engaged, total[c]	n.a.	n.a.	n.a.	59,091[d]	125,110	n.a.
(5)	Proprietors and firm members	n.a.	n.a.	n.a.	16,213	14,223	n.a.
(6)	Number performing manual labor	n.a.	n.a.	n.a.	2,155	1,987	n.a.
(7)	Salaried employees[e]	n.a.	2,312	4,956	6,129[d]	17,682	11,770
(8)	Wage earners (average for the year)	11,477[f]	12,500[g]	23,000[g]	36,749[d]	93,205	108,735
(9)	Principal expenses, total[h]	n.a.	n.a.	$62,780,144	$92,461,649	$452,506,043	n.a.
(10)	Salaries	n.a.	$1,535,317	$4,797,105	$7,241,881	$33,468,388	$20,741,815
(11)	Wages (net earnings of employees)	$7,179,000[f]	$8,747,972	$16,178,640	$27,091,650	$134,521,247	$144,550,000
(12)	Percent of value of products[i]	32.8	n.a.	n.a.	15.4	14.9	12.8
(13)	Amount paid contractors	$3,730,000[j]	n.a.	$17,415,632[k]	$16,736,510	$68,663,659	n.a.
(14)	Percent of principal expenses[l]	n.a.	n.a.	27.7	18.1	15.2	n.a.
(15)	Percent of value of products[m]	17.0	n.a.	n.a.	9.5	7.6	n.a.
(16)	Supplies and materials	n.a.	$22,690,432[o]	$24,388,767	$39,947,013	$195,058,693	$99,016,000[n]
(17)	Fuel	n.a.			$1,444,595	$19,828,776	$19,592,000
(18)	Purchased power	n.a.	n.a.	(p)		$965,300	$6,953,000
(19)	Royalties and rent of wells and plants	n.a.	n.a.	$11,463,786	$21,282,820	$106,458,518	n.a.
(20)	Taxes	n.a.	n.a.	$10,260,197	$2,576,986	$38,690,630	n.a.
(21)	Miscellaneous expenses[q]	n.a.	n.a.		$9,428,312	n.a.	n.a.
(22)	Value of products at point of production, total[r]	$21,918,658	n.a.	n.a.	$175,544,807	$902,979,752	$1,142,782,000[s]
	Petroleum						
(23)	Quantity (barrels of 42 gallons)	24,354,064	35,163,513	89,275,302	171,559,394	350,112,253	996,596,000
(24)	Value	$21,918,658[t]	$28,963,340	$71,397,739	$117,696,529	$694,026,948	$961,440,000
	Natural gas (marketed production)						
(25)	Quantity (M cubic feet)	0	250,000,000[u]	281,000,000[u]	431,852,530[v]	727,295,000[v]	1,916,595,000
(26)	Value	0	n.a.	n.a.	$57,716,520[v]	$127,098,361[v]	$110,402,000
	Natural gasoline						
(27)	Quantity (gallons)	0	0	0	271,000	454,089,466	1,651,986,000
(28)	Value	0	0	0	$29,000	$78,760,835	$70,940,000
(29)	Other products, value[w]	0	0	0	$102,758	$3,095,608	n.a.

See footnotes at end of table.

Table A-10.- COMPARATIVE SUMMARY OF SALIENT CENSUS STATISTICS FOR PRODUCING ENTERPRISES, EXCLUDING CONTRACTORS, IN CRUDE-PETROLEUM, NATURAL-GAS, AND NATURAL-GASOLINE PRODUCTION, 1880-1935[a] - *Continued*

[a]Data for 1880 (year ending May 31, 1880) from *Tenth Census of the United States: 1880*, Vol. X, "Special Reports on Petroleum, Coke and Building Stones" (U. S. Dept. Int., Census Office, 1884), pp. 139-40, 147; for 1889 from *Eleventh Census of the United States: 1890*, "Minerals Industries" (1892), pp. 431, 433, 435-6, 523-5; for 1902 from *Special Reports of the Census Office*, "Mines and Quarries: 1902" (U. S. Dept. Com. and Labor, 1906), pp. 56, 722, 764, 767, 780; for 1909 from *Thirteenth Census of the United States: 1910*, Vol. XI, "Mines and Quarries: 1909" (U. S. Dept. Com., Bur. Census, 1913), pp. 263-5, 271, 289; for 1919 from *Fourteenth Census of the United States: 1920*, Vol. XI, "Mines and Quarries: 1919" (1922), pp. 304-6, 310-11; and for 1935 from *Census of Business: 1935*, "Petroleum Industry in 1935" (U. S. Dept. Com., Bur. Census in cooperation with U. S. Dept. Int., Bur. Mines, mimeo., June 21, 1937), "Natural Gas Industry in 1935" (Mar. 30, 1937), and "Natural Gasoline Industry in 1935" (Mar. 3, 1937).

[b]Figure for 1889 includes 3,209 flowing wells and 31,954 pumping wells; that for 1902, 694 flowing wells and 107,950 pumping wells. The 1909 figure includes 18,627 wells not classified according to principal product and may therefore include some gas wells. The 1919 figure includes 70,901 wells of enterprises which reported petroleum and natural gas as products and an additional 65,589 wells of enterprises which reported petroleum, natural gas, and natural gasoline as products.

[c]Sum of items (5), (7), and (8).

[d]Includes employees engaged in natural-gasoline production - five wage earners and one salaried employee. The number of wage earners represents the average of the number employed on the 15th day of each month. This figure was selected as the one most nearly comparable with data for other years.

[e]Includes general officers, superintendents, managers, foremen, technical employees, office forces of clerks and stenographers, and all others on a salary basis. Central administrative-office employees are included for all years except 1889 and 1935.

[f]Includes workmen employed by contractors.

[g]As adjusted for comparability with data from census reports for other years. The reported numbers were 28,911 and 22,230 for 1889 and 1902, respectively. For source of basic figures see table A-11, ftn. h.

[h]To preserve comparability, the total of principal expenses is made up of the same items for all years; these include salaries (10), wages (11), contract work (13), supplies and materials (16), fuel (17), and purchased power (18). Note that other items of expense are shown for 1902, 1909, and 1919, although they are not included in the total.

[i]Item (11) divided by item (22).

[j]Represents cost of drilling wells in the Bradford and Lower Country districts of Pennsylvania and in West Virginia and southern Ohio. See *Tenth Census of the United States: 1880*, "Special Reports on Petroleum, Coke and Building Stones," p. 147. See also *Special Reports of the Census Office*, "Mines and Quarries: 1902," p. 721.

[k]The census reported an estimate of 11,217 workmen employed by contractors in 1902 - 7,949 in the petroleum and 3,268 in the natural-gas branch of the industry.

[l]Item (13) divided by item (9).

[m]Item (13) divided by item (22).

[n]Includes $585,000 expended for blending materials in natural-gasoline production.

[o]Includes all expenditures for materials in the natural-gas branch of the industry ($13,184,497) and value of materials used in caring for and operating oil wells ($9,505,935); the latter excludes materials used in drilling oil wells, building oil-well drilling rigs, etc.

[p]Probably negligible, if any.

[q]Includes rent of offices, insurance, interest, and sundries. Excludes depreciation, losses due to bad debts, selling expenses, interest on capital, and a few similar items.

[r]Sum of items (24), (26), (28), and (29).

[s]Exclusive of an undetermined but probably small amount representing receipts for minor byproducts, power sold, or miscellaneous services rendered to other enterprises.

[t]Estimated by multiplying the number of barrels of oil produced in the census year ending May 31, 1880, by the average value per barrel at wells in 1879 and 1880 as reported in *Mineral Resources of the United States, 1930* (U. S. Dept. Com., Bur. Mines, 1932), Part II, p. 787.

[u]As calculated by F. G. Tryon "from contemporary estimates of the quantity of coal displaced by gas or of the value of the gas sold." See A. F. Burns, *Production Trends in the United States Since 1870* (New York: National Bureau of Economic Research, Inc., Publication 23, 1934), pp. 292, 333. This figure is believed to state more correctly the amount of gas produced and marketed than the estimate made by contemporary census officials and which included gas consumed in drilling and operating oil wells.

[v]Represents the net quantity and corresponding value of gas marketed after eliminating duplications resulting from the purchase of natural gas for gasoline extraction and resale.

[w]Represents the value of minor byproducts, other than natural gasoline, and receipts for power sold or miscellaneous services rendered to other enterprises.

n.a. Data not available.

Table A-11.- NUMBER OF WAGE EARNERS EMPLOYED IN PETROLEUM, NATURAL-GAS, AND NATURAL-GASOLINE PRODUCTION, 1880-1937[a]

Year	Wage earners employed by regular producers[b]			Wage earners employed by contractors		Total	
	Average number	Estimated number of man-hours worked[c] (thousands)	Estimated number of man-hours per wage earner[d]	Estimated number of man-hours worked[e] (thousands)	Estimated number of wage earners[f]	Estimated number of wage earners	Estimated number of man-hours worked (thousands)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1880	n.a.	n.a.	n.a.	n.a.	n.a.	11,477[g]	41,317[g]
1889	12,500[h]	44,967	3,597	22,359	6,000	18,500	67,326
1902	23,000[h]	81,824	3,558	41,000	10,400[i]	33,400	122,824
1909	36,749[j]	111,488	3,034	29,394	10,000	46,749	140,882
1919	93,205[k]	230,345	2,471	44,958	18,000	111,205	275,303
1929	142,000[l]	328,032	2,310[m]	85,288	37,000	179,000[n]	413,320
1935	108,735[o]	187,727	1,726	48,533	28,000	136,735	236,260
1936	119,100[p]	228,633	1,920	59,445	31,000	150,100	288,078
1937	126,800[p]	250,733	1,977	65,191	33,000	159,800	315,924

[a] Space limitations permit inclusion, in the following footnotes, of only the most important explanations and basic computations. Additional material from the records of this study will be made available on request to those particularly interested in the detailed explanations and the supplementary figures.

[b] Excludes data for nonproducing enterprises as represented by enterprises reporting employment but no production.

[c] Data for 1889-1935 derived from total wage payments (as reported by the census of mines and quarries) and average hourly earnings (as reported by the census and the U. S. Bureau of Labor Statistics); data for 1936 and 1937 from reports of oil and gas companies to the U. S. Bureau of Mines, with estimated data for salaried employees excluded.

[d] Col. (2) divided by col. (1).

[e] Data for 1902-19 derived from total wages paid by contractors estimated from amounts paid contractors (as reported by the census of mines and quarries) and from estimated hourly earnings of wage earners employed by contractors; data for 1889 estimated from man-hours worked by regular producers in 1889 and the ratio of man-hours worked by wage earners employed by contractors to man-hours worked by wage earners employed by regular producers in 1902; data for 1929, 1936, and 1937 estimated by a method similar to that for 1889, using the ratio for 1935; and data for 1935 derived from reports of a sample of contractors to the U. S. Bureau of Mines, from wage costs of drilling wells, from the estimated number of wells drilled by contractors, and from average hourly earnings of contractors' employees.

[f] Col. (4) divided by col. (3). All figures, except that for 1902, were rounded to the nearest thousand. These estimates represent the number of wage earners that are equivalent to the number working the same number of hours per year as were worked by wage earners employed by regular producers. Inasmuch as the latter probably work more continuously than contractors' employees, the actual number of wage earners employed by contractors may be somewhat higher than the estimates indicate.

[g] Data from S. F. Peckham, "Production, Technology, and Uses of Petroleum and Its Products," *Tenth Census of the United States: 1880*, Vol. X, "Special Reports on Petroleum, Coke and Building Stones" (U. S. Dept. Int., Census Office, 1884), pp. 142,147. In determining the number of employees, Mr. Peckham first estimated the total number of man-days worked, and then divided the total by 300. The total number of man-hours presented in this table were estimated by multiplying man-days by the approximate length of shift worked in 1880. These data are for the drilling and operation of oil wells only, but the natural-gas industry was negligible at this time.

[h] As adjusted for comparability with data from census reports for other years. Basic figure for 1889 from *Eleventh Census of the United States: 1890*, "Mineral Industries" (U. S. Dept. Int., Census Office, 1892), pp. 435, 524; and that for 1902 from *Special Reports of the Census Office*, "Mines and Quarries: 1902" (U. S. Dept. Com. and Labor, 1905), pp. 783, 778.

[i] As reported in the 1902 census (11,217), minus an estimated 7 percent of total representing salaried employees; the latter was derived from reports for 1935, the only year for which such data were available, from a sample of drilling contractors reporting to the U. S. Bureau of Mines.

[j] Represents the average of the number of wage earners employed on the 15th day of each month. This figure was selected as the one most nearly comparable with data for other years. Data from *Thirteenth Census of the United States: 1910*, Vol. XI, "Mines and Quarries: 1909" (U. S. Dept. Com., Bur. Census, 1913), pp. 271, 279.

[k] Data from *Fourteenth Census of the United States: 1920*, Vol. XI, "Mines and Quarries: 1919" (1922), p. 305.

[l] Derived by subtracting 37,000, the estimated number of wage earners employed by contractors, from 179,000, the estimated number of wage earners employed by both regular producers and contractors.

[m] Derived by dividing the estimated total number of man-hours worked by wage earners employed by both regular producers and contractors by 179,000, the estimated total number of wage earners employed.

[n] See table A-1, ftn. f.

[o] Table A-3.

[p] Data are from reports of oil and gas companies to the U. S. Bureau of Mines, with estimated number of salaried employees excluded.

Table A-12.- NUMBER OF GAINFUL WORKERS ATTACHED TO THE CRUDE-PETROLEUM AND NATURAL-GAS EXTRACTIVE INDUSTRY, 1870-1930[a]

Item	Date of census[b]						
	June 1, 1870	June 1, 1880	June 1, 1890	June 1, 1900	Apr. 15, 1910	Jan. 1, 1920	Apr. 1, 1930
Oil- and gas-well operatives[c]	n.a.	n.a.	n.a.	n.a.	25,562	85,550	105,224[d]
Oil-well employees[e]	3,803	7,340	9,147	18,011	32,634[f]	n.a.	n.a.
Total number attached to oil and gas industry[g]	n.a.	n.a.	n.a.	n.a.	55,305	n.a.	198,446[h]
Index of number of gainful workers[i] (1910=100)	11.7	22.5	28.0	55.2	100.0	334.7	411.6

[a]Data include an enumeration of persons 10 years old and over who usually derive their livelihood from the oil and gas industry, even though they may not have been actually employed at the time the census was taken. The number of unemployed persons was enumerated in the 1930 census only. The occupations in the several decennial census reports have not always been treated alike; a new census organization was built up for each individual census, and, though it is difficult to determine what coding procedures were followed in the early years, the occupational classifications in the 1870-1910 series were probably not entirely consistent. Thus the figures presented for "oil-well employees" (1870-1910) are approximately comparable; those for "oil- and gas-well operatives" (1910-1930) are strictly comparable. Note, however, as stated in the 1930 census report, that "because of indefinite returns by census enumerators, there probably is some overlapping between persons engaged in the production of natural gas and those engaged in the production of artificial gas, and between persons working at petroleum refineries or on pipe lines and persons working at oil wells." (*Fifteenth Census of the United States: 1930*, "Population" [U. S. Dept. Com., Bur. Census, 1933], V., 408, ftn. 1.) It may be pointed out also that a comparison of the 1930 figures with those for 1920 may be somewhat misleading due to the unusual amount of drilling and other conditions prevailing in 1920, a year closely following the World War. As a result of all these factors, the figures presented should be accepted only as representative of general trends, and not as absolutely accurate measurements. The authors are indebted to Daniel Carson of the National Research Project for a careful analysis of comparability of data on occupations from the various censuses.

[b]The changes in the date of census-taking affect the comparisons to a small extent only, for the oil and gas industry exhibits only minor seasonal fluctuations. Moreover, the census reports purport to indicate the total number of gainful workers attached to the industry even though temporarily unemployed, and most of the latter in midwinter off seasons were probably included in the enumerations.

[c]The group designated "operatives" includes the semiskilled class of workers that are in many respects occupationally homogeneous and typical of the industry. This classification excludes skilled wage earners not typical of the industry, clerical and professional salary earners, proprietors, managers, and superintendents. Data are from *Fifteenth Census of the United States: 1930*, "Population," IV, 7; see also *Thirteenth Census of the United States: 1910*, "Population" (1914), IV, 310-2.

[d]Includes 13,325 Class A unemployed persons (out of a job, able to work, and looking for a job) and 2,702 Class B unemployed persons (having jobs but on lay-off without pay, excluding those sick or voluntarily idle). Data from *Fifteenth Census of the United States: 1930*, "Unemployment" (1931), II, 13.

[e]Data for 1870-1900 from *Twelfth Census of the United States: 1900*, "Special Reports - Occupations" (U. S. Dept. Com. and Labor, Bur. Census, 1904), pp. xlii, xliii.

[f]This figure was derived by a special reclassification to achieve comparability with preceding censuses. See *Thirteenth Census of the United States: 1910*, "Population," IV, 55; see also note on comparability with previous censuses on pp. 52-3.

[g]A complete enumeration of all persons attached to the oil and gas industry is available only for 1910 and 1930. A detailed break-down of the totals into the numerous occupations comprising it may be found in the following: *Thirteenth Census of the United States: 1910*, "Population," IV, 310-2, and *Fifteenth Census of the United States: 1930*, "Population," V, 422-4.

[h]Includes 17,606 Class A and 3,749 Class B unemployed persons. Data from *Fifteenth Census of the United States: 1930*, "Unemployment," I, 53-4.

[i]Based on oil-well employees for 1870 to 1910, and on oil- and gas-well operatives for 1910 to 1930.

n.a. Data not available.

Table A-18.- BARRELS OF CRUDE OIL RUN TO STILLS, EMPLOYMENT, AND OUTPUT PER MAN IN THE PETROLEUM-REFINING INDUSTRY, 1880-1937

Year	Crude oil run to stills[a] (thousands of 42-gallon barrels)	Employment of wage earners[b]		Barrels of crude oil refined	
		Average number	Estimated number of man-hours worked	Per man-year[c]	Per man-hour[d]
	(1)	(2)	(3)	(4)	(5)
1880[e]	17,417	9,869	n.a.	1,765	n.a.
1889	30,663	11,403	n.a.	2,689	n.a.
1899	52,011	12,199	n.a.	4,264	n.a.
1904	66,983	16,770	n.a.	3,994	n.a.
1909	120,775	13,929	42,010,000[f]	8,671	2.9
1914	191,263	25,366	73,866,000[f]	7,540	2.6
1919	365,272	58,889	154,643,000	6,203	2.4
1921	443,363	63,189	166,591,000	7,016	2.7
1923	581,238	66,717	173,811,000	8,712	3.3
1924	643,719	62,301	162,954,000	10,332	4.0
1925	739,920	65,324	171,541,000	11,327	4.3
1926	779,264	71,811	189,323,000	10,852	4.1
1927	828,835	71,234	188,542,000	11,635	4.4
1928	913,295	67,862	180,323,000	13,458	5.1
1929	987,708	80,596	214,998,000	12,255	4.6
1930	927,447	80,918	211,228,000	11,462	4.4
1931	894,608	68,824	165,701,000	12,998	5.4
1932	819,997	63,913	142,577,000	12,830	5.8
1933	861,254	69,047	139,668,000	12,473	6.2
1934	895,636	77,533	143,529,000	11,552	6.2
1935	968,243	77,402	142,884,000	12,483	6.8
1936	1,068,570	78,420	148,026,000	13,626	7.2
1937	1,183,440	83,183[g]	155,719,000[h]	14,227	7.6

[a] Data for 1880-1914 from *Fourteenth Census of the United States: 1920*, Vol. X, "Manufactures: 1919" (U. S. Dept. Com., Bur. Census, 1923), p. 757; for 1919 and 1925-37 from table A-27; and for 1921-24 from the American Petroleum Institute, *Petroleum Facts and Figures* (5th ed.; New York: 1937), p. 118.

[b] Data for 1880-1914 from *Fourteenth Census of the United States: 1920*, Vol. X, "Manufactures: 1919," p. 757. Average number of wage earners for 1919-36 from H. Magdoff, I. H. Siegel, and M. B. Davis, *Production, Employment, and Productivity in 59 Manufacturing Industries, 1919-36* (WPA National Research Project, Report No. S-1, May 1939), Part Three. Numbers of man-hours for 1919-36 were supplied by H. Magdoff. These data are based on statistics of the U. S. Bureau of the Census and the U. S. Bureau of Labor Statistics.

[c] Col. (1) divided by col. (2).

[d] Col. (1) divided by col. (3).

[e] Census year ending May 31, 1880.

[f] As estimated from the average number of wage earners and prevailing hours worked per week in 1909 and 1914, after the latter were adjusted to the level of actual hours by multiplication by the 1929 ratio of actual to prevailing hours. Prevailing hours per week in 1909 and 1914 were reported in *Census of Manufactures: 1914* (U. S. Dept. Com., Bur. Census, 1919), II, 578.

[g] *Census of Manufactures: 1937*, "Petroleum Refining" (mimeo., Dec. 28, 1938), p. 1.

[h] The number of man-hours for 1937 was estimated from the number of wage earners and average number of hours worked per week as obtained from the *Monthly Labor Review*.

n.a. Data not available.

Table A-14.- NUMBER OF GAINFUL WORKERS ATTACHED TO THE PIPE-LINE INDUSTRY, 1910, 1920, 1930[a]

Occupation	1910[b]	1920[b]	1930[c]
Total	n.a.	n.a.	25,001
Proprietary, official, and supervisory pursuits	n.a.	n.a.	2,093
Professional pursuits	n.a.	n.a.	252
Clerical and kindred pursuits	n.a.	n.a.	1,197
Skilled trades	n.a.	n.a.	3,162
All other pursuits	2,605	7,369	13,704
Laborers	n.a.	n.a.	4,593
Other			

[a] Data include an enumeration of persons 10 years old and over who usually derive their livelihood from the pipe-line industry, even though they may not have been actually employed at the time the census was taken.

[b] *Fifteenth Census of the United States: 1930*, "Population" (U. S. Dept. Com., Bur. Census, 1933), IV, 12.

[c] *Ibid.*, V, 548.

n.a. Data not available.

Table A-15.- VOLUME OF TRANSPORTATION SERVICE, NUMBER OF WAGE EARNERS, AND OUTPUT PER MAN IN OIL TRANSPORTATION BY PIPE LINES UNDER THE JURISDICTION OF THE INTERSTATE COMMERCE COMMISSION, 1922-37[a]

Year	Volume of transportation service				Average number of employees				Indicators of output per man[b]			
	Miles of pipe line[c]	Barrels of oil transported[d]	Barrel-miles of oil transported[e] (millions)	Pipe-line operating revenue[f]	Total	Wage earners[g]	Salaried employees: Field[g]	Salaried employees: At central administrative offices	Miles of line operated per wage earner	Barrels of oil transported per wage earner	Barrel-miles per wage earner (thousands)	Revenue received per wage earner
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
1922	57,349	n. a.	156,169	$128,058,803	17,399	14,619	835	1,945	3.9	n. a.	10,683	$8,760
1923	64,760	n. a.	160,015	131,212,582	24,055	20,730	1,183	2,142	3.1	n. a.	7,719	6,330
1924	68,185	n. a.	179,172	146,921,073	22,460	19,323	1,103	2,034	3.5	n. a.	9,272	7,603
1925	70,009	831,199,821	200,786	164,644,740	20,693	17,863	978	1,852	3.9	46,532	11,240	9,217
1926	72,846	835,582,970	211,067	173,074,958	27,346	24,198	945	2,203	3.0	34,531	8,722	7,152
1927	76,070	989,427,028	238,489	195,561,065	28,411	25,252	1,063	2,096	3.0	39,182	9,444	7,744
1928	81,676	1,053,190,757	270,821	222,073,003	25,270	21,849	1,188	2,233	3.7	48,203	12,395	10,164
1929	85,796	1,156,350,772	306,599	251,410,920	23,457	19,976	1,067	2,414	4.3	57,887	15,348	12,586
1930	88,728	1,172,165,080	290,134	237,910,083	21,948	19,037	530	2,381	4.7	61,573	15,241	12,497
1931	93,090	1,109,514,636	271,883	222,944,026	19,854	16,708	1,256	1,890	5.6	66,406	16,273	13,344
1932	92,782	1,120,848,200	258,279	211,788,647	16,291	13,476	1,090	1,725	6.9	83,174	19,166	15,716
1933	93,724	1,189,086,224	264,869	217,192,354	18,884	16,189	930	1,765	5.8	73,450	16,361	13,416
1934	93,070	1,213,652,108	242,885	199,165,597	20,853	17,901	1,024	1,928	5.2	67,798	13,568	11,126
1935	92,037	1,058,840,489	250,119	197,368,209	21,515	17,853	1,613	2,049	5.2	59,309	14,010	11,055
1936	94,060	1,101,716,905	271,008	219,057,109	23,235	19,826	1,345	2,064	4.7	55,569	13,669	11,049
1937	96,612	1,288,419,973	303,018	248,645,057	24,168	20,803	1,188	2,177	4.6	61,934	14,566	11,952

[a] Unless otherwise noted data are from *Statistics of Oil Pipe Lines, 1921-37* (Interstate Commerce Commission, Bur. Statistics, Statement No. 396, Feb. 1939), pp. 6, 15, 16, 20, 29.

[b] Cols. (1), (2), (3), and (4) respectively divided by col. (6).

[c] Data represent 82, 81, 81, and 82 percent of the total gathering and trunk oil pipe-line mileage in the United States in 1924, 1926, 1931, and 1936, respectively.

[d] Data include crude and refined oil transported and represent the sum of the oil originated on the lines of each reporting company and that received from connecting lines. Since some of the oil was handled by two or more companies and was included in the reports of each company, this aggregate involves a considerable amount of duplication and is larger than the actual quantity of oil transported. It is believed that the duplication amounts to about one-fourth of the shipments indicated and that the amount of duplication has not varied widely from year to year; hence the figures indicate the approximate *trend* of the quantity of oil transported.

[e] Data for 1935-37 as reported to the Interstate Commerce Commission, including an estimate for three companies in 1935 and two companies in 1936 that failed to report barrel-miles. These estimates were made on the basis of reported figures of barrels of oil transported by the companies and the ratio of barrel-miles to barrels of oil transported for all other companies. Data on barrel-miles for 1922-34 were estimated from data on pipe-line operating revenue and the factor of 82 cents of operating revenue per thousand barrel-miles, derived from data for 1937. The estimates of barrel-miles, therefore, are based on the assumption that the average revenue per thousand barrel-miles remained approximately the same throughout the period, which is believed to be approximately correct.

[f] Includes transportation, storage, demurrage, rent, and miscellaneous revenues. However, a break-down of the total for 1936 (from data supplied by the Bureau of Statistics of the Interstate Commerce Commission) indicated that 98 percent of the total represented transportation revenue.

[g] Data for 1925-36 are based upon a special tabulation by the U. S. Bureau of Mines of data reported to the Interstate Commerce Commission. The segregation of wage earners and field salaried employees for 1922-24 and for 1937 was estimated by applying the 1925-36 average of the ratios of the number of employees in these classes to the total number of employees.

n.a. Data not available.

Table A-16.- INDEXES OF PRODUCTION, MAN-HOURS, AND OUTPUT PER MAN-HOUR IN CRUDE-PETROLEUM, NATURAL-GAS,

estimates were made on the basis of reported figures of barrels of oil transported by the

n.a. Data not available.

Table A-16.- INDEXES OF PRODUCTION, MAN-HOURS, AND OUTPUT PER MAN-HOUR IN CRUDE-PETROLEUM, NATURAL-GAS, AND NATURAL-GASOLINE PRODUCTION, 1880-1937

Item	1880	1889	1902	1909	1919	1929	1935	1936	1937
Production, volume[a]									
Crude petroleum (M bbls.)	24,354	35,164	89,275	171,559	350,112	1,007,323	996,596	1,099,687	1,279,160
Natural gas (MM cu. ft. marketed)	(b)	250,000	281,000	431,853	727,295	1,917,693	1,916,595	2,167,802	2,447,620
Natural gasoline (M gal.)	0	0	0	271	454,089	2,233,688	1,651,986	1,796,340	2,065,434
Production, B. t. u. equivalents (billions)	146,124	460,984	816,650	1,461,240	2,882,458	8,229,674	8,094,409	8,981,485	10,370,432
Crude petroleum[c]	146,124	210,984	535,650	1,029,354	2,100,672	6,043,938	5,979,576	6,598,122	7,674,960
Natural gas[d]	(b)	250,000	281,000	431,853	727,295	1,917,693	1,916,595	2,167,802	2,447,620
Natural gasoline[e]	0	0	0	33	54,491	268,043	198,238	215,561	247,852
Production indexes (1935=100)									
B. t. u. equivalents	1.8	5.7	10.1	18.1	35.6	101.7	100.0	111.0	128.1
Weighted aggregate[f]	2.0	4.2	8.7	16.2	34.7	104.0	100.0	110.5	128.0
Man-hours[g]									
Thousands[h]	41,317	67,326	122,824	140,882	275,303	413,320	236,260	288,078	315,924
Index (1935=100)	17.5	28.5	52.0	59.6	116.5	174.9	100.0	121.9	133.7
Output per man-hour									
B. t. u. equivalents (thousands)	3,537	6,847	6,649	10,372	10,470	19,911	34,261	31,177	32,826
Indexes (1935=100)									
B. t. u. equivalent production[i]	10.3	20.0	19.4	30.3	30.6	58.1	100.0	91.0	95.8
Weighted aggregate of production[j]	11.4	14.7	16.7	27.2	29.8	59.5	100.0	90.6	95.7

[a] Except for figure for 1929, which is from tables A-6 to A-8, data for 1880-1935 are from table A-10; data for 1936 are from *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), pp. 815-911, 950; and data for 1937 are from *Crude Petroleum and Petroleum Products, 1937 - Final Summary* (U. S. Dept. Int., Bur. Mines, Annual Petroleum Statement No. P. 177, Nov. 10, 1938), p. 1, and *Natural Gas Consumption Sets New Record in 1937* (U. S. Dept. Int., Bur. Mines, Mineral Market Reports No. M. M. S. 682, Dec. 13, 1938), p. 1.

[b] Quantity negligible in this year.

[c] On basis of 6,000,000 B. t. u. per barrel. See *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), p. 703.

[d] On basis of 1,000 B. t. u. per cubic foot. This approximate heat value of natural gas is a little less than that given in *ibid.*, for it excludes the heat value of natural gasoline extracted.

[e] On basis of 120,000 B. t. u. per gallon. This value is roughly the midpoint between the heat value per gallon of normal pentane (113,200 B. t. u.) and of average gasoline (129,060 B. t. u.). Natural gasoline consists primarily of the hydrocarbon known as pentane, with some hexane and heavier hydrocarbons. See *Letter Circular No. 292* (U. S. Dept. Com., Bur. Standards, Dec. 1, 1930), and Roy Cross, *A Handbook of Petroleum, Asphalt, and Natural Gas* (Kansas City, Mo.: Kansas City Testing Laboratory, 1931), pp. 396, 484. See also Donald B. Dow, *Effects of Gasoline Removal on the Heating Value of Natural Gas* (U. S. Dept. Int., Bur. Mines, Tech. Paper 283, 1920).

[f] The volume of production of each product was multiplied by the following weights: Crude petroleum, $1.49; natural gas, $0.0001; and natural gasoline, $0.10. The weighted production figures were aggregated and the aggregates were converted to index numbers. The weights represent the average unit value at point of production in the 3-year period 1923-25, determined from data reported in *Mineral Resources of the United States, 1925* (U. S. Dept. Com., Bur. Mines, 1929), part II, pp. 343, 176.

[g] Man-hours worked by wage earners of producers and contractors.

[h] Table A-11.

[i] Computed from B. t. u. output per man-hour.

[j] Weighted aggregative production index divided by index of man-hours.

Table A-17.- AVERAGE OUTPUT PER OIL WELL IN SELECTED STATES IN YEAR OF HIGHEST PRODUCTION FOR RESPECTIVE STATES (THROUGH 1937)

State	Peak year	Production[a] (thousands of barrels)	Number of producing wells on December 31[b]	Average output per well (barrels)
Pennsylvania and New York	1891	33,009	23,433	1,409
Ohio	1896	23,941	17,317	1,383
West Virginia	1900	16,196	6,746	2,401
Indiana	1904	11,339	15,228	745
Illinois	1908	33,686	9,500	3,546
Wyoming	1923	44,785	2,300	19,472
Oklahoma	1927	277,775	61,750	4,498
California	1929	292,534	10,550	27,728
Texas	1937	510,318	77,360	6,597
Louisiana	1937	90,924	4,160	21,857
New Mexico	1937	38,854	1,920	20,236

[a]Data from *Minerals Yearbook, 1937* (U. S. Dept. Int., Bur. Mines, 1937), pp. 1008-9, and *Crude Petroleum and Petroleum Products, 1937 - Final Summary* (U. S. Dept. Int., Bur. Mines, Annual Petroleum Statement No. P. 177, Nov. 10, 1938), p. 4.

[b]Data from R. Arnold and W. J. Kemnitzer, *Petroleum in the United States and Possessions* (1st ed.; New York: Harper & Bros., 1931), pp. 100, 172, 306, 388, 632, 788, 820, 826, and *Crude Petroleum and Petroleum Products, 1937 - Final Summary*, p. 8.

Table A-18.- PERCENTAGE OF TOTAL CRUDE OIL SUPPLIED BY SELECTED STATES, 1880-1937[a]

Year	Total	Texas	California	Oklahoma	Louisiana	Wyoming	New Mexico
1880	0.2	0	0.2	0	0	0	0
1881	0.4	0	0.4	0	0	0	0
1882	0.4	0	0.4	0	0	0	0
1883	0.6	0	0.6	0	0	0	0
1884	1.1	0	1.1	0	0	0	0
1885	1.5	0	1.5	0	0	0	0
1886	1.3	0	1.3	0	0	0	0
1887	2.4	0	2.4	0	0	0	0
1888	2.5	0	2.5	0	0	0	0
1889	0.9	*	0.9	0	0	0	0
1890	0.7	*	0.7	0	0	0	0
1891	0.6	*	0.6	*	0	0	0
1892	0.8	*	0.8	*	0	0	0
1893	1.0	*	1.0	*	0	0	0
1894	1.4	*	1.4	*	0	*	0
1895	2.3	*	2.3	*	0	*	0
1896	2.1	*	2.1	*	0	*	0
1897	3.2	0.1	3.1	*	0	*	0
1898	5.1	1.0	4.1	0	0	*	0
1899	5.8	1.2	4.6	0	0	*	0
1900	8.1	1.3	6.8	*	0	*	0
1901	19.0	6.3	12.7	*	0	*	0
1902	36.8	20.4	15.8	*	0.6	*	0
1903	43.2	17.9	24.3	0.1	0.9	*	0
1904	48.0	19.0	25.3	1.2	2.5	*	0
1905	52.3	20.9	24.8	(b)	6.6	*	0
1906	43.3	9.9	26.2	(b)	7.2	*	0
1907	60.5	7.4	23.9	26.2	3.0	*	0
1908	60.3	6.3	25.1	25.7	3.2	*	0
1909	63.3	5.2	30.3	26.1	1.7	*	0
1910	67.2	4.2	34.8	24.8	3.3	0.1	0
1911	71.5	4.3	36.8	25.4	4.9	0.1	0
1912	72.4	5.3	39.1	23.1	4.2	0.7	0
1913	77.0	6.0	39.4	25.6	5.0	1.0	(d)
1914	79.5	7.6	37.5	27.7	5.4	1.3	0
1915	82.5	8.9	30.8	34.8	6.5	1.5	0
1916	82.2	9.2	30.2	35.6	5.1	2.1	0
1917	75.9	9.7	28.0	32.1	3.4	2.7	0
1918	75.3	10.9	27.4	29.0	4.5	3.5	0
1919	78.7	21.0	26.7	23.0	4.5	3.5	(b)

See footnotes at end of table.

Table A-18.- PERCENTAGE OF TOTAL CRUDE OIL SUPPLIED BY SELECTED STATES, 1880-1937[a] - *Continued*

Year	Total	Texas	California	Oklahoma	Louisiana	Wyoming	New Mexico
1920	81.1	21.9	23.3	24.0	8.1	3.8	(b)
1921	80.4	22.5	23.8	24.3	5.7	4.1	(b)
1922	84.0	21.3	24.8	26.8	6.3	4.8	(b)
1923	85.3	17.9	35.9	22.0	3.4	6.1	(b)
1924	83.7	18.8	32.1	24.3	3.0	5.5	*
1925	79.0	18.9	30.4	23.1	2.7	3.8	0.1
1926	80.5	21.7	29.1	23.2	3.0	3.3	0.2
1927	85.6	24.1	25.7	30.8	2.5	2.4	0.1
1928	86.8	28.5	25.7	27.7	2.4	2.4	0.1
1929	87.9	29.5	29.0	25.3	2.0	1.9	0.2
1930	87.4	32.3	25.3	24.1	2.6	2.0	1.1
1931	88.6	39.1	22.2	21.2	2.6	1.7	1.8
1932	88.1	39.8	22.7	19.5	2.8	1.7	1.6
1933	89.2	44.5	19.0	20.1	2.8	1.2	1.6
1934	87.9	42.0	19.2	19.8	3.6	1.4	1.9
1935	87.5	39.4	20.9	18.6	5.1	1.4	2.1
1936	88.3	38.9	19.5	18.8	7.3	1.3	2.5
1937	88.0	39.9	18.6	17.9	7.1	1.5	3.0

[a]Computed from data in *Minerals Yearbook, 1937* (U. S. Dept. Int., Bur. Mines, 1937), pp. 1008-9 and *Crude Petroleum and Petroleum Products, 1937 - Final Summary* (U. S. Dept. Int., Bur. Mines, Annual Petroleum Statement No. P. 177, mimeo., Nov. 10, 1938), p. 4.

[b]Not reported separately.

*Less than 0.05 percent.

Table A-19.- OUTPUT, NUMBER OF WAGE EARNERS EMPLOYED BY REGULAR PRODUCERS, NUMBER OF WELLS, AVERAGE OUTPUT PER WAGE EARNER, AND AVERAGE NUMBER OF WAGE EARNERS PER WELL IN CRUDE-PETROLEUM PRODUCTION, BY STATE, 1935[a]

Table A-19.- OUTPUT, NUMBER OF WAGE EARNERS EMPLOYED BY REGULAR PRODUCERS, NUMBER OF WELLS, AVERAGE OUTPUT PER WAGE EARNER, AND AVERAGE NUMBER OF WAGE EARNERS PER WELL IN CRUDE-PETROLEUM PRODUCTION, BY STATE, 1935[a]

State	Production (thousands of barrels)	Average number of wage earners employed by regular producers[b]	Number of producing wells on December 31	Average output per wage earner (barrels)	Average number of wage earners per producing well
United States	996,596	93,450	340,990	10,664	0.27
Arkansas	11,008	1,853	2,680	5,941	0.69
California	207,832	14,900	12,780	13,948	1.17
Colorado	1,560	132	200	11,818	0.66
Illinois	4,322	1,412	14,330	3,061	0.10
Indiana	777	220	1,220	3,532	0.18
Kansas	54,843	6,884	19,250	7,967	0.36
Kentucky	5,258	1,240	13,800	4,240	0.09
Louisiana	50,330	5,404	3,400	9,313	1.59
Michigan	15,776	913	1,160	17,279	0.79
Montana	4,603	460	1,650	10,007	0.28
New Mexico	20,483	821	840	24,949	0.98
New York	4,236	1,566	19,600	2,705	0.08
Ohio	4,082	2,150	32,100	1,899	0.07
Oklahoma	185,288	19,260	54,600	9,620	0.35
Pennsylvania	15,810	5,550	82,050	2,849	0.07
Texas	392,666	26,200	59,110	14,987	0.44
West Virginia	3,902	2,855	18,710	1,367	0.15
Wyoming	13,755	1,620	3,380	8,491	0.48
Other States[c]	65	10	130	6,500	0.08

[a]Data from *Census of Business: 1935*, "Petroleum Industry in 1935" (U. S. Dept. Com., Bur. Census in cooperation with U. S. Dept. Int., Bur. Mines, mimeo., June 21, 1937), pp. 3-4.

[b]Excludes workers performing services on contract.

[c]Mississippi, Missouri, Tennessee, and Utah.

Table A-20.- NUMBER OF OIL FIELDS DISCOVERED, BY METHOD OF DISCOVERY, 1922-38[a]

Year	Total	Fields of over a million barrels of ultimate production, by method of exploration			Other fields[b]
		Geological	Geophysical	Random drilling	
1922	26	14	(c)	8	4
1923	27	13	(c)	8	6
1924	34	26	(c)	1	7
1925	32	19	1	2	10
1926	42	27	2	4	9
1927	42	23	3	3	13
1928	51	34	1	2	14
1929	51	24	10	3	14
1930	43	18	4	1	20
1931	27	9	8	3	7
1932	25	10	4	1	10
1933	31	14	7	(c)	10
1934	70	26	18	1	25
1935	131	58	30	4	39
1936	168	56	38	3	71
1937	160	63	44	4	49
1938	223	78	64	2	79

[a] Compiled by J. Brian Eby.

[b] Comprises fields of less than a million barrels of ultimate production.

[c] No discoveries reported.

Table A-21.- CUMULATIVE ULTIMATE PRODUCTION AND CUMULATIVE PRODUCTION FROM OIL FIELDS WITH MORE THAN A MILLION BARRELS OF ESTIMATED ULTIMATE PRODUCTION, BY METHOD OF DISCOVERY, 1922-38[a]

(Thousands of barrels)

Year	Geological			Geophysical			Random drilling		
	Cumulative ultimate production	Cumulative production	Reserves on December 31	Cumulative ultimate production	Cumulative production	Reserves on December 31	Cumulative ultimate production	Cumulative production	Reserves on December 31
1922	342,578	2,012	340,566	(b)	(b)	(b)	501,478	7,089	494,389
1923	874,943	47,285	827,658	(b)	(b)	(b)	649,309	49,341	599,968
1924	1,425,251	155,401	1,269,850	(b)	(b)	(b)	666,191	105,993	560,198
1925	1,968,868	315,879	1,652,989	5,000	(b)	5,000	673,683	209,826	463,857
1926	3,671,561	515,821	3,155,740	13,250	83	13,167	916,509	293,876	622,633
1927	4,315,686	887,402	3,428,284	220,750	425	220,325	938,783	361,182	577,601
1928	6,683,694	1,226,133	5,457,561	310,750	2,667	308,083	945,320	470,719	474,601
1929	7,531,026	1,656,326	5,874,700	393,250	9,068	384,182	1,028,093	562,275	465,818
1930	7,696,706	2.095,286	5,601,420	437,257	29,635	407,622	4,458,093	623,374	3,834,719
1931	7,751,846	2,462,841	5,289,005	799,764	56,949	742,815	5,205,297	774,591	4,430,706
1932	7,903,609	2,777,888	5,125,721	812,390	86,502	725,888	5,239,425	956,162	4,283,263
1933	8,083,602	3,114,524	4,969,078	899,580	122,248	777,332	5,239,425	1,223,182	4,016,243
1934	8,468,189	3,450,847	5,017,342	1,522,697	171,044	1,351,653	5,240,425	1,455,445	3,784,980
1935	9,102,733	3,836,494	5,266,239	2,203,137	244,208	1,958,929	5,270,546	1,680,161	3,590,385
1936	9,526,249	4,302,335	5,223,914	2,575,297	348,653	2,226,644	5,278,386	1,895,366	3,383,020
1937	9,856,856	4,830,769	5,026,087	3,329,528	514,186	2,815,342	5,289,593	2,095,533	3,194,060
1938	10,138,001	5,285,899	4,852,102	3,853,607	719,417	3,134,190	5,296,673	2,277,475	3,019,198

[a] Compiled by J. Brian Eby.

[b] No discoveries reported.

Table A-22.- NUMBER OF GEOPHYSICAL CREWS IN PETROLEUM EXPLORATION OPERATING IN SELECTED MONTHS, 1934-38[a]

Year and month	Seismo-graph	Torsion balance	Gravi-tometer	Magne-tometer	Electric and miscel-laneous
1934					
January	74	30	5	6	0
April	82	38	3	5	0
July	97	44	4	3	0
October	104	43	5	2	0
1935					
January	104	45	6	8	5
April	117	36	5	11	4
July	126	37	4	7	6
October	141	39	3	6	4
1936					
January	144	31	7	4	4
April	160	32	2	4	3
July	185	31	2	4	3
October	177	34	2	2	3
1937					
January	182	29	7	2	5
April	194	25	13	1	6
July	213	28	10	7	5
October	226	39	15	6	5
1938					
January	208	23[b]	19[b]	10[b]	6[b]
April	225	11[b]	21[b]	11[b]	6[b]
July	211	17[b]	21[b]	12[b]	9[b]
October	196	15[b]	24[b]	9[b]	8[b]

[a] Compiled by J. Brian Eby.

[b] Data cover the Mid-Continent and Gulf Coast regions only; the work done in these areas, however, is believed to represent more than three-fourths of the total discovery activity.

Table A-23.- COST OF GEOPHYSICAL FIELD WORK IN PETROLEUM EXPLORATION, BY QUARTER, 1934-38[a]

Year and quarter	Seismograph	Torsion balance	Gravitometer	Magnetometer	Electric and miscellaneous
Total	$71,280,000	$4,702,500	$523,500	$180,750	$342,750
1934					
1st	1,665,000	225,000	15,000	9,000	0
2nd	1,845,000	285,000	9,000	7,500	0
3rd	2,182,500	330,000	12,000	4,500	0
4th	2,340,000	322,500	15,000	3,000	0
1935					
1st	2,340,000	337,500	18,000	12,000	22,500
2nd	2,632,500	270,000	15,000	16,500	18,000
3rd	2,835,000	277,500	12,000	10,500	27,000
4th	3,172,500	292,500	9,000	9,000	18,000
1936					
1st	3,240,000	232,500	21,000	6,000	18,000
2nd	3,600,000	240,000	6,000	6,000	13,500
3rd	4,162,500	232,500	6,000	6,000	13,500
4th	3,982,500	255,000	6,000	3,000	13,500
1937					
1st	4,095,000	217,500	21,000	3,000	22,500
2nd	4,365,000	187,500	39,000	1,500	27,000
3rd	4,792,500	210,000	30,000	10,500	22,500
4th	5,085,000	292,500	45,000	9,000	22,500
1938					
1st	4,691,250	172,500[b]	57,000[b]	15,000[b]	27,000[b]
2nd	5,096,250	82,500[b]	64,500[b]	16,500[b]	27,000[b]
3rd	4,747,500	127,500[b]	51,000[b]	18,750[b]	14,250[b]
4th	4,410,000	112,500[b]	72,000[b]	13,500[b]	36,000[b]

[a]Compiled by J. Brian Eby.

[b]Data cover the Mid-Continent and Gulf Coast regions only; the cost of work done in these areas, however, is believed to represent more than three-fourths of total expenditures.

Table A-24.- COST OF DRILLING WELLS TO PRODUCING FORMATIONS, 1931[a]

Field or district	Depth of well (feet)	Cost per foot of depth[b]
California		
Santa Fe Springs	8,200	$26.89
Kettleman Hills	7,694	32.40
Oklahoma		
Oklahoma City	6,650	18.45
Seminole	4,275	16.41
Texas		
Gulf Coast	6,000	10.60
East Texas	3,650	6.51
Hobbs, New Mexico	4,200	21.37
North and West Texas	3,500	10.80
Wyoming	3,000	10.98
Central Ohio and West Virginia	3,000	4.99
Bradford, Pennsylvania	1,650	2.22
Kansas and Oklahoma	850	3.13
Owensboro, Kentucky	750	3.51

[a]Data from H. C. Miller and B. E. Lindsly, "Report on Petroleum Development and Production," *Petroleum Investigation* (U. S. Congress, House of Representatives, Hearings on H. Res. 441, 73d Cong., Recess, 1934), part 2, p. 1158.

[b]Cost of pumping equipment is not included.

Table A-25.- WHOLESALE-PRICE INDEXES OF PETROLEUM PRODUCTS AND ALL COMMODITIES, 1913-37[a]

(1926=100)

Year	Yearly average	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	Petroleum products												
1913	73.3	72.0	74.0	74.0	74.0	72.8	72.2	72.2	73.1	73.3	73.6	74.4	73.6
1914	65.8	75.3	75.7	75.7	75.5	69.3	66.9	63.7	62.0	61.6	55.8	54.4	53.9
1915	54.1	53.5	52.5	48.4	47.8	47.8	47.8	46.9	50.3	55.5	60.1	65.5	73.5
1916	87.3	80.9	85.7	90.9	92.6	92.3	92.8	92.7	88.6	81.7	80.4	83.5	85.9
1917	112.1	98.3	105.3	106.6	107.0	107.2	108.5	111.7	111.7	119.0	122.1	122.7	124.6
1918	135.3	126.8	126.8	129.2	133.4	136.0	138.1	138.4	137.6	138.4	138.5	139.9	139.8
1919	128.0	134.6	126.4	126.0	126.0	125.5	126.1	125.1	124.1	123.6	124.2	128.1	146.4
1920	183.5	154.8	163.4	183.2	190.6	196.1	197.2	197.3	198.9	193.8	184.2	175.0	169.2
1921	104.4	162.3	117.3	110.2	113.5	101.8	87.1	79.8	78.0	77.3	97.7	115.5	111.2
1922	102.9	105.7	106.7	107.7	111.3	119.6	123.8	113.6	94.5	94.4	91.2	85.5	83.5
1923	82.6	88.7	101.4	103.7	98.5	87.5	86.0	79.1	75.0	71.3	69.6	64.7	65.5
1924	83.5	83.3	94.7	94.0	92.9	89.1	83.0	81.2	76.7	76.6	73.2	75.7	80.2
1925	95.0	83.5	104.2	99.9	94.3	96.4	104.2	102.3	95.4	89.3	87.4	89.4	91.7
1926	100.0	92.3	96.3	98.9	99.4	106.3	106.6	103.3	104.6	105.4	100.9	94.1	93.7
1927	72.7	93.0	90.9	80.0	70.0	68.0	68.0	68.1	66.5	66.4	67.5	66.6	66.2
1928	72.0	65.6	66.6	66.6	69.0	71.2	71.9	73.5	76.8	77.1	76.3	75.5	73.9
1929	71.3	71.9	68.9	68.5	71.1	72.5	76.6	73.3	70.3	70.2	70.8	70.9	69.9
1930	61.5	67.3	65.7	63.7	65.6	66.5	63.6	61.0	60.9	62.0	59.4	53.3	51.1
1931	39.5	50.4	50.2	41.8	37.4	35.9	30.7	30.3	37.5	38.9	39.2	42.5	39.6
1932	45.4	38.8	38.6	39.8	45.5	47.2	48.2	49.7	48.9	48.7	47.4	48.2	45.0
1933	41.0	38.7	34.3	33.1	32.5	31.2	34.4	41.3	40.9	49.6	52.7	51.6	51.6
1934	50.5	51.1	50.3	48.7	49.4	50.7	50.6	51.3	51.6	51.3	50.4	50.5	49.8
1935	51.3	48.8	48.7	49.8	51.0	52.2	53.2	52.9	52.4	50.6	50.1	52.5	52.8
1936	57.3	54.4	55.7	56.0	57.9	58.2	57.7	58.1	57.9	57.5	57.9	58.1	58.0
1937	60.5	58.3	59.1	58.6	59.8	60.9	61.5	61.8	62.0	62.2	61.7	60.6	59.5
	All commodities												
1913	69.8	70.3	69.8	69.9	68.7	68.9	69.0	69.5	69.7	70.6	70.4	70.1	69.1
1914	68.1	68.6	68.3	68.0	67.6	67.4	67.4	67.3	69.6	70.2	68.0	67.5	67.3
1915	69.5	68.1	68.6	68.2	68.7	69.0	68.3	69.3	68.6	68.3	70.2	71.7	74.0
1916	85.5	77.0	78.5	80.4	81.7	82.5	82.9	83.4	85.1	86.9	91.1	97.4	99.2
1917	117.5	102.1	104.5	107.7	114.1	120.7	122.0	123.0	124.8	123.5	122.2	122.8	122.9
1918	131.3	125.0	122.7	126.4	128.3	128.1	129.0	132.0	134.3	137.5	136.3	136.3	136.3
1919	138.6	134.4	129.8	131.3	133.0	135.3	135.6	141.1	144.3	141.1	141.6	144.5	150.5
1920	154.4	157.7	157.1	158.6	165.5	167.2	166.5	165.8	161.4	155.2	144.2	133.4	120.7
1921	97.6	114.0	104.9	102.4	98.9	96.2	93.4	93.4	93.5	93.4	94.1	94.2	92.9
1922	96.7	91.4	92.9	92.8	93.2	96.1	96.3	99.4	98.6	99.3	99.6	100.5	100.7
1923	100.6	102.0	103.3	104.5	103.9	101.9	100.3	98.4	97.8	99.7	99.4	98.4	96.1
1924	98.1	99.6	99.7	98.5	97.3	95.9	94.9	95.6	97.0	97.1	98.2	99.1	101.5
1925	103.5	102.9	104.0	104.2	101.9	101.6	103.0	104.3	102.9	103.4	103.6	104.5	103.4
1926	100.0	103.2	102.0	100.6	100.3	100.5	100.4	99.5	99.1	99.7	99.4	98.4	97.9
1927	95.4	96.5	95.8	94.7	94.1	94.2	94.1	94.3	95.2	96.3	96.6	96.3	96.4
1928	96.7	96.4	95.8	95.5	96.6	97.5	96.7	97.4	97.6	98.6	96.7	95.8	95.8
1929	95.3	95.9	95.4	96.1	95.5	94.7	95.2	96.5	96.3	96.1	95.1	93.5	93.3
1930	86.4	92.5	91.4	90.2	90.0	88.8	86.8	84.4	84.3	84.4	83.0	81.3	79.6
1931	73.0	78.2	76.8	76.0	74.8	73.2	72.1	72.0	72.1	71.2	70.3	70.2	68.6
1932	64.8	67.3	66.3	66.0	65.5	64.4	63.9	64.5	65.2	65.3	64.4	63.9	62.6
1933	65.9	61.0	59.8	60.2	60.4	62.7	65.0	68.9	69.5	70.8	71.2	71.1	70.8
1934	74.9	72.2	73.6	73.7	73.3	73.7	74.6	74.8	76.4	77.6	76.5	76.5	76.9
1935	80.0	78.8	79.5	79.4	80.1	80.2	79.8	79.4	80.5	80.7	80.5	80.6	80.9
1936	80.8	80.6	80.6	79.6	79.7	78.6	79.2	80.5	81.6	81.6	81.5	82.4	84.2
1937	86.3	85.9	86.3	87.8	88.0	87.4	87.2	87.9	87.5	87.4	85.4	83.3	81.7

[a] Based on wholesale-price data of the U. S. Bur. Labor Statistics. The items included in the index for petroleum products are described by J. M. Cutts in *Wholesale Prices: Specifications of Commodities Entering Into the Composite Weighted Index* (U. S. Dept. Labor, Bur. Labor Statistics, mimeo., Sept. 1926), p. 11, as follows:

Fuel oil, Oklahoma, 24-28 gravity, per barrel, f. o. b. refinery, tank cars
Fuel oil, Pennsylvania, 36-40 gravity, per gallon, f. o. b. refinery, tank cars
Gasoline, natural, Oklahoma, grade 28-30, per gallon, refinery
Gasoline, 54-56, U. S. motor, California, outside state shipment, per gallon, refinery
Gasoline, North Texas, U. S. motor, 65-70, octane number, per gallon, refinery
Gasoline, Oklahoma, U. S. motor, 65-70, octane number, per gallon, refinery
Gasoline, Pennsylvania, 58-62, U. S. motor, per gallon, refinery
Kerosene, refined for export, Eagle, standard, white 150° fire test, cargo bulk, per gallon, bulk refinery
Kerosene, water white, 47 Pennsylvania, per gallon, refinery
Petroleum, crude, California, 200 to 20.99, Signal Hill, Seal Beach, Long Beach Regions, per barrel at well
Petroleum, crude, California, 220 to 25.99, per barrel (42 gallons) at well
Petroleum, crude, Oklahoma-Kansas, 33.00 to 35.99, per barrel at well
Petroleum, crude, Pennsylvania, Net. Trans. Co. Lines, per barrel at well

The index for all commodities is based on 550 separate commodities for 1913-26 and on 784 separate commodities for 1926-37. The commodities were weighted in accordance with their relative importance. See *Wholesale Prices, 1931* (U. S. Dept. Labor, Bur. Labor Statistics, Bull. No. 572, 1932), p. 16.

Table A-26.- CRUDE OIL CONSERVED BY THE CRACKING PROCESS, 1920-37[a]

(Millions of barrels)

Year	Amount run to stills	Estimated amount which would have been required by straight-run distillation methods	Estimated amount conserved by cracking process
1920	434	500	66
1921	443	532	88
1922	501	632	132
1923	581	756	175
1924	644	860	217
1925	740	1,036	296
1926	779	1,189	410
1927	829	1,255	426
1928	913	1,424	511
1929	988	1,568	580
1930	927	1,606	679
1931	895	1,612	717
1932	820	1,537	717
1933	861	1,657	795
1934	896	1,687	792
1935	966	1,882	916
1936	1,069	2,170	1,101
1937[b]	1,183	2,451	1,268

[a] Data for 1920-34 from American Petroleum Institute, *Petroleum Facts and Figures* (5th ed.; New York: 1937), p. 118. Crude runs to stills for 1935-37 are from *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), p. 815; conservation for the same years was computed from data in *ibid.*, pp. 867-8, *Minerals Yearbook, 1936* (1936), pp. 710, 715, and *Minerals Yearbook, 1937* (1937), pp. 1031-2.

[b] Preliminary; subject to revision.

Table A-27.- FUEL EFFICIENCY IN PETROLEUM REFINING, 1909-37

Year	Energy consumed (billions of B. t. u.)[a]					Barrels of crude petroleum run to stills[b] (thousands)	Energy consumed per barrel of crude run to stills (thousands of B. t. u.)	
	Heat value of all fuels consumed at refineries	Heat equivalent of purchased electricity[c]		Total energy consumed				
		At constant fuel equivalent[d]	At prevailing central-station fuel equivalent[e]	With purchased electricity at constant fuel equivalent[f]	With purchased electricity at prevailing central-station fuel equivalent[g]		Excluding influence of central-station fuel efficiency[h]	Including influence of central-station fuel efficiency[i]
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1909	103,853	3	4	103,856	103,857	120,775	860	860
1914	154,010	1,302	1,627	155,312	155,637	191,263	812	814
1919	306,451	4,660	4,660	311,111	311,111	365,272	852	852
1925	613,479	9,385	6,159	622,864	619,638	739,920	842	837
1926	648,517	12,243	7,461	660,760	655,978	779,264	848	842
1927	597,494	14,873	8,552	612,367	606,046	828,835	739	731
1928	609,212	21,130	11,622	630,342	620,834	913,295	690	680
1929	630,837	23,856	12,599	654,693	643,436	987,708	663	651
1930	623,443	34,388	17,409	657,831	640,852	927,447	709	691
1931	601,122	38,186	18,496	639,308	619,618	894,608	715	693
1932	567,490	35,186	16,493	602,676	583,983	819,997	735	712
1933	568,460	37,459	17,208	605,919	585,668	861,254	704	680
1934	571,471	42,556	19,283	614,027	590,754	895,636	686	660
1935	594,231	44,589	20,344	638,820	614,575	966,243	661	636
1936	638,149	49,547	22,296	687,696	660,445	1,068,570	644	618
1937	663,866	54,520	23,853	718,386	687,719	1,183,440	607	581

[a] Data for heat values of all items, except heat value of purchased electricity at constant fuel equivalent, are from table A-28.

[b] Data for 1909, 1914, and 1919 are from *Fourteenth Census of the United States: 1920*, Vol. X, "Manufactures: 1919" (U. S. Dept. Com., Bur. Census, 1923), p. 762; data for all other years are from reports of petroleum refineries to the U. S. Bureau of Mines and published in reports indicated in table A-28, fn. a.

[c] Purchased electricity was converted into its heat equivalent on the basis of the B. t. u. of fuel consumed per kilowatt-hour generated by fuel-burning central electric-power stations. This procedure was followed in preference to the use of the theoretical heat equivalent of 1 kilowatt hour (3,420 B. t. u.), as the purpose was to take account of the heat value of all fuel consumed, even though indirectly in the case of purchased electricity. Data on kilowatt-hours of electricity purchased by petroleum refineries are from sources indicated in table A-28. Data on fuel consumed per kilowatt-hour by central power stations for 1909-36 are from N. Yaworski, V. Spencer, G. A. Seeger, and O. E. Kiessling, *Fuel Efficiency in Cement Manufacture, 1909-1935* (WPA National Research Project in cooperation with U. S. Department of the Interior, Bureau of Mines, Report No. E-5, Apr. 1938), pp. 70-1; data for 1937 are from *Minerals Yearbook, 1938* (U. S. Dept. Int., Bur. Mines, 1938), p. 716.

[d] Purchased electricity was converted into its heat equivalent on the basis of the constant factor of 3.2 pounds of coal equivalent (41,000 B. t. u.) per kilowatt-hour, the average rate of consumption of fuel by central power stations in 1919, so as to exclude the influence of the fuel-efficiency progress of central power stations.

[e] Purchased electricity was converted into its heat equivalent on the basis of the B. t. u. of fuel consumed per kilowatt-hour by fuel-burning power stations in each year.

[f] Sum of cols. (1) and (2).

[g] Sum of cols. (1) and (3).

[h] Col. (4) divided by col. (6).

[i] Col. (5) divided by col. (6).

Table A-28.- ENERGY CONSUMED IN PETROLEUM REFINING, BY TYPE, 1909-37[a]

Year	Total	Coal	Petroleum coke[b]	Fuel oil	Natural gas	Refinery gas	Acid sludge	Purchased electricity[c]
	Billion B. t. u. consumed[d]							
1909	103,857	72,126	2,988	20,843	7,896		0	4
1914	155,637	93,002	4,729	44,736[e]	11,543		(e)	1,627
1919	311,111	126,300	9,587	142,299[e]	28,265		(e)	4,660
1925	619,638	159,978	9,420	302,790[e,f]	92,234	49,057	(e)	6,159
1926	655,978	157,352	12,240	278,496[e]	127,521	72,908	(e)	7,461
1927	606,046	130,806	13,500	248,772[e]	129,565	74,851	(e)	8,552
1928	620,834	87,412	14,100	278,764[e,g]	120,698	108,238	(e)	11,622
1929	643,436	59,800	14,640	309,264[e]	108,915	138,218	(e)	12,599
1930	640,852	50,674	17,400	281,736[e]	103,784	169,849	(e)	17,409
1931	619,618	36,712	15,870	233,478	79,325	209,894	25,843	18,496
1932	583,983	24,908	9,990	208,806	70,840	226,288	26,658	16,493
1933	585,668	27,794	7,890	199,752	69,650	240,919	22,455	17,208
1934	590,754	30,914	5,820	198,978	83,963	230,637	21,159	19,283
1935	614,575	31,746	9,282	188,982	84,184	256,736	23,301	20,344
1936	660,445	34,060	6,342	182,724	97,842	294,964	22,217	22,296
1937	687,719	31,434	10,731	167,094	118,655	314,577	21,375	23,853
	Percent of B. t. u. consumed							
1909	100.0	69.4	2.9	20.1	7.6		0	*
1914	100.0	59.8	3.0	28.7[e]	7.4		(e)	1.1
1919	100.0	40.6	3.1	45.7[e]	9.1		(e)	1.5
1925	100.0	25.8	1.5	48.9[e,f]	14.9	7.9	(e)	1.0
1926	100.0	24.0	1.9	42.5[e]	19.4	11.1	(e)	1.1
1927	100.0	21.6	2.2	41.0[e]	21.4	12.4	(e)	1.4
1928	100.0	14.1	2.3	44.9[e,g]	19.4	17.4	(e)	1.9
1929	100.0	9.3	2.3	48.1[e]	16.9	21.5	(e)	1.9
1930	100.0	7.9	2.7	44.0[e]	16.2	26.5	(e)	2.7
1931	100.0	5.9	2.6	37.7	12.8	33.9	4.1	3.0
1932	100.0	4.3	1.7	35.8	12.1	38.7	4.6	2.8
1933	100.0	4.8	1.4	34.1	11.9	41.1	3.8	2.9
1934	100.0	5.2	1.0	33.7	14.2	39.0	3.6	3.3
1935	100.0	5.2	1.5	30.7	13.7	41.8	3.8	3.3
1936	100.0	5.1	1.0	27.7	14.8	44.6	3.4	3.4
1937	100.0	4.6	1.6	24.3	17.2	45.7	3.1	3.5

[a] Basic data on quantities of fuel consumed and on horsepower of electric motors using purchased electric energy for 1909 from *Thirteenth Census of the United States: 1910*, Vol. X, "Manufactures: 1909" (U. S. Dept. Com., Bur. Census, 1913), p. 661; for 1914 from *Census of Manufactures: 1914* (U. S. Dept. Com., Bur. Census, 1919), II, 585; for 1919 from *Fourteenth Census of the United States: 1920*, Vol. X, "Manufactures: 1919" (1923), pp. 760-1. Data for all other years are from reports of petroleum refineries to the U. S. Bureau of Mines, and are published in the Bureau's series entitled "Report of Investigations." The serial numbers used are as follows: 2829, 2886, 2964, 3038, 3145, 3198, 3222, 3270, 3281, 3332, 3367, 3430. Each of these reports was written by G. R. Hopkins.

[b] The consumption of purchased steam was reported in 1935, 1936, and 1937 and its B. t. u. equivalent is included with data for coke. The total heat value of purchased steam was 5,973 billion B. t. u. in 1936 and 8,211 billion in 1937.

[c] The quantity of electricity consumed in 1909-28 was estimated from the rated horsepower of electric motors driven by purchased electricity, assuming a consumption of 2,180 kilowatt-hours per horsepower, as was indicated for 1929; for all other years the number of kilowatt-hours of purchased electricity consumed by refineries was reported to the U. S. Bureau of Mines. The kilowatt-hours of purchased electricity were converted into their heat equivalent on the basis of the B. t. u. of fuel consumed per kilowatt-hour by fuel-burning central electric-power stations in each year. This procedure was followed in preference to the use of the theoretical heat equivalent of 1 kilowatt-hour (3,420 B. t. u.), as the purpose was to take account of the heat value of all fuel consumed, even though indirectly in the case of purchased electricity.

[d] The quantities of fuels consumed were converted into their approximate heat values by using the following unit B. t. u. values: Coal, 26,000,000 per short ton; petroleum coke, 30,000,000 per short ton; fuel oil, 6,000,000 per barrel; natural gas, 1,050 per cubic foot; refinery gas, 1,400 per cubic foot; acid sludge, 4,500,000 per barrel; wood (included with oil in 1925), 18,000,000 per cord; purchased steam (included with coke in 1935-37), 1,013 per pound; and refuse (included with oil in 1925), 30,000,000 per ton.

[e] The quantity of acid sludge consumed was not reported separately for 1914-30 but was included with data for fuel oil.

[f] Includes 60 billion B. t. u. in the form of wood.

[g] Includes refuse equivalent to about 384 billion B. t. u.

* Less than 0.05 percent.

Table A-29.- PERCENTAGE YIELDS (BY VOLUME) OF THE MAJOR REFINED PRODUCTS FROM CRUDE OIL RUN TO STILLS, 1904-37[a]

Year	Gasoline	Kerosene	Fuel oil	Lubricants
1904	10.3	48.2	12.8	11.2
1909	10.7	33.0	33.5	10.6
1914	14.9	24.1	46.1	6.4
1916	19.8	14.0	45.0	6.0
1917	21.5	13.0	49.2	5.7
1918	25.3	13.3	53.5	6.1
1919	25.2	15.4	50.2	5.6
1920	26.1	12.7	48.6	5.7
1921	27.1	10.4	51.9	4.7
1922	28.8	11.0	50.9	4.7
1923	30.0	9.6	49.5	4.5
1924	31.2	9.3	49.8	4.3
1925	32.4	8.1	49.3	4.2
1926	34.9	7.9	46.9	4.1
1927	36.0	6.8	47.4	3.8
1928	37.4	6.5	46.8	3.8
1929	39.3	5.7	45.5 43.4[b]	3.5
1930	42.0	5.3	40.2	3.7
1931	44.3	4.7	37.7	3.0
1932	44.7	5.3	36.0	2.7
1933	43.7	5.7	36.1	2.8
1934	43.4	6.0	37.4	2.9
1935	44.2	5.8	36.0	2.9
1936	44.1	5.2	38.5	2.9
1937	43.9	5.5	38.8	3.0

[a]Data for 1904 from *Census of Manufactures: 1905* (U. S. Dept. Com. and Labor, Bur. Census, 1908), part IV, p. 575; for 1909 from *Thirteenth Census of the United States: 1910*, Vol. X, "Manufactures: 1909" (U. S. Dept. Com., Bur. Census, 1913), p. 662; for 1914 from *Census of Manufactures: 1914* (U. S. Dept. Com., Bur. Census, 1919), II, 582; for 1916-30 from G. R. Hopkins, *Petroleum Refinery Statistics, 1930* (U. S. Dept. Com., Bur. Mines, Bull. No. 367, 1932), p. 42; for 1931-37 from reports of petroleum refineries to the U. S. Bureau of Mines.

[b]Beginning with 1929, data were computed on a new basis whereby certain duplications were eliminated.

Table A-30.- ESTIMATED TREND OF FUTURE CRUDE-OIL REQUIREMENTS, 1944-69[a]

Year	Estimated number of motor vehicles in use (thousands)	Estimated motor-fuel demand per vehicle (barrels)	Estimated total motor-fuel requirements[b] (thousands of barrels)	Estimated ratio of gasoline produced to crude run to stills	Estimated crude oil required[c] (thousands of barrels)
	(1)	(2)	(3)	(4)	(5)
1944	30,700	21.15	649,000	0.50	1,298,000
1949	34,500	22.40	773,000	.55	1,405,000
1954	38,000	22.90	870,000	.59	1,475,000
1959	41,000	23.20	951,000	.65	1,463,000
1964	43,500	23.30	1,014,000	.71	1,428,000
1969	45,000	23.30	1,049,000	.74	1,418,000

[a]The methodology employed in making these estimates and the figure on estimated motor-fuel demand for 1944 are from an unpublished study by H. A. Breakey, "The Measurement and Forecasting of Domestic Motor Fuel Demand." For the purposes of this survey, Dr. Breakey has extended his original estimates, by 5-year intervals, through 1969.

[b]Col. (1) multiplied by col. (2).

[c]Col. (3) divided by col. (4).

Table A-31.- COMPARISON OF TWO ESTIMATES OF FUTURE CRUDE-OIL REQUIREMENTS

(Barrels)

Year	American Petroleum Institute[a]	Parsons and St. Clair[b]	
1935	919,500,000	n.a.	
1936	n.a.		[c]
1940	1,099,000,000		
1945	1,104,080,000		
1950	1,109,800,000		
1954	n.a.	Minimum:	1,380,000,000
		Maximum:	1,520,000,000
1955	1,087,930,000	n.a.	
1960	1,071,020,000	n.a.	

[a]American Petroleum Institute, *American Petroleum Industry* (New York: 1935), p. 32.

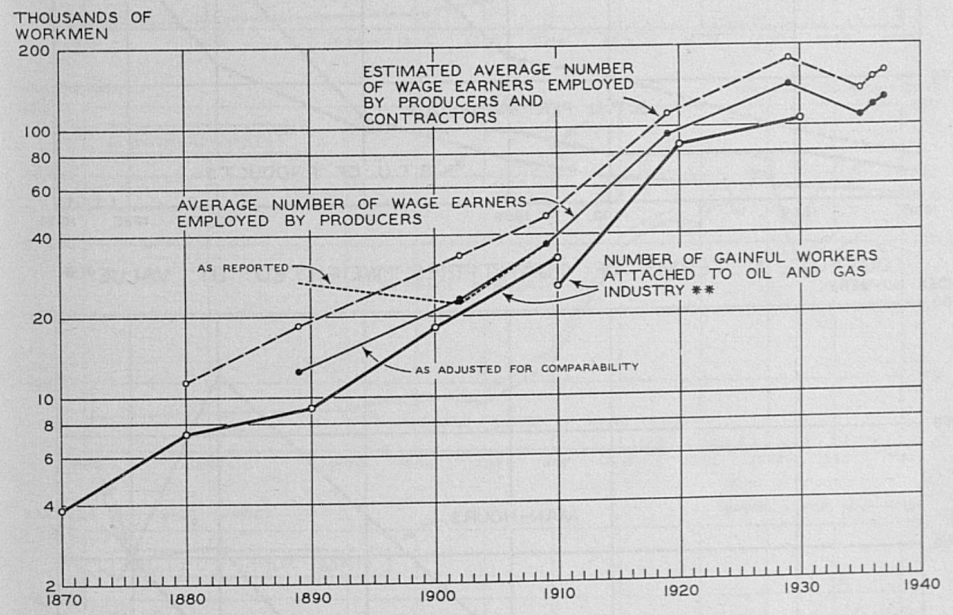
[b]A. B. Parsons and S. St. Clair, "Outlook for World Consumption of Metals and Fuels," *Mining and Metallurgy*, Vol. 18, No. 364 (Apr. 1937), pp. 194-5.

[c]As an estimated trend from 1936 to 1954, Parsons and St. Clair projected a straight line determined by actual production for 1936 (1,099,687,000 barrels) and by the minimum estimate for 1954 (1,380,000,000 barrels).

n.a. Data not available.

Figure A-1.- COMPARISON OF NUMBER OF WAGE EARNERS EMPLOYED, AS REPORTED IN CENSUS OF MINES AND QUARRIES, WITH NUMBER OF GAINFUL WORKERS ATTACHED, AS REPORTED IN CENSUS OF OCCUPATIONS, IN THE OIL AND GAS INDUSTRY, 1870-1937*

(Ratio scale)



* NUMBER OF WAGE EARNERS FOR 1929 ESTIMATED; NUMBERS FOR 1936 AND 1937 DERIVED FROM REPORTS OF OIL AND GAS COMPANIES TO THE U. S. BUREAU OF MINES.

** DATA FOR 1870-1910 INCLUDE A LARGER NUMBER OF OCCUPATIONS THAN DO DATA FOR 1910-30.

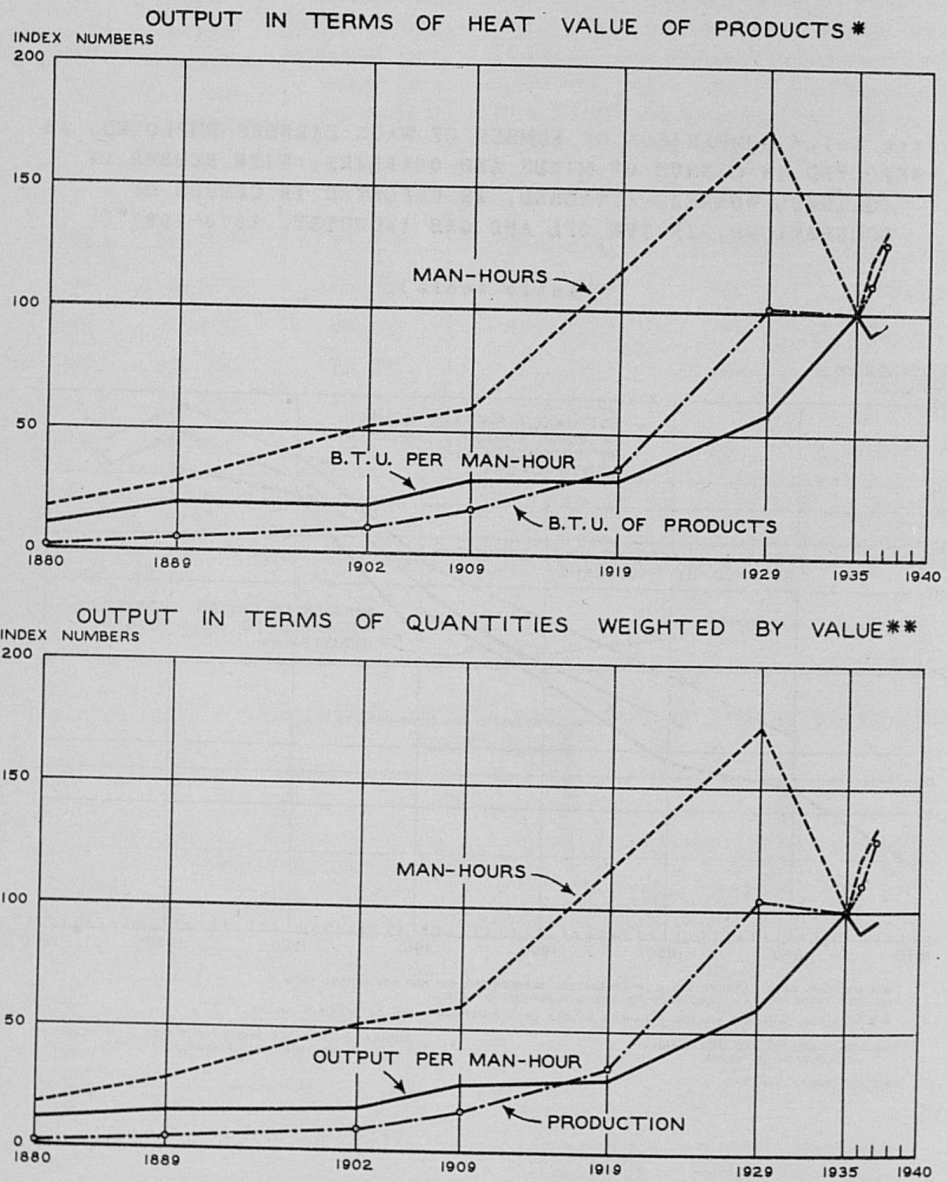
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BASED ON TABLES A-11, A-12

Figure A-2.- INDEXES OF PRODUCTION, MAN-HOURS, AND OUTPUT PER MAN-HOUR IN CRUDE-PETROLEUM, NATURAL-GAS, AND NATURAL-GASOLINE PRODUCTION, 1880-1937

(1935=100)



*UNIT HEAT VALUES EMPLOYED ARE: PETROLEUM, 6,000,000 B.T.U. PER BARREL; NATURAL GAS, 1,000 B.T.U. PER CUBIC FOOT; NATURAL GASOLINE, 120,000 B.T.U. PER GALLON.

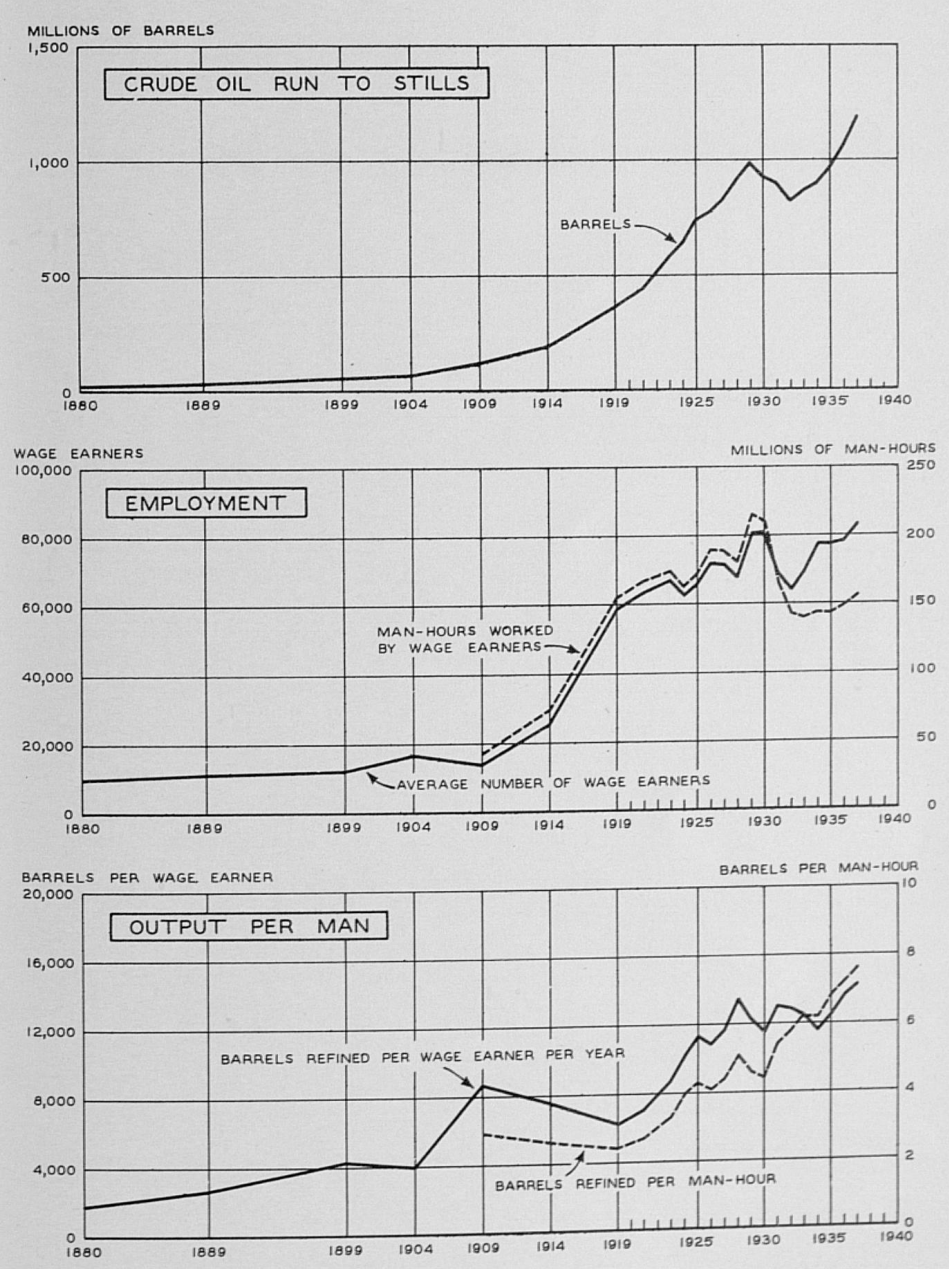
**BASED ON PRODUCTION OF CRUDE PETROLEUM, NATURAL GAS, AND NATURAL GASOLINE; WEIGHTED BY 1923-25 AVERAGE UNIT VALUES AT POINTS OF PRODUCTION.

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BASED ON TABLE A-16

Figure A-3.- CRUDE PETROLEUM RUN TO STILLS, EMPLOYMENT, AND OUTPUT PER MAN IN PETROLEUM REFINING, 1880-1937



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BASED ON TABLE A-13

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