PETROLEUM PRODUCTION

The story of Project 37, a fundamental research program which has produced some spectacularly practical results in the petroleum industry

IN 1927 the Institute became interested in a study of the behavior of the fluids produced from oil wells. The industry was familiar with the properties of natural gas, crude oil, and brackish water as they were collected at the well head. However, little was known as to their states under conditions prevailing before they entered the bottom of the well. This situation seemed to offer an opportunity for providing some basic knowledge which would be of practical interest both to science and to technology.

The study program was initiated under a research grant from funds furnished jointly by John D. Rockefeller and the Universal Oil Products Company, administered through a central committee of the National Research Council.

Research Project 37 at the Institute was one of some forty researches supported by this fund during its limited life. When the original fund was depleted, the American Petroleum Institute took over administration of the program, but because it was necessary to operate on annual donations from individual oil companies, a sharp cut-back in support resulted. The program was reduced to three investigations and Project 37 in the chemical engineering laboratory of the Institute was very fortunate in being retained in active service.

This form of cooperation between the American Petroleum Institute and the California Institute has continued without interruption for nearly twenty-six years, and its largest annual budget to date has already been allotted for work during the twenty-seventh year. During this period the API research program has expanded to a total of nine projects with an annual budget of nearly half a million dollars.

The term "oil field" usually applies to an area at the surface of the earth within which a number of wells are located. Beneath this location may lie a series of "reservoirs" at increasing depths below the surface. Often these reservoirs are essentially completely segregated from each other at time of discovery. The reservoir or producing formation consists of a slightly porous stratum in the earth's crust in the interstices of which hydrocarbon fluids have collected during geologic time.

Not all porous strata contain hydrocarbons: in fact, only are they so enriched when a combination of factors happens to prove favorable. These factors include nearness of organic sediments which can be changed to hydrocarbons, suitable conditions for this change, and channels for movement of the hydrocarbons to the collecting "trap"—such as that offered by an anticlinal fold in a porous stratum.

The mineral material making up favorable strata for petroleum collection is of sedimentary origin and varies in constitution from lightly cemented coarse sandstone to hard, shalelike rock, with exceedingly small pore spaces between the fine grains of clay. In some cases porous or shattered limestone formations serve as a collecting zone.

As a well is drilled deeper into the earth's crust, the temperature and pressure at the bottom of the hole are found to increase. Wells have been driven to depths of approximately 20,000 feet while subsurface temperatures exceeding 350° F and pressures approximating 9000 pounds per square inch or more have been measured.

Although these extreme conditions had not been encountered at the time Project 37 was started—when shallower wells were sufficient to supply the demand—it nevertheless seemed likely that a mixture of crude oil, natural gas, and water, when subjected to high pressure and temperature, would have decidedly different properties than when existing at normal room conditions. The available knowledge regarding this situation at that time was very meager.

The petroleum production engineer, who is in charge of the economic and effective exploitation of any given petroleum reservoir, bears a heavy responsibility to his company and the nation because, by improper manipulation, it is very easy to permit a severe loss of a vital natural resource by leaving unnecessarily large amounts of oil in the formation in an economically unrecoverable condition. In order to avoid such losses, the engineer requires not only skill, but an accurate knowledge of the behavior of the materials with which he is working, under all the conditions to be met in practice. It was the objective of Project 37 to add as much as possible to his fund of information.

The hydrocarbons found in a petroleum reservoir comprise a very large number of compounds of carbon and hydrogen, made up of molecules containing from one carbon atom to many tens of them, and varying correspondingly in physical properties. Those with the smallest molecules are gaseous under ordinary conditions, or at least highly volatile; whereas the largest molecules correspond to viscous liquids of low volatility, or even to solids when in the pure state. Because of a family similarity between these compounds, they are all soluble in each other to some extent.

The behavior of the mixture

It might at first be thought that in mixtures of hydrocarbons, each one might contribute to the composite properties of the mixture in direct proportion to the fractional part its molecules contribute to the whole. This relationship does hold in a semi-quantitive way, and it has been very useful to the industry in predicting properties of complex hydrocarbon mixtures when applied under the most favorable conditions. However, the very important compounds of low molecular weight digress markedly from such behavior, particularly at high temperatures and pressures. Under these latter conditions, which have come more to be the rule than the exception in petroleum production, the behavior of mixtures is very complex, and not susceptible to accurate prediction by means of any simple relation.

These facts were determined early in the life of the project, and it became evident that much information would have to be collected before the problem could be solved. One way to approach the investigation would be to make direct measurements of the important properties of all the complex mixtures found in the underground reservoirs. However, because of the wide variation in composition found in these mixtures, and the great differences in temperature and pressure between reservoirs, this attack did not seem to offer as much chance of giving fundamental understanding of the individual effects of composition, temperature, and pressure, as did an approach consisting of studying first the behavior of single hydrocarbons, then of mixtures of various pairs, to be followed by studies of ternary systems. This procedure would serve to ascertain the contribution of each hydrocarbon to the behavior of the mixture.

The project developed equipment and experimental methods for measuring the volume occupied by known weights of hydrocarbon material under pressures from that of the atmosphere up to 10,000 pounds per square inch, at temperatures ranging from little above the freezing point of water to over 450° F. It was also possible to ascertain quantitatively how much of this volume was occupied by liquid and how much was gas phase.

This type of information was needed by the petroleum engineer for a number of reasons. From a knowledge of the composition and volume of material withdrawn from a well and gauged at surface conditions, he had need to know the corresponding volume of the material when still in the reservoir, and also how much of it had been liquid and how much gas under the conditions prevailing there. If he knew the extent of the reservoir and the porosity of the "sand", he could then estimate the reserve of petroleum contained in the reservoir, and to how much oil and gas at the surface it would correspond. If the reservoir was one of fixed total volume, he could estimate the rate of decline of pressure to be expected for a given rate of withdrawal through wells.

The project also studied the energy involved in changes of state of hydrocarbons. These thermodynamic properties are important to the production engineer because, in many cases, the energy stored in the hydrocarbons under high pressure is relied upon to force the material up the bore of the well a number of thousand feet above its original location. If this stored energy is unnecessarily dissipated by poor production practice, the costly process of pumping must be resorted to earlier in the life of the field. Also, in many cases, this stored energy must be used in moving petroleum fluids through the fine pore channels toward the well in order that they may be lifted thence to the surface.

Theory and practice

As an example of the use which could be made of these types of information by men in the industry, there can be cited the case of a deep well drilled in Texas which showed what was thought to be very peculiar behavior. Wells drilled to the bottom of this particular reservoir produced a relatively heavy brown crude oil, and only moderate amounts of gas, when the mixture was brought to the surface.

On the other hand, wells which only went down to the upper part of the reservoir produced a large quantity of gas, and a smaller amount of liquid which was entirely different from the oil issuing from the same formation through deeper wells. This liquid was pale yellow, relatively non-viscous, and rather volatile. The ratio of gas to this light liquid stayed constant with different rates of production, although most wells vary in gas-to-oil ratio under these conditions. Project 37 was able, by drawing upon its findings from studies of simple systems, to explain this anomaly to the production men.

Under conditions of high temperature and pressure, when both gas and liquid phases are present, the dense gas phase will hold much greater quantities of intermediate hydrocarbons than under normal surface conditions. As a result, when some of this rich gas is brought to the surface, and its temperature and pressure lowered thereby, a separation occurs which results in a normal natural gas, together with some liquid consisting only of the intermediate hydrocarbons formerly held in the reservoir gas.

This liquid, which was later called condensate, was not greatly different from gasoline, and was thus of more than average value. The heavy brown oil produced from the deep wells of the same reservoir was drawn from the liquid phase underground, and, when brought to the surface at lower pressure, some of the gas constituents which were dissolved in it underground separated, giving a comparatively small gas-to-oil ratio.

Another peculiarity of this well was that the water produced with the hydrocarbons from the upper part of the reservoir was fresh water, whereas that coming out with the heavy oil was brackish, as is usually the case. Here again an explanation was available, because the dense gas phase underground was able to contain more water vapor than normal, and when the material was brought out to surface conditions this excess water condensed out, thus producing substantially distilled water.

The project was able to point out to the industry that, in the case of fields containing rich gases of this type, if the pressure in the reservoir was allowed to decrease to any great extent, the same sort of deposition of liquids would occur underground, and the valuable liquid would be partially lost in the pores of the rock.

The cycling process

As time went on, a large number of fields of the condensate type were discovered, and in nearly all cases it was possible, because of understanding the necessary procedures, to arrange to operate a whole field as a single production unit and carry out the process known as cycling. This consisted in making the separation of condensate at the surface, recompressing the resulting natural gas to a pressure higher than that in the reservoir, and then reinjecting the gas underground in order to keep the pressure there high enough to prevent premature condensation.

Today many millions of dollars have been invested in cycling plants, and undoubtedly very large quantities of liquid hydrocarbons have been recovered which would otherwise have been lost.

Because the project elected to take the long range approach, its early experimental results were of necessity only applicable in principle to the complex problems of the field. Enough work was done with field samples to show their general behavior and to test various ways of sampling the fluids from producing wells. The experimental methods and apparatus developed were of immediate interest to the industry, and in a relatively short time a number of producing companies had set up laboratories to study their own immediate problems. Upon graduation, a number of students who had had experience with the project took an active part in these developments.

In addition to the volumetric and energy characteristics of hydrocarbon mixtures there are several properties which are of direct interest to the engineer. One of these is the interfacial tension between liquid hydrocarbons and gaseous hydrocarbons, water, or rock solids. Although Project 37 has made no measurements of this sort, some work done under one of the earlier projects carried out at the Institute indicated that when the hydrocarbon liquids were in equilibrium contact with gas at high pressure, the tendency to drain from wetted pore spaces increased with increase in pressure. This points to an advantage to be gained by keeping the formation pressure as high as practicable.

Effects of temperature and pressure

A second important property is the viscosity of the fluids, particularly the liquids, because high viscosity tends to lower the mobility of the oil through the minute rock channels toward the well, and increases the energy required to accomplish the movement. Project 37 studied the effect of pressure and temperature upon the viscosity of gases and liquids under the conditions characteristic of petroleum reservoirs. From these measurements also appeared good reasons for pressure maintenance, because a molasses-like crude oil, when saturated with natural gas at reservoir conditions, can have its viscosity lowered almost to that of kerosene—a tremendous gain for ease of movement in flow channels.

The findings of the project in favor of pressure maintenance came at a time when conservation measures in petroleum production were becoming much more important, and they served to reinforce the belief of forward-looking engineers that, whenever possible, field operations should be unitized for each reservoir as soon as possible after discovery, and steps should be taken to avoid unnecessary decrease in formation pressure.

In the case of reservoirs in which the pressure had already declined, consideration was given to the desirability of trying to restore higher pressure by injection of natural gas from other sources. The project found that, although energy for movement of oil could thus be supplied, it was by no means as simple to restore in solution in the oil, the gas which earlier gave the liquid desirable drainage and flow properties. When thin films of oil were exposed to gas at higher pressure they were quickly saturated with dissolved gas, but if high-pressure gas were to be brought into contact with the limited surface of a large body of oil, such as is to be found in some of our reservoirs, completion of the process of dissolving—and thus affecting the properties of *all* the oil—would require hundreds or even thousands of years. Despite this discouraging outlook for massive bodies of oil, repressuring operations have been carried out in certain fields and the recovery of much oil has thus been accomplished.

If the oil in a reservoir is originally saturated with gas at the existing pressure, and withdrawals are made through a producing well, the pressure near the well will drop somewhat below the original value. This decrease of pressure tends to cause dissolved gas to separate from the liquid to some extent. As production from a well proceeds, the zone of lowered pressure extends farther back into the formation surrounding the well. The gas separating from the liquid in the very small pore spaces in the rock forms small bubbles. Energy is required to force these bubbles through the minute, devious channels toward the well and flow of oil to the well is thus impeded. A certain amount of this difficulty is unavoidable, but it again points to the desirability of keeping gas in solution in the oil just as long as possible in its travel through the reservoir. Lower rates of production require less pressure differential near the well, and are therefore desirable for the sake of better long-term recoveries. Other means of keeping formation pressures high are also helpful in this regard.

Project 37 pointed out to the industry that, with suitable precautions, the pressure upon a saturated solution of gas in oil could be lowered by several hundred pounds per square inch without the evolution of any gas bubbles. This type of supersaturated solution could, in many cases, be maintained so long as no agitation or turbulence occurred in the liquid. The advantages of this phenomenon in keeping the oil as long as possible in its most mobile condition are sufficiently great that the project is now undertaking an extensive program of research and investigation of this particular type of behavior.

The scientific information gathered by the workers of the project over a period of twenty-five years has been made available to the public through technical publication channels. In addition to two book-length works, some 130 scientific journal articles have appeared, and the series is extending at the rate of about five each year. Considered broadly, this form of cooperation between industry and educational institutions offers interesting opportunities for benefit to all.

THE MEN BEHIND PROJECT 37

THE AMERICAN PETROLEUM INSTITUTE, at its 32nd annual meeting in Chicago in November, celebrated the 25th anniversary of Project 37. The high point of this celebration was the presentation of Certificates of Appreciation to two Caltech scientists, for their work on the project—Drs. William N. Lacey and Bruce H. Sage, Professors of Chemical Engineering.

Dr. Lacey has directed this hydrocarbon research at Caltech since it was first begun 25 years ago. Dr. Sage has co-sponsored the research since 1937. In making its awards to the two men the American Petroleum Institute noted that their work "has been of untold value to refiners and others because it enabled them to predict accurately how hydrocarbon mixtures would react under given circumstances" and "to save tens of millions of barrels of high-grade distillate which otherwise might have been lost forever."

This is not the first time Dr. Lacey and Dr. Sage have been honored for their hydrocarbon research. In 1946 Dr. Lacey received the Hanlon Award of the Natural Gasoline Association of America "for meritorious service to the natural gas industry." In 1947 he was given the Anthony F. Lucas Gold Medal of the American Institute of Metallurgical Engineers.

In 1949 Dr. Sage was named the first recipient of the Precision Scientific Company Award of the American Chemical Society for achievement in petroleum chemistry for his "contributions to the knowledge of petroleum and its products."

At Caltech, the Chemical Engineering department is under the joint direction of Dr. Lacey and Dr. Sage. Though the hydrocarbon work is, and always has been, their chief research project, it is certainly not the only activity they are engaged in.

Dr. Lacey, for example, successfully manages to fill out a large portion of his time by serving as Dean of Graduate Students at the Institute. Like all good deans, most of the work he does in this position is above and beyond the call of duty. He functions variously as career consultant, financial adviser, substitute father, and court of final appeal to the Institute's 600-odd graduate students.

One of his minor chores is to read every thesis presented by every candidate for Engineer and Ph.D. degrees at Caltech. There are about 90 of these theses every year running to a total of about 10,000 typed pages, and covering, of course, a rather wide range. In one sitting, for example, Dr. Lacey may run through "Complex Function Theory for Functions with Values and Arguments in Locally Convex Linear Topological Spaces," and top it off with "The Course of Vitamin B_1 Metabolism in Man as Indicated by the Use of Radioactive Sulfur, a New Synthesis of 4-methyl-5-beta-hydroxyethylthiazole, and a Demonstration of Anti-coincidence Radioactive Counting Techniques."

Dr. Lacey came to Caltech as an instructor in Chemistry in 1916. A graduate of Stanford (1911), he received the degree of Chemical Engineer there in 1912. He served as an assistant in Chemistry at the University of California from 1912 to 1915, while studying for his doctorate there. After he received his degree in 1915 he worked for a year as a research chemist for the Giant Powder Works in San Francisco, then served as a Research Associate at MIT before joining the Caltech faculty in 1916.

He became a full professor at Caltech in 1931, and was made Dean of Graduate Students in 1946, succeeding the late Richard C. Tolman. He was Chairman of