THE IMPACT OF PROJECT 37

by John E. Sherborne

Project 37 was set up at Caltech in 1927 to investigate the retention of oil by sand. In time the work was directed toward the experimental study of the volumetric and phase behavior and the transport properties of hydrocarbons and their mixtures at pressures up to 10,000 pounds per square inch in the temperature interval between 40 and 460°F.

The project was originally directed by Robert A. Millikan and William N. Lacey and was supported by a grant from John D. Rockefeller and Universal Oil Products. After the first few years, support for the program was transferred to the administration of the American Petroleum Institute.

Bruce H. Sage, professor of chemical engineering, has been director of the project since 1959. He became associated with the work in 1930 when he was a Caltech graduate student and was made co-director with Dr. Lacey in 1942. Working with Dr. Sage since 1938 has been H. Hollis Reamer, senior research fellow in chemical engineering. Many research assistants have aided these two men through the years.

In July 1969, after 42 years of experimental work, this program will be brought to a close. "The Impact of Project 37" records some of the far-ranging effects it has had on the petroleum industry. The article has been adapted from a talk given by John E. Sherborne '34, associate research director of the Union Oil Company of California, on April 26 at a Conference on Hydrocarbon Research sponsored by Caltech's Office for Industrial Associates and the American Petroleum Institute. Mr. Sherborne served as an API research fellow on Project 37 from 1934 to 1936 and was chairman of the API advisory committee for the project for 1952 and 1953.

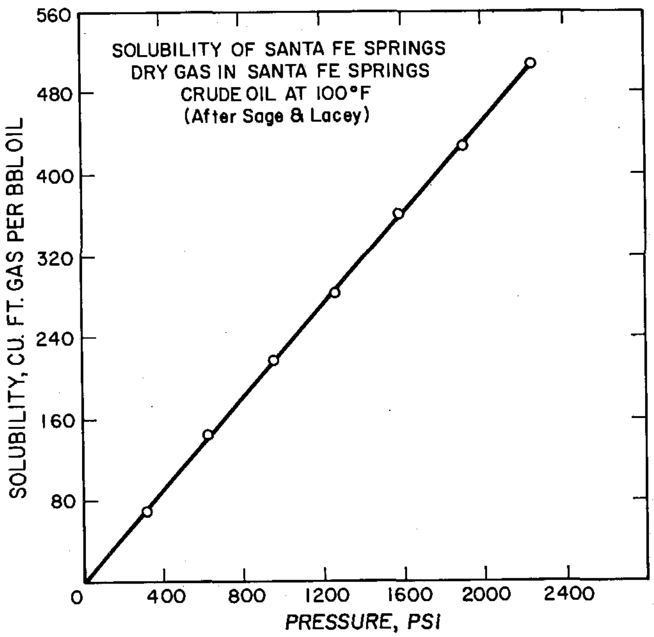
Oil is currently consumed in the United States at the prodigious rate of 12 ¼ million barrels per day--which is 37 percent of the free world's production. An appreciable part of this production would not be available today without knowledge of the behavior of hydrocarbons under oilfield conditions that has been developed by Project 37 in the chemical engineering laboratory at Caltech.

When Project 37 was initiated in 1927, little was known about the nature of oil-bearing formations and the fluids contained within them. In the early 1920's, Henry L. Doherty, an outstanding petroleum industry executive and engineer, speculated that oil and gas must behave differently in underground

Bruce H. Sage, professor of chemical engineering and director of the American Petroleum Institute's Research Project 37 conducted at Caltech since 1927.

A Caltech research project makes major contributions to the petroleum industry over a period of 40 years.

reservoirs than they do at the surface. In response to these speculations, two important studies were made, and the results were reported in the technical literature of 1926.



Graphs showing the solubility of dry gas in crude oil at specific temperatures, such as this one for the Santa Fe Springs reservoir, illustrate early work of Project 37. The cubic feet of gas shown on the ordinate is measured at 60°F and 14.73 pounds per square inch (psi). The oil volume is that which the oil will have free of gas under those same conditions. There is roughly a linear relationship between the gas solubility and pressure for this particular crude oil and natural gas system. This is approximately true for most such systems.

The studies did show that oil and gas properties are not the same under the conditions of temperature and pressure existing in underground reservoirs as they are at the surface. They also pointed out the need for a great deal more knowledge about conditions existing in the reservoir. Project 37 was set up to obtain this knowledge.

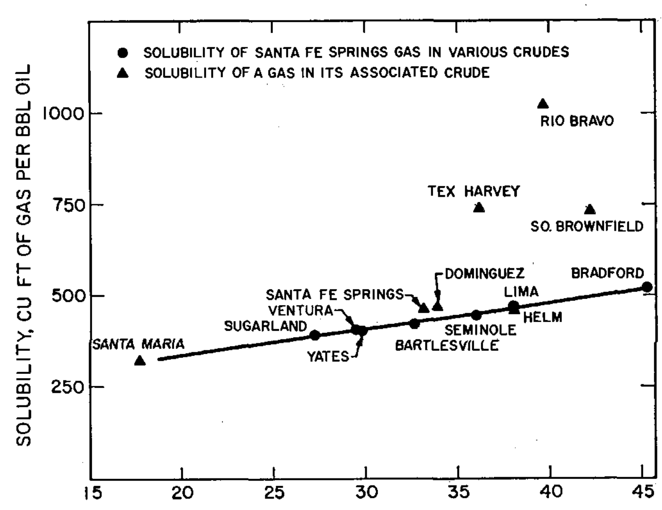
Among the early contributions of Project 37 was the investigation of oil and gas solubilities and the rates of solution of gas and oil at pressures and temperatures much higher than those previously reported. The two graphs on this page show some of the results of this work.

Early work of this sort led to the belief that it would be feasible to treat the petroleum in a producing reservoir as a binary system in which the produced gas was one of the components and the tank oil was the other component. This practice, although far from being scientifically rigorous, has worked very well for engineering purposes and is in current use.

During the early years of Project 37 a number of natural gas-oil systems were studied, and one of the main contributions of the project was the development of apparatus for making such studies. This equipment was eagerly adopted by the industry.

It soon became recognized that because of the large number of compounds present in crude oils and because of the great variation in the amounts and types of compounds in crudes from different fields it would be desirable to study simpler systems. As a consequence, Project 37 turned its attention primarily to the study of pure substances and binary or ternary mixtures of these pure substances, leaving the experimental study of natural systems to industry.

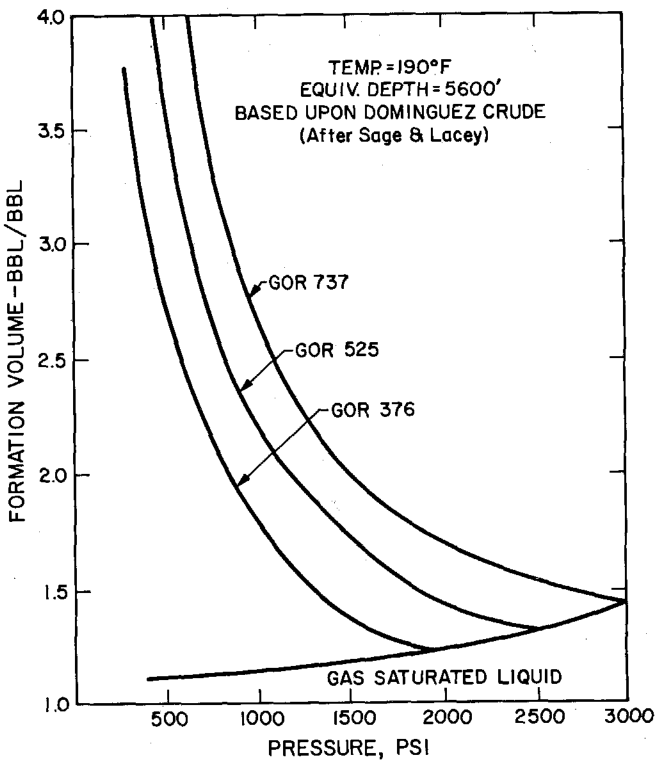
The PVT (pressure, volume, temperature) dia-



Graphs showing the solubility of natural gas in a variety of crude oils, shown here for 100°F and 2,000 psi, show some results of Project 37 research. Solubility of gas in crude oil is largely dependent on gas composition. For this particular gas there is a linear relationship between the solubility and the American Petroleum Institute (API) gravity of the oil at 60°F. However, gases of different composition have different solubilities, as can be seen from the triangles. When the gas is similar to Santa Fe Springs gas, the triangles fall near the line. In general, the greater the number of components of higher molecular weight in a gas, the greater its solubility.

gram below, typical of those first turned out by Project 37 and now in common use in the industry, shows the formation volume as a function of pressure and gas-oil ratio, in this case for a temperature of 190°F.

Formation volume is the ratio of the volume which would be occupied by the oil and its associated gas under reservoir conditions to the volume which the oil itself would occupy at 60°F and at atmospheric pressure.



The PVT (pressure, volume, temperature) diagram, now in common use in the industry, was developed to show the formation volume of the gas-saturated liquid as a function of pressure. In the diagram above, the formation volume, at pressures where both a liquid and a gas phase coexist, is shown for three gas-oil ratios (gor).

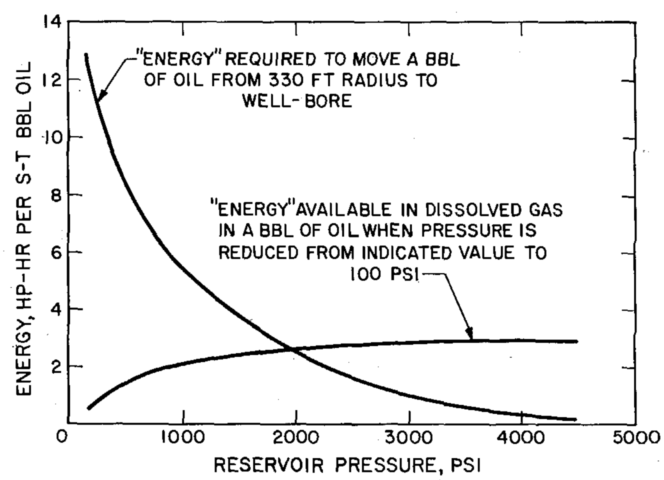
Assuming that the material in a reservoir is at 2,500 pounds per square inch (psi) and there is a gas-oil ratio of 525 cubic feet per barrel, then the material is at the bubble-point liquid condition. At this condition only a trace of gas exists. As material is withdrawn, the pressure declines. The formation volume of this system in the reservoir will follow the line for a gas-oil ratio of 525 cubic feet per barrel, showing an increase as the pressure goes down. The liquid, on the other hand, will decrease in formation volume, because gas is coming out of solution in the reservoir. The volume of the gas soon becomes far greater than that of the liquid, and hence there will be a relative displacement of gas to the well-bore. This will drive liquid with it; however, the producing gas-oil ratio will increase as the volume of gas in the reservoir increases relative to the oil volume.

It was apparent that, with large quantities of gas dissolved in oil in the reservoirs and the change in the formation volume of the oil, significant difference in oil viscosity could be expected. Project 37 was one of the first to produce a range of information on the change of viscosity of oil in reservoirs with pressure, temperature, and gas saturation. This, in turn, led to an appreciation of the very important role played by viscosity in the displacement of oil from the minute pore channels within the reservoir rocks.

At the inception of the project two methods were in use to estimate the quantities of oil available in a reservoir. The first of these, the volumetric method, attempted to define the total oil in place. The second, known as the decline-curve method, was used to help predict the amount of oil which could be economically recovered. These quantities are referred to as reserves, and engineers distinguish between reserves-in-place and producible reserves.

Neither of these methods of estimating reserves was satisfactory, although in 1927 the decline-curve method was the more useful. One fact was clear. There was a vast difference between the amounts of oil estimated to be in place by the volumetric method and that which would be produced as predicted by the decline-curve method. Results such as those produced by the project made it possible to reconcile these differences and to provide means to increase the recovery.

As more information became available, a number of investigators attempted to relate the volu-



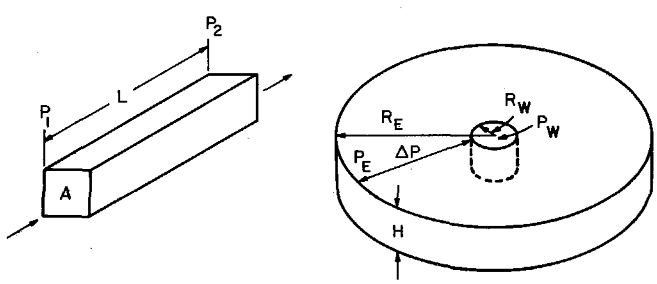
"Energy" diagrams aid in planning the production of oil. The "energy," as expressed in horsepower-hours per standard-tank barrel, of dissolved gas is shown as a function of reservoir pressure. The change in "energy" associated with one barrel of tank oil is plotted as a function of reservoir pressure for a crude oil of moderately high gravity.

metric data to the "energy" associated with the fluids which could be expected to be encountered in the reservoir and in the well-bore.

The significant thing illustrated by the "energy" diagram on page 22 is that, as the pressure decreases, less and less energy is available to drive the oil, and more and more energy is required to move it. By the time the pressure has dropped to 2,000 psi, the oil no longer contains enough energy to drive itself to the well-bore, and the situation rapidly deteriorates.

But "energy" is not the only factor which affects production. Data from Project 37 was also necessary for a quantitative evaluation of the microscopic displacement within the reservoir. The drawings below demonstrate the formula and conditions which pertain to the permeability of a formation for a single phase flow.

LINEAR FLOW　　　RADIAL FLOW



$$Q = \frac{K \phi A (P_1 - P_2)}{\mu L}$$

$$Q = \frac{K \phi H (P_E - P_W)}{\mu \log \frac{R_E}{R_W}}$$

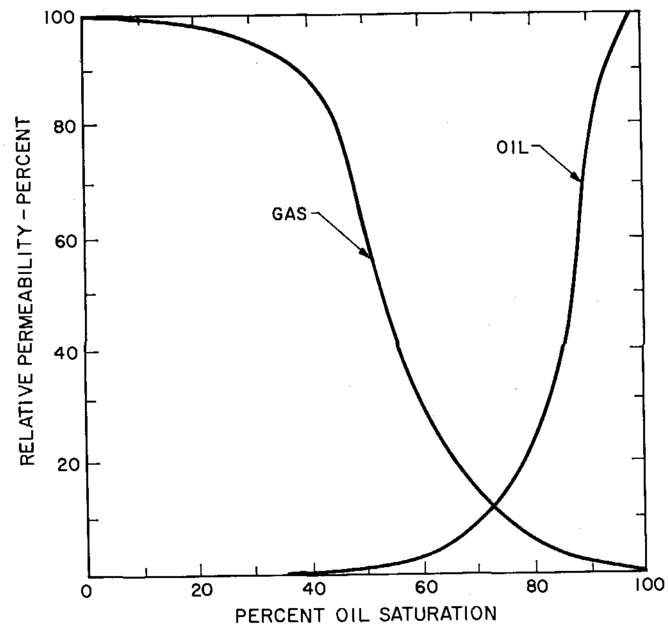
LEGEND

Q = RATE OF FLOW
K = PERMEABILITY
ϕ = POROSITY
A = CROSS SECTIONAL AREA
μ = VISCOSITY
P = PRESSURE
R_E = DRAINAGE RADIUS
R_W = WELL-BORE RADIUS

The effect of permeability is a factor in oil production. On the left is a porous matrix with a single fluid flowing in at A through the conduit and out the other end in a linear manner. While linear flow is important, primary concern in oil production is with radial flow, in which a well-bore is draining an essentially cylindrical drainage volume surrounding the bore, as shown in the drawing at the right.

When two or more phases are present in the pore spaces, it becomes necessary to introduce the concept of relative permeability. This concept may be described as the ratio of the permeability for a given fluid in the presence of other fluids to the permeability which would occur if only the one fluid were present and flowing as a single phase.

It has been shown by a number of investigators that relative permeability can be described as a function of the saturation of the porous medium. Assuming that no water exists in the pore space, then the space is filled with oil and gas, and the relative permeability (expressed as a percentage) is shown as a function of the oil saturation, as in the diagram below.



The relationship of the permeability to the percent of oil saturation is important in the production of oil. Starting at 100 percent oil saturation, as gas is liberated from solution, the permeability to gas is not very great for the first 10 percent of the gas liberated, but this 10 percent has a great effect on the permeability to oil, dropping it to about 40 percent. As more gas is liberated, the oil permeability is reduced to a negligible amount by the time the gas saturation has reached 50 percent, and the gas permeability is increased to within 70 percent of its single phase value.

The presence of a second fluid phase markedly affects the permeability to the other phase. Thus, the flowing gas-oil ratio increases rapidly with increased gas saturation, and the gas quickly becomes an inefficient driving mechanism. In the reservoir, in spite of the increasing gas velocity as pressure declines, most of the oil remains in the formation. In practice, oil recovery by dissolved-gas drive alone seldom produces as much as 20 percent of the oil originally in place. By means of relative permeability data and the associated volumetric data, it is possible to determine what the flow conditions will be at any point in the reservoir as a function of time or as a function of the pressure decline.

The work of Project 37 has thus provided information of great value to the reservoir engineer. It has made possible a quantitative evaluation of the change of specific volume of oil and gas in the reservoir with pressure; it has shown the effect on viscosity of the oil with change in composition under reservoir conditions and on the effect of this oil-gas relationship on the effective permeability.

With such information at his disposal, the reservoir engineer can now determine the maximum efficient rate of operation for a given oil field. Such calculations are routine today. Earlier these calculations led to the recognition that pressure maintenance would be a valuable means to improve the recovery of oil. The use of re-injected gas or water to maintain the pressure at or near the original value has, in many cases, doubled the amount of oil which was recoverable from a formation.

In many cases oil fields are found in which a substantial amount of gas exists as a gas cap above the oil phase. Sometimes the reservoir is so large that a number of wells may be drilled before it is established that the gas cap is in fact associated with appreciable amounts of oil. In the early days, the gas had little value, and great quantities of it were blown into the air to recover the small amount of oil produced from the gas cap.

One might expect that, for the gas cap production, the gas-oil ratio would increase with decreases in reservoir pressure, as it does in the production of ordinary oil. And such expectations are correct. However, it was *not* expected that the original gas-oil ratio for this material would be as high as 20,000 cubic feet per barrel or more, or that the oil would be an almost colorless liquid ranging in gravity from 20° to 60° API. Even more surprising was the observation that, as the gas-oil ratio increased, the gravity of the produced liquid also increased. This behavior was contrary to normal experience since it was accompanied by a pressure decline.

This occurred in so many very large fields that Project 37 was urged to examine the phenomenon. It was in this research that the project made one of its greatest contributions. It was discovered that this behavior was the result of retrograde condensation, the condensation of liquid from a gas associated with a pressure decline. One might expect that much of the liquid deposited from the gas as a result of retrograde condensation could be revaporized if the reservoir pressure could be lowered sufficiently. In most cases, unfortunately, the low pressures required are either physically or economically unattainable. As the pressure reaches very low values, some of the liquid revaporizes and is produced with the gas. However, even if the reservoir pressure were reduced to atmospheric pressure, almost 4 percent of the pore space would still be filled with liquid. In a large reservoir this could amount to many millions of barrels. On the other hand, by maintaining the reservoir pressure at or near the original pressure, virtually no liquid would be lost to the formation.

The fact that the work on retrograde condensation explained what was happening in the reservoir was of great importance. More important still was the fact that such research provided a quantitative means to determine the type and size of the processing plant necessary to perform the suggested cycling operation, as well as to establish the future field performance, and thereby to determine the cost and possible profit of such a venture. Since a cycling operation usually involves a capital expenditure of many millions of dollars and deferred income on trillions of cubic feet of gas (but, if done correctly, commensurate profits), the need for good engineering information is paramount.

The research of Project 37 has not only made it possible for engineers to increase the recovery of petroleum; it has added to the understanding of multiphase flow in the well-bore and pipelines. It has made possible the design of better flow strings and valves. The work has also thrown much light on the conditions under which bitumen and wax are deposited and hydrates are formed—and how to control their occurrence in production equipment as well as in the formation.

The volumetric data allow optimum design of oil-gas separators at the surface and of tank vapor recovery systems. The research has demonstrated the dependence of gas-liquid equilibrium coefficients on composition and has made possible much improved values of these coefficients. Valuable data on the thermodynamic behavior of systems involving hydrocarbons and such compounds as nitrogen, carbon dioxide, and hydrogen sulfide have been obtained. Similar experimental information on systems involving these substances and water has been made available. All of these are of importance in the production of petroleum.

The project's work on non equilibrium behavior and transport phenomena has been of value in better understanding fluid flow behavior. Equilibrium thermodynamic data which have been developed are finding increasing value as the industry turns to thermal methods of recovery.

Finally, the goal of all engineers is to have a neat bundle of graphs, tables, and equations which will aid them in predicting the consequences of a proposed undertaking. The work of Project 37 has materially advanced the development of equations of state for hydrocarbon systems and has laid a firm foundation for others working in this field.

There are many in the industry who feel that Project 37 is by far the most important fundamental research project sponsored by the American Petroleum Institute.