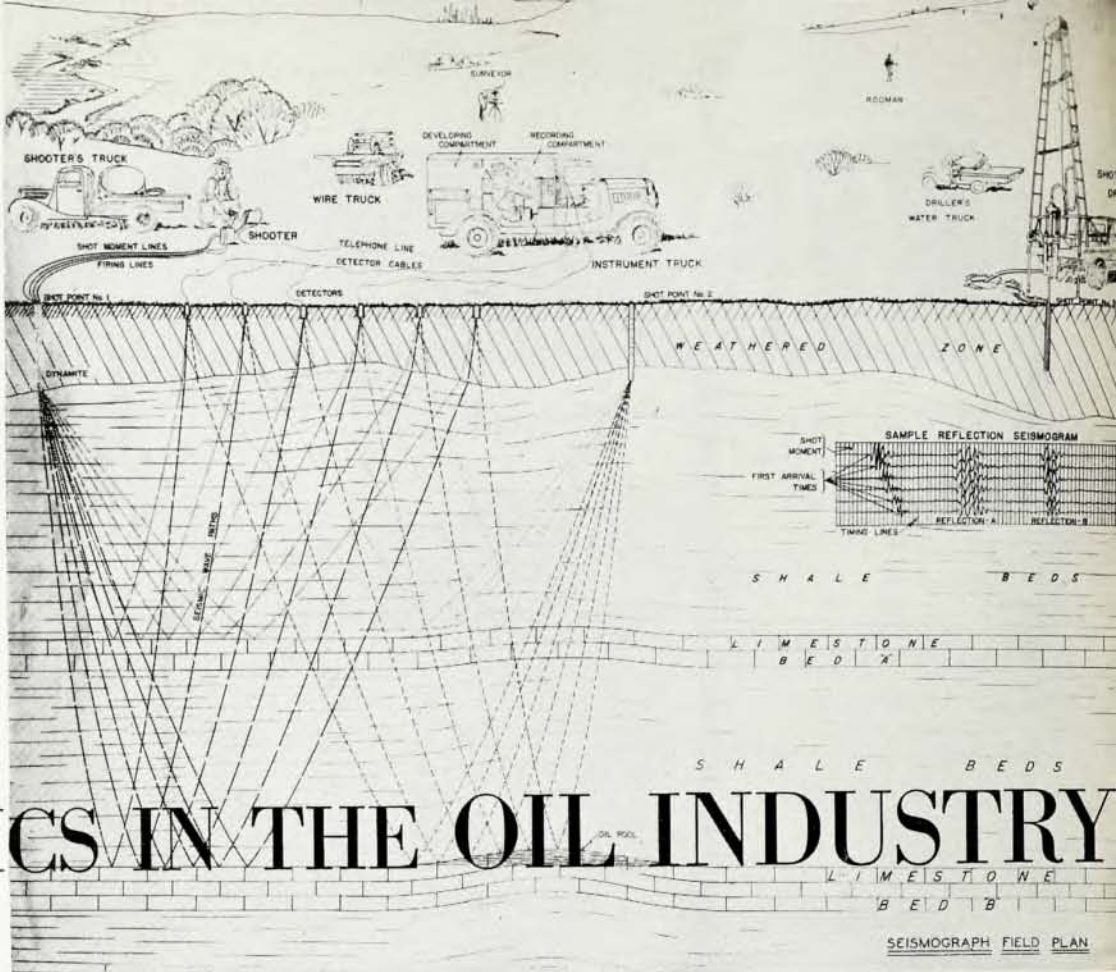


PHYSICS IN THE OIL INDUSTRY



The physics in oil prospecting, production, and testing is recounted here.

by *Frank Morgan*

Long before Drake, in 1859, demonstrated that oil could be obtained by sinking wells, primitive man found it necessary to lubricate the axles of his carts and wagons to reduce friction and diminish wear. Lubricant taken from the axle of a chariot in a tomb sealed in about 1400 BC was analyzed and found to be beef or mutton tallow or a product of similar characteristics suitable for use in a warm climate. The first steam engines were lubricated with tallow, castor oil, and lard oil. While such animal and vegetable oils served their purpose in the primitive machine, they would be impractical in the engines of today, largely because of their inability to withstand the high temperatures involved. Oil in the crankcase of a heavy duty engine will

reach one hundred and fifty degrees centigrade and the temperature at the upper piston ring grooves may exceed two hundred and fifty degrees centigrade. These high temperatures and the large quantities of air pulled through the crankcase ventilator make conditions especially favorable for oxidizing the oil which increases its viscosity, forms and precipitates sludge, and develops acidity. Fortunately chemical inhibitors have been found, small traces of which can be added to oils to reduce their susceptibility to oxidation.

Lubrication

Although the art of lubrication has been practiced for hundreds of years, it was not until 1883

that Beauchamp Tower noticed that a plug inserted in a hole on the loaded side of a bearing was forced out by pressure generated in the oil film in the space separating the journal and bearing. This observation led to the formulation by Osborne Reynolds of the hydrodynamic theory of lubrication which was published in 1886. An essential part of this theory is that the center of the journal must be displaced from the center of the bearing to permit a wedge to form. Lubricant is pumped or dragged by the motion of the journal into the converging section. Actual tests have shown that a well designed bearing will shift under load and that pressures are established which are capable of supporting the load with no actual contact between the surfaces. In fact, where hydrodynamic lubrication prevails, experiment is now substantially in agreement with theory.

Such is not the case, however, in the so-called thin film or boundary region of lubrication. Although theory predicts a steadily decreasing coefficient of friction as a dimensionless variable (which combines viscosity, speed, and load) diminishes, experimental data show a decrease and then a rapid increase. The exact behavior has been found to depend upon the bearing materials, the condition of the surfaces, and on the lubricant itself. In fact, an additional property, called oiliness, has been widely introduced, the lubricant giving the lowest coefficient of friction at a particular stage being considered the most oily. Numerous physical mechanisms, including film orientation, polishing by the formation of low melting point alloys, and the effect of pressure on viscosity, have been proposed to account for the observed effects. While much progress has been made, no theory has yet been presented which even approximately explains the facts. A unified theory of wear is likewise lacking, although recent studies of the wear of carbon brushes and experiments on metals using radioactive tracers have contributed significantly to the subject. A better understanding of the physics and chemistry of surfaces is needed for the elucidation of problems in this field, as well as in other branches of petroleum research such as catalysis and the displacement of oil from porous media.

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Prospecting

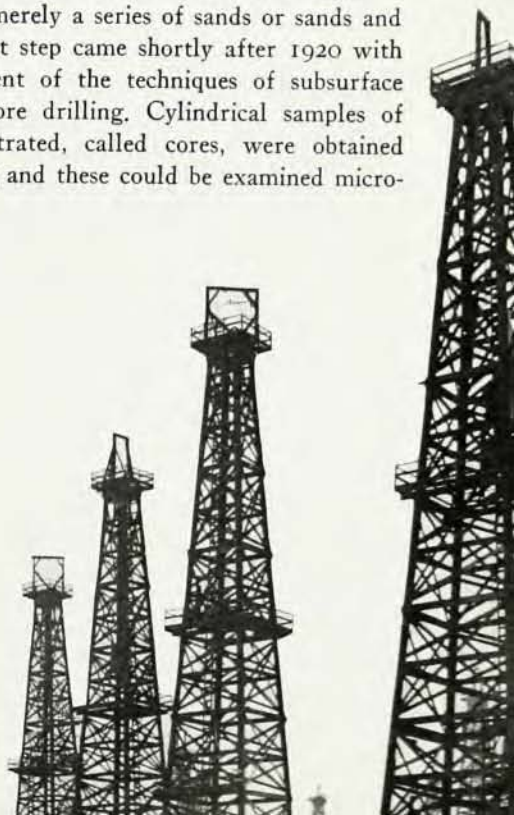
From the beginning of American oil development in the Pennsylvania oil fields in 1859, through the Spindletop discovery well in Texas in 1901, and up to 1910 or even later, prospecting was carried out on a casual or random basis. Wells were drilled on oil or gas seepages, along the beds of streams, at some location which bore a resemblance to another area which was known to be oil productive, or merely on the basis of a hunch. Drilling depths were not great and sufficient oil could be obtained to satisfy the demand.

With the advent of the automobile and oil consuming devices, the old methods of prospecting were no longer adequate. Geology, which had been largely speculative as far as oil was concerned, was accepted as a guide for prospecting. It was realized that anticlinal or domal structures were the best prospects for oil pools and these were sought by examining the rocks at their outcrops. Thus surface geology came to be applied.

It was soon evident, however, that this information was insufficient and dry holes were drilled that could have been avoided had more data been available on the character of the subsurface. Of great importance was information that might be obtained from other wells in the vicinity. At first the records that were kept of the drilling of a well were very poor. The driller's log was of little use, his records noted merely a series of sands or sands and limes. The next step came shortly after 1920 with the establishment of the techniques of subsurface geology and core drilling. Cylindrical samples of the rock penetrated, called cores, were obtained during drilling and these could be examined micro-

Oilfields on coast near Santa Barbara, California

Photo by K. Stephen, Black Star



scopically for fossils and minerals as well as tested to determine porosity, permeability or fluid conductivity, and oil saturation.

Beyond a doubt, the most prominent single contribution of the physicist to the petroleum industry up to the present time has been in the development of techniques and apparatus for geophysical prospecting for oil. Such methods were first applied for this purpose in Oklahoma and the Gulf Coast area in the early 1920's with the refraction seismograph and torsion balance.

The conditions under which oil is found in an underground reservoir have been known for a long time. An oil pool is not an underground lake as the name might imply, but is a region of porous rock which is more or less saturated with oil. For oil to accumulate in a porous limestone or sandstone bed, two conditions must be satisfied. First, there must be source beds, which are usually shales containing organic material. The exact mechanism involved in the migration of oil is not very well known but probably oil and water are expelled from the source beds during the compaction of the sediments to form shales. Secondly, there must be a trap which will hold the oil and prevent its further migration. The spaces between the grains of a porous rock are never void but are filled with oil, gas, or water, or a combination of the three. When the fluids move, the lighter ones tend to come to the top. As oil and gas migrate upwards through the porous beds they may encounter obstacles such as traps or domes around which they cannot go. In such localities oil will stop and an oil pool will be formed.

Theoretically a method of prospecting for oil may be based on any characteristic property of oil itself, or of the distribution or nature of the rocks contributing to a discontinuity that can be measured at the surface through vast quantities of intervening rock. At present, however, oil cannot be found directly; geophysical oil exploration is a search for geologic structures which, it is hoped, bear oil. Many procedures have been proposed and tried but practically all of the search for oil is based on the application of a few fundamental physical principles.

Normally, the most effective and precise of the instruments used for geophysical prospecting, though also the most expensive in terms of area covered, is the seismograph and its associated equipment. Seismic waves, whether natural or artificial, are merely

elastic waves or vibrations which travel outward in all directions from a source or shot point. Sensitive seismic detectors, set at various distances from the shot point, are connected to oscillograph elements which record the ground movements on a photographic film. From measurements on these films the time required for waves to travel to reflecting or refracting beds and thence to the detectors may be ascertained. Previous knowledge of the velocity of sound in the various media is then all that is required from which to determine the distances to the various surfaces of discontinuity. Such data are normally obtained from time-distance curves in known media or by shooting in a well or at a well in which the geologic horizons are known. Under favorable conditions it is possible to piece together the information acquired from many such shot points and numerous detector locations into contour maps showing the position of the reflecting horizons, the degree of the dips, the buried hills and valleys and, with luck, the faults in the rocks.

Gravitational methods of exploration are based upon measurements, at the surface, of small changes in the gravitational field due to lateral variations in the distribution of mass in the earth's crust. In general the deeper sedimentary rocks are the more dense. If, therefore, there is a deeply buried hill in the sedimentary rocks the pull of gravity over the anomaly will be slightly greater than over the surrounding region. In the case of salt domes, the contrary is true. Salt is less dense than the rocks usually surrounding the dome, so a gravity minimum is normally found over the plug. This type of anomaly has been quite important in the Gulf Coast region where oil is frequently found trapped in beds over the top or leaning against the flanks of the domes.

The magnetic method is a third common way of exploring for oil. It is probably the most qualitative and empirical of the three and is primarily useful in reconnaissance work. Normally, where feasible, it is followed by other more quantitative geophysical methods. The method is based upon the fact that sedimentary rocks are usually nearly nonmagnetic, while the igneous or basement rocks are much more strongly magnetized. Hills and domes in igneous rocks cause variations in the magnetic field at the surface. Corresponding to these hills and domes are structures in the sedimentary rocks which may contain oil. Also magnetic surveys

often yield information on the depth and form of the basement surface, and even rough estimates of such depths are frequently valuable in giving an indication of the thickness of the sedimentary section in which oil accumulations may occur.

Although the magnetic method is fast and economical, difficulties which arise in interpreting the data in terms of geology have largely discouraged the use of measurements made at the surface. With the advent of the flying magnetometer, however, the picture has been greatly changed. Fluctuations in magnetic intensity due to magnetic materials near the surface formerly rendered the data almost meaningless. They are greatly attenuated and often disappear entirely when the magnetometer is flown a few hundred feet above the surface. Furthermore, areas not previously accessible by any method can now be surveyed almost as readily as the most available sections and the work is speeded up enormously.

Due to the extremely high sensitivity and great ruggedness required of apparatus that nevertheless must be portable, much attention has of necessity been devoted to the development of instrumentation for geophysical exploration. For example, it can be shown that the effect on gravity of a moderate geologic structure may be of the order of a few parts in ten million to a few parts in a million of gravity itself. To be effective in geophysical prospecting for oil, instruments must therefore be capable of measuring reliably to one ten-millionth part of gravity.

The first instrument used for gravity measurements in the United States was the torsion balance, which measures the space variation of gravity rather than gravity itself. This was followed by the pendulum which measures changes of gravity by variations in its period of oscillation. Pendulum apparatus developed and used extensively in the years from 1930 to 1935 is an excellent example of precision physical equipment. The pendulums themselves were made of fused quartz bars and were designed as "minimum pendulums" with a period of about nine-tenths of a second. The quartz knife edges rested on solid pyrex glass flats. The pendulums were mounted in pairs, which were swung in opposition to eliminate sway, in vacuum tight, temperature controlled, cast-aluminum cases. Electrostatic disturbances were minimized by placing small amounts of radium inside the cases. The usual run required half an hour and time measurements were made to better than

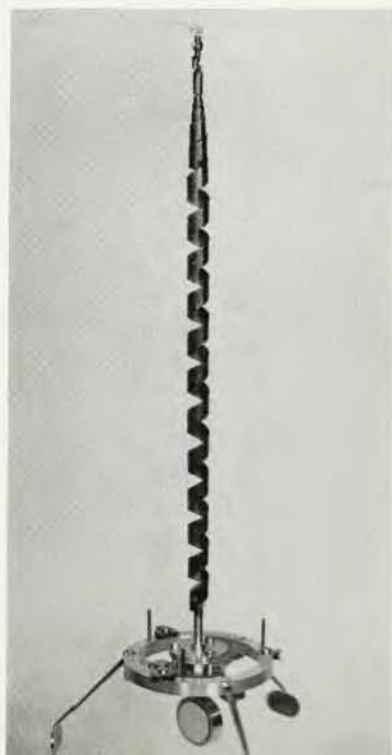
one part in ten million. At the beginning and end of each day's work the periods of the field pendulums were standardized by comparison with pendulums at the base station. Three to five stations were made per day.

In exploring for oil by gravity methods the pendulum has now been almost entirely replaced by the faster and more portable gravimeter which is simply an extremely sensitive weighing device on which only differences in gravity are measured. Such instruments are of two types, stable and unstable. An example of the stable class is the Gulf gravimeter. In this instrument the change of angle which results when a special spring is stretched is magnified by a system of multiple reflections so that a change of gravity of one part in one hundred million can be measured. A new gravimeter of the unstable, null indicating type is currently attracting much attention in geophysical circles. The essential parts of the instrument are fabricated of fused quartz and are contained in a Thermos bottle, the entire assembly weighing only six pounds. The element itself is reported to be so light that it can be dropped without damage, yet the probable error of a single measurement is only two parts in one hundred million.

The practical realization of an airborne magnetometer suitable for oil prospecting followed essential developments which occurred near the beginning of World War II and were almost immediately applied to the detection of submerged

*Spring
System
of
Gulf
Gravimeter*

Spring elongation due to gravity increase turns mirror at bottom. Angle of rotation is greatly magnified by multiple reflection of a light beam



Radioactivity well logging has come into extensive use in recent years. Because they usually contain more radium, thorium, and potassium, shales can be distinguished from sands by a gamma ray survey. Neutron logs find a unique application in porous limestone beds where hydrogenous materials, oil or water, cause a drop in the neutron curve. Both gamma rays and neutrons penetrate considerable thickness of iron, so information can be obtained on strata behind the casing in old wells or in wells which have not been adequately surveyed by other methods. Radioactivity logging has other uses. For example, carnotite, an ore containing radium, is often added to cement that is used to set or seal the casing in a well. The location and extent of the cement can then be determined at a later date by a radioactivity survey.

Production

In the early days of the oil industry little thought was given either to the physical conditions under which oil occurs in a petroleum reservoir or to the mechanics of oil production. The practice was to

*Earliest mention
of petroleum
—by Cassius Felix.*

*It was called
Mountain Oil since
it was found in
stone formations
cracked by volcanic
eruptions. Wood-
cut, 1491.*



Bettman Archive

let the wells produce wide open, the oil being driven to the surface by and with the gas, and the gas was flared or allowed to escape into the air. No obligation was assumed to produce the oil efficiently, and the wasteful use of gas was defended on the grounds that the destruction of gas was necessary in order to obtain the oil.

Research in production started in a small way some twenty-five years ago. It was not until the thirties, however, that real progress was made toward a clear understanding of the nature of the oil reservoir and its contents and the basic physical principles underlying the production of oil. The development of the core barrel and coring techniques made it possible for the first time to obtain

samples of the oil bearing sands for determinations of fluid content, porosity or fluid capacity, and permeability or fluid conductivity. Strange as it may now seem, in view of the fact that oil reservoirs were originally filled with brine, it was not recognized until late in the thirties that oil bearing sands contain water.

Not until the twenties was it realized that oil in an undisturbed pool is different in character and behavior from the same oil when brought to the surface of the earth and that gas dissolved in the oil causes a marked reduction in viscosity and surface tension as well as an increase in specific volume. Sensitive instruments have now been developed for measuring temperatures and pressures in a well, and samplers have been built for collecting reservoir fluid at the bottom of the hole. Measurements of the solubility of natural gases in crude oils, the expansion of the oil due to dissolved gases, and the viscosity of the fluids are now made under reservoir conditions as a matter of routine on bottom hole or surface recombined samples.

Oil, without solution gas, has no inherent energy by which it can be expelled from the reservoir. The recovery of oil from sand is a process involving the displacement of the oil by gas or by water. Depending on the mechanism of production and the source of energy for expulsion, oil reservoirs are divided into three main classes, namely: gas-drive reservoirs, water-drive reservoirs, and gravity-drainage reservoirs. In actual operation probably no one of the methods applies to a field over its complete life, but rather a combination of two or even all three may be in effect.

A homogeneous fluid flows through a porous medium in a manner which depends on the pressure gradient and the permeability of the medium through which it flows and its viscosity. But experiment has shown that for nonhomogeneous fluids, such as water-oil or gas-oil mixtures, the flow is not so simply described because the effective permeability of a medium to one phase is dependent in a complex manner upon the relative concentrations of the various components of the fluid and, in general, the sum of the permeabilities of the medium to the components is not equal to the homogeneous permeability. Furthermore, the permeability to gas becomes, in effect, zero, while there is still an appreciable quantity of gas locked in the sand and, except by a process of evaporation, the liquid or

wetting phase saturation cannot be reduced to zero by the flow of gas. Data on the initial fluid distribution in the producing section, the pressure-volume-temperature data on the gas and liquid phases, and the permeability-saturation relationship for the oil saturated zone suffice, in principle, for the computation of the ultimate recovery from a reservoir under natural depletion. Furthermore, they provide means for predicting the reservoir behavior under gas and water injection.

In solution gas-drive reservoirs the energy required for oil expulsion is supplied by the gas originally in solution in the oil. The efficiency of oil recovery from such reservoirs is generally low and two-thirds or more of the original oil may be left underground. By gas injection, or water flooding, the ultimate recovery may generally be increased. In the Pennsylvania oil fields it is estimated that about one-third of the oil in the place was produced by primary recovery, that secondary recovery methods using gas or water injection will recover roughly another third of the oil, and that the remaining third will not be recoverable by any means now available.

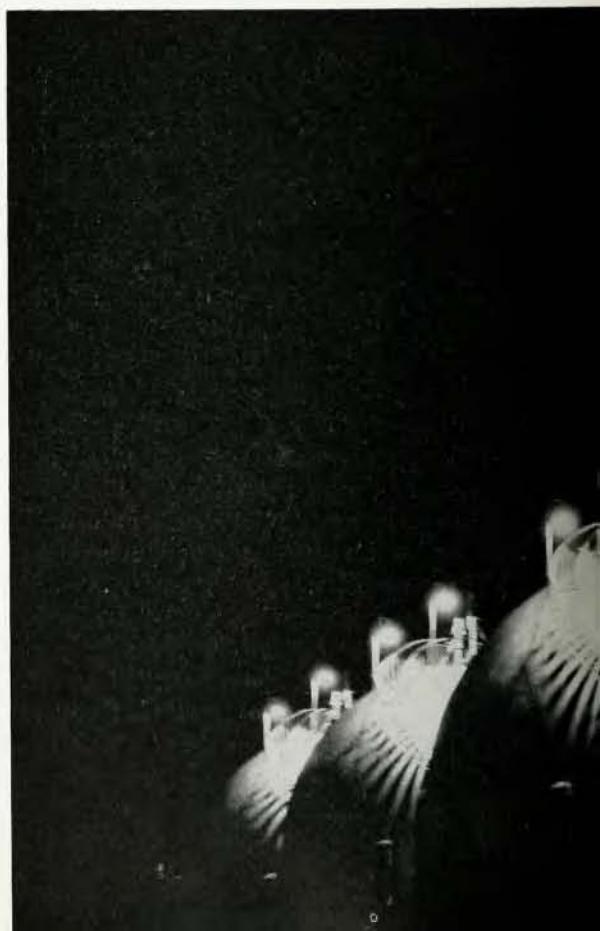
In water-drive reservoirs oil is displaced by the encroachment of water from the surrounding water bearing bed. The efficiency of recovery is generally higher than in straight solution gas-drive reservoirs and usually lies in the range of forty to eighty percent of the oil originally in place. Gravity-drainage reservoirs are frequently referred to as gas cap expansion reservoirs and efficiencies of recovery approximately equal to those in water drive reservoirs may be attained by keeping producing wells below the gas cap and utilizing to the greatest possible extent the energy inherent in the gas compressed in the section above the oil.

In deep, high pressure, and high temperature fields, gas reserves are frequently found which contain hydrocarbons that condense with the reduction of pressure to form a light-colored oil known as condensate. Since this behavior is the opposite of that commonly experienced, the process is called retrograde condensation. Although in petroleum reservoirs the phenomenon was observed for the first time about ten years ago, the physical conditions under which it occurs had been investigated about fifty years earlier. In its initial state in the reservoir such a hydrocarbon mixture is gaseous or vaporous. A reduction in pressure causes liquid to appear. Partial revaporization will occur on further

pressure reduction, but the heavier components, once they condense, will remain in the sand. The remedy is to maintain the reservoir pressure and not permit it to decline appreciably below its original value. This may be accomplished by returning the "dry" gas from which the condensate has been removed to the formation through appropriately spaced injection wells. To determine the best locations and the optimum injection rates for such wells electrolytic and potentiometric models have been built which are based on the analogy between flow systems in porous media and the conduction of electricity.

Physical Methods of Analysis

In the last few years extensive applications have been made in the petroleum industry of physical methods for the chemical analysis of materials. Infrared, ultraviolet, and mass spectrometers are used as a matter of routine for analyzing quantitatively in minutes or hours hydrocarbon samples that formerly required days, or could not be done, by chemical methods. Continuous flow analyzers based on these principles are now applied to the control of plant processes. The investigation of the chemical structure of materials by infrared and ultra-



violet absorption spectra and x-ray diffraction is already an important field, and neutron diffraction shows promise of being useful in studies of light hydrocarbons. Uses for the emission spectrograph are rapidly growing. Determinations of the inorganic constituents in crude oils, lubricating oils, catalysts, and oil field brines are examples of the applications of this equipment.

Both stable and radioactive isotopes are used extensively as tracers in following chemical reactions and in studying mechanisms of catalysis. In the conversion of coal to gasoline by the Fischer-Tropsch process, hydrogen and carbon monoxide are first produced and then passed over a metal catalyst. The assumption has generally been made that gasoline is formed by the reaction of hydrogen with metal carbides which have been formed during the process from carbon monoxide and the metal catalyst. In recent experiments carbon-14 was incorporated as a tracer in iron carbide, and ordinary carbon monoxide and hydrogen were circulated over this material as a catalyst. The hydrocarbon products, in the initial stages of the reaction, were found to have a radioactivity much less than that predicted by the usual theory on the basis of the activity of the

surface of the iron carbide catalyst.

The efficiency of a gas or water injection project may be seriously impaired by channeling from an input to a producing well thereby by-passing oil in place in the formation. A small quantity of helium or a radioactive tracer mixed with the injected fluid enables the operator to trace the underground travel of the fluid and to determine the time of its arrival at a producing well. Radioactive tracer experiments on a laboratory scale have also demonstrated that connate water may be effectively displaced by flood water.

Recently a method has been proposed for distinguishing between bio-methane and petro-methane on the basis of the ratio of ordinary carbon to carbon-14. Deeply buried carboniferous materials of age greater than fifty thousand years or so have been shown to be deficient in the radioactive isotope. While this discovery is significant, its practicability seems to be limited because analyses are tedious and expensive, and ideal sampling conditions are scarce.

Since pile-produced radioisotopes are now available to the industry at reasonable prices, many new applications both physical and chemical in nature will undoubtedly soon be found.

