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It is possible that the authors' correlations can be made to show maximum phase-boundary pressure effects by consideration of additional fluids of lower molal average boiling point. Their Figs. 3 to 16 inclusive in the boiling-point range presently shown indicate that, for given values of "weight average equivalent molecular weight," W_m, the saturation pressure increases continuously as the "molal average boiling point," $\overline{B}$, decreases. If gas were added to fluid without limit to provide mixtures with successively lower molal average boiling points, then, at some boiling point not much lower than the lowest shown in the figures, the curves of saturation pressure should begin to indicate lower and lower pressures as the boiling point was lowered. At the limit, when the mixture is essentially of the composition of the added gas, the saturation pressures indicated may be lower than 2,000 psia.

This result could be obtained whether or not the experiment was conducted in such way as to maintain W_m constant. It follows, moreover, that, for a given value of the property T_{ce}, as given by Equation (1) above, there may be two restricted compositions and two molal average boiling points.

It is entirely possible that the dew point pressure of gas-condensate fluids of average composition may equal reservoir pressure. The results[*] of Bureau of Mines tests made at flowing wells show for seven reservoir fluids that the reservoir pressure exceeded the dew point pressure at reservoir temperatures by an average of only 152 psi and in no case by more than 300 psi. The dew-point pressures measured ranged from 2,946 to 4,900 psia and are estimated to be accurate to ±25 psi. Reservoir temperatures ranged from 191° to 251°F. It does not seem likely that this close agreement between reservoir and fluid dew point pressure for seven reservoirs is only coincidental. The original pressure of a gas-condensate reservoir depends on factors associated with the origin, accumulation, and retention of petroleum hydrocarbons, but the reason for the agreement between dew point and reservoir pressures must be latent in substances associated with dew point phenomena; the presence of a liquid phase in the reservoir would be an explanation. Twenty to 30 per cent of the volume of the reservoir pore space could be filled with liquid without appreciable entry of liquid into the well bore during fluid flow, and part of this liquid can be a mixture of hydrocarbons in equilibrium with the reservoir-gas phase. It would, therefore, be expected that the flowing fluid would be the reservoir-gas phase, with a dew point equal to reservoir pressure at reservoir temperature.

GOLDING'S REPLY TO MR. EILERTS

As Eilerts points out, the use of functions of the type (Eilerts' nomenclature)

$$T_{ce} = \frac{N_1B_1T_{c1} + N_2B_2T_{c2} + \ . \ . \ .}{N_1B_1 + N_2B_2 + \ . \ . \ .}$$

for direct computation of phase boundary properties is generally unsuitable. These functions may often, however, be used satisfactorily as correlating parameters to help systematize the observed behavior of hydrocarbon systems. Thus, although the functions used in this paper would not serve for direct calculation of maximum or minimum values of phase boundary properties, the combination of these functions as empirical correlating parameters does serve to correlate such properties. The critical loci presented in this paper, for instance, were taken in their final smoothed form from another paper by one of the authors (reference 5 of text) in which the correlation techniques described in the present paper are extended to the direct correlation of the critical temperatures and pressures of complex hydrocarbon mixtures ranging from condensate gases to refinery mixtures. Though no cricondenbar loci are presented in the present paper, the authors feel that visual inspection of Figs. 3 to 16 will reveal the approximate location of such loci with as much accuracy as the presently available experimental information permits.

The present correlation indicates that, at a given temperature and pressure, a single restricted composition (that is, only one set of parameter values) represents all possible saturated fluids. Eilerts speculates that in some cases two restricted compositions may be possible at the same temperature and pressure. If such behavior is indeed found, it would result in an interesting addition to the present correlation. The curves of constant W_m, as shown in Fig. 2 of the paper would then reach a maximum at some point of lower $\overline{B}$ than their present termination, and turn downwards to lower saturation pressures at still lower values of $\overline{B}$. Extension of the correlation into such regions will, at any rate, have to wait upon publication of additional experimental data.

Eilerts suggests that "if gas were added to fluid without limit . . . then at some boiling point not much lower than the lowest shown in the figures, the curves of saturation pressure should begin to indicate lower and lower pressures . . . " This behavior can actually be followed on the correlation charts if a gas which is itself within the range of the correlation is used. As gas is added to the initial liquid, both $\overline{B}$ and W_m decrease, the initial decrease in $\overline{B}$ being relatively the greatest. The corresponding saturation pressures will normally increase initially, reach a maximum pressure, and eventually decrease to the saturation pressure of the gas itself.

Eilerts also suggests that the dew point pressure of gas condensate fields of average composition may be equal to reservoir pressure. It is worth emphasizing that those condensate fields which are not in two phase equilibrium upon discovery are often of especial engineering interest. In particular, condensate reservoirs in which the intial reservoir pressure is above the dewpoint pressure may offer the possibility of increasing the expected economic yield through cycling above the dew point, thus reducing the amount of heavier hydrocarbons lost through retrograde condensation in the reservoir.

The correlation presented in this paper allows an engineer to tell quickly from the well stream analysis and the reservoir temperature and pressure whether a new field is possibly in two phase equilibrium or whether it is definitely a single phase reservoir. It is furthermore often possible to predict the general production behavior of a given reservoir from the relationship between the reservoir temperature and the indicated critical temperature of the particular reservoir material. An estimation of the probable retrograde condensation in gas-condensate fields can often be made from this temperature relationship, for instance. Even more important in some cases is the knowledge of whether a field will produce as a volatile oil reservoir or as a rich condensate reservoir. The sum of this information is often sufficient in itself to permit an engineer to decide whether a given reservoir should be produced by routine techniques or whether further experimental study and economic analysis is warranted.

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[*] "Gas Condensate Reservoir Engineering" by C. Kenneth Eilerts, Oil and Gas Jour., (Feb. 8, 1947) pp 63-68.

VISUAL EXAMINATIONS OF FLUID BEHAVIOR IN POROUS MEDIA—PART I

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PENNSYLVANIA STATE COLLEGE, STATE COLLEGE, PA., MEMBER AIME

ABSTRACT

An exploratory study was made to examine the possibilities of a visual approach in investigations into microscopic mechanisms of fluid behavior in porous media. Appropriate apparatus and techniques were developed so that microscopic phenomena could be recorded on color movie film as well as be observed visually. The observation flow cells in which the fluid behavior studies were made were essentially single-layered matrices of spheres between plates, sometimes all-glass, sometimes all-Lucite and sometimes a combination of the two. The fluids were limited to water and a filtered crude oil.

Two flow regimes were observed during the flow of the immiscible liquids: channel flow and slug flow. In the former, transport was effected through stable networks of interconnecting channels; and in the latter, part of the movement took place in the form of slugs. Under certain conditions, flood-front patterns were found to be different depending upon which liquids were the displacing and displaced phases and not depending upon whether the matrix was water-wet glass or oil-wet Lucite. Residual formations of oil and water were observed and are described. Some of the ramifications and significance of the observed phenomena are discussed.

INTRODUCTION

In recent years considerations of microscopic mechanisms of fluid flow in porous media have taken on greater significance. Much needs to be learned before the fundamentals of petroleum technology are completely established. For example, many unanswered questions exist in connection with relative permeability, displacement phenomena, residual fluid formations, flow structure, etc.; and further analytical mathematical formulations are seriously indicated. It is hoped that systematic investigations into the microscopic mechanisms connected with the behavior of fluids in porous media will shed some light on some of the problems extant.

Until recently microscopic mechanisms have been considered almost exclusively as speculative hypotheses. Within the past few years, however, the problem has been submitted to a limited number of experimental investigations. Nuss and Whiting[1] made some studies on the pore-space geometry of sandstones and limestones by impregnating cores with an inert plastic and leaching the solid matrices to leave behind plastic models of the pore spaces. Schaefer[2] traced pore spaces microscopically through lengths of limestone cores by cutting away thin sections from the exposed faces normal to the line of view.

In 1949 two projects were organized in which dynamic flow phenomena were examined microscopically to uncover microscopic mechanisms. One was set up at the Pennsylvania State College where Lowman[3] observed heterogeneous fluid flow phenomena in capillaries. The second was the American Petroleum Institute Research Project 47B at the University of Oklahoma where microscopic studies of dynamic fluid phenomena in synthetic porous matrices have been made by visual observation and cinephotomicrography.[4] It is with the latter that this paper is concerned, treating the techniques involved and the observations made.

TECHNIQUES

Observation Flow Cells

The observation flow cells formed a focal point in the techniques employed. Essentially, these were matrices composed of a single layer of spheres sandwiched between two flat plates. This design was arrived at after a series of pre-

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[1] References given at end of paper.

Manuscript received in the office of the Petroleum Branch, AIME, May 21, 1951. Paper presented at the Petroleum Branch Fall Meeting in Oklahoma City, Okla., Oct. 3-5, 1951.

The movie film which records studies reported in this paper is available from the offices of Elmer O. Mattocks, American Petroleum Institute, 50 West 50th St., New York, 20, N. Y.

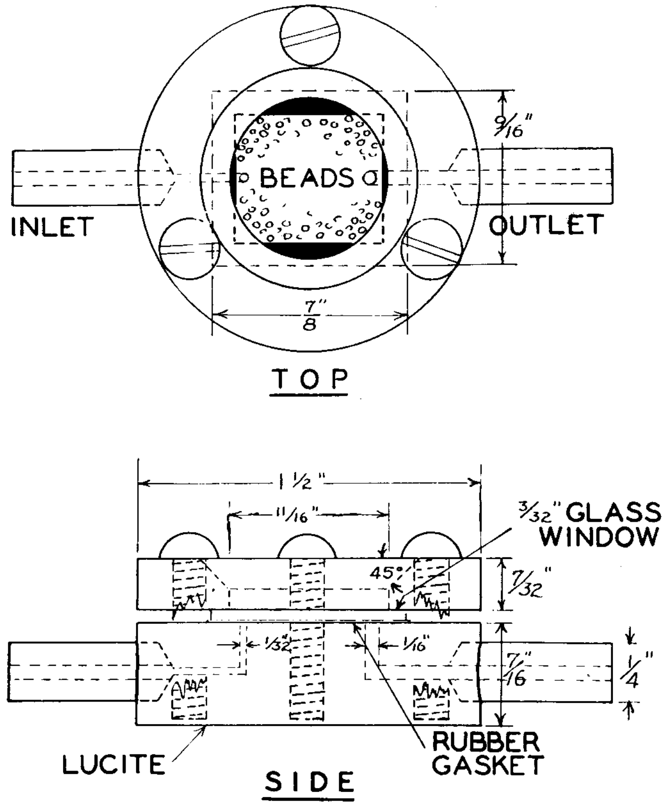

FIG. 1 — TYPE "B" CELL.

liminary investigations. It has been found that in multi-layered cells it was extremely difficult to differentiate one phase from another and the observations of flow phenomena were almost hopelessly complicated. For matrices that were opaque, it was impossible to carry out continuous microscopic observations through the depth of the beds. Thus a single-layered matrix, composed of glass spheres where possible, was decided upon as the structure most likely to produce easily observed flow phenomena despite its highly ideal nature. Flow phenomena established in this way would then provide a basis for further studies in more natural systems.

Two types of flow cells have been used. The first of these is the Type B cell of which a typical example is diagrammed in Fig. 1. The four principal parts of this cell are the base, the compression cover, the observation window and the gasket. The diagram is explicit with regard to the functions of the different components.

The base in all cells of this type was either wholly or principally Lucite. It was prepared from a Lucite cylinder (1½-in. diam. and 7/16 in. height) that was molded from molding powder at 140°C and 3,000 psig. The dimensions and shape, which in turn determined the dimensions and shape of the rest of the cell, were dictated primarily by the more ready availability of the molding equipment involved. In the diagram two ports are shown. These could be changed in number and position at will. Tubing connections were either cemented in as shown or threaded in. In those cases where it was desired to make an all-glass matrix composed of a glass top, glass spheres and a glass base, a glass plate was molded into the Lucite base in a press. This was done by pouring the requisite amount of molding powder over the glass plate in a cylindrical mold and molding in an hydraulic press at 140°C and 3,000 psig. With the ports drilled in by means of a carbide milling cutter type burr, this plate served as the base for the all-glass cell.

The compression ring, by means of which force was brought to bear against the sealing gasket through the observation window, was made of Lucite as diagrammed or aluminum. The Lucite rings were cut from molded Lucite discs. The aluminum rings were machined and could be prepared slightly thinner. The observation window served as the top wall of the matrix and provided a means for observing the phenomena. It was limited in thickness by the working distance of the microscope objective under which it was to be used. In general, the thicker glass windows were less liable to breakage and buckling than were the thinner ones. For all-Lucite matrices requiring a Lucite top wall, a thin Lucite disc was used backed up by a glass window. In this way the undesirable optical properties of the Lucite were reduced to a minimum and the necessary rigidity was maintained. The gasket was usually cut from rubber commonly found in toy ballons.

Before assembling any of the cells all but one port were first plugged up with 150-mesh screens to keep the spheres from flowing out. Then the gasket was placed in its proper position and covered by the observation window and compression ring. With the components in place, the compression screws were turned down evenly until the cell bed was of the desired depth (0.0075 in.). The spheres used to fill the flow beds were carefully screened so as to be uniform in size (0.007 in.). They were introduced through the free port and packed into place by the use of an air stream, tapping and vibration. In this way single-layered cells closely approximating a rhombic pattern of packing were attained.

The second cell design that found wide use was the Type C cell of which a typical example is shown in Fig. 2. The component parts are quite similar to the corresponding parts in the Type B cell except for shape and size. The greatest difference lay in the structure of the base. In most instances, the base was made in two pieces as indicated in Fig. 2. For all-glass cells aluminum was most often used for the framework holding the inlets and outlets. The other material that found some use was Lucite. With aluminum it was necessary to cut a window to permit the use of transmitted light for the examinations. The Lucite framework could be used in its solid form. For an all-glass cell, the lower plate of the flow bed was simply a plate of glass with holes drilled through it to match those of the inlets and outlets in the framework. Where a sealing aid was required to prevent leakage between the plate and the framework an inert lacquer was used. In those cells requiring a Lucite plate on the bottom of the flow bed, a one-piece solid Lucite base was used.

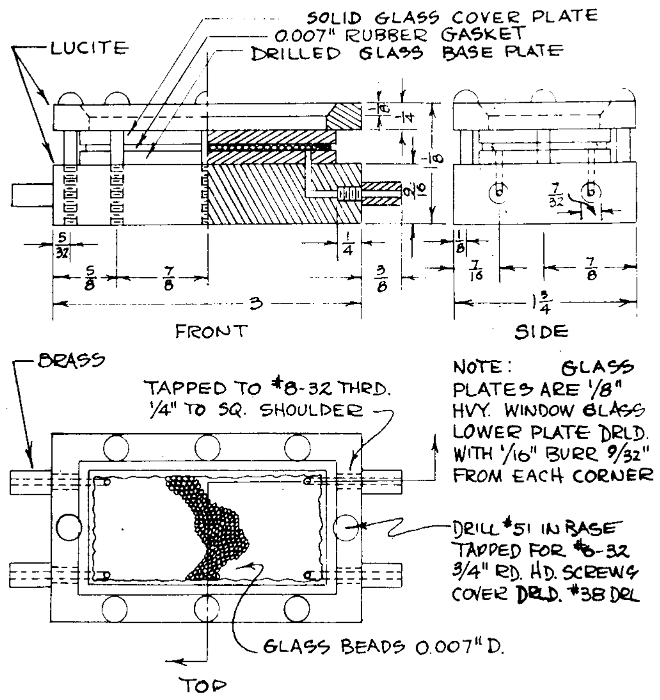

FIG. 2 — TYPE "C" CELL.

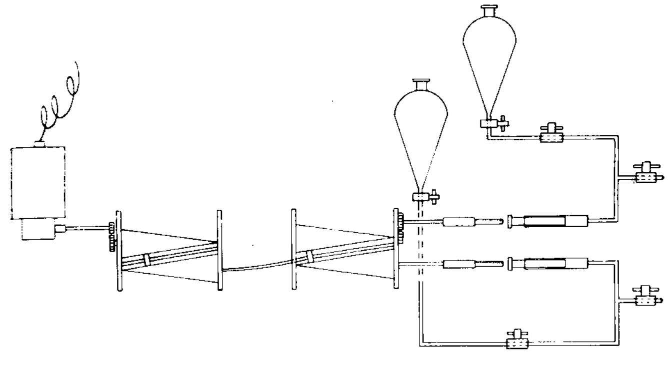

FIG. 3 — PUMPING APPARATUS.

The gaskets, upper plates and compression frame were functionally the same as with the Type B cell. In addition to rubber, lead foil was used for gaskets in these designs. The cells were assembled and filled with the same spheres and in the same manner as were the Type B cells. The principal advantage offered by this design was a much larger observable flow bed.

Positive displacement pumps provided the means of moving the fluids through the cells. One pumping system was constructed as diagrammed in Fig. 3. With this apparatus, two liquids could be pumped through hypodermic syringes which were activated by micrometer heads. Each micrometer head was rotated by the shaft of one of two cones placed base-to-apex and driven by a common friction pulley. By positioning this pulley along the length between the cones, different flow ratios could be established between the two fluids. The pulley in turn was driven by a motor at the various desired speeds. A second system was composed of Zenith gear pumps, one for each fluid, driven through Revco variable speed reducers.

Since the flow beds were packed with uniformly dimensioned spheres, the cross-sectional pore area available for fluid flow was fairly uniform down the length of the bed. Basing calculations upon this cross sectional area and volume flows, it was estimated that the range of flow velocity lay between 1.5 and 2,000 ft per day.

Cinephotomicrography

Color cinephotomicrography proved itself to be an indispensible tool for studying as well as recording dynamic flow phenomena. A phenomenon on film could be examined in much greater detail than is possible in a single viewing through the microscope at experimental rates. The apparatus involved consisted of an appropriate microscope and accessories, a 16-mm movie camera, a beam splitter, an arc illuminator and an exposure meter.

The microscope used was a research type microscope with a substage condenser and mechanical stage. The mechanical stage was fitted so as to accommodate the observation flow cells. Objectives with magnifications up to 10X were used in conjunction with eye-pieces of 10X magnification. The stage was kept in a horizontal position and the illumination was reflected by a mirror up through the flow bed lying parallel to the plane of the stage. The techniques for properly aligning the optical illuminating systems for even lighting and undistorted image reproductions may be found in treatises on photomicrography.[5]

A camera that was found adaptable to this work was of the Bell and Howell G.S.A.P. type. This was motor-driven and accommodated a 50-ft, 16-mm film magazine. It was capable of taking pictures at a rate as high as 64 frames per second, but only speeds of 16 and 32 frames per second were employed. The camera was used with and without its lens. A special viewer was built so that the image in the focal plane of the camera could be observed for purposes of synchronization. This was simply an empty magazine fitted with a clear or ground glass in the film aperture, a magnifying glass to enlarge the image and a viewing aperture at the other end. When it was inserted into the magazine chamber with the camera shutter open, the image in the focal plane could be easily seen. The film used was Kodachrome, daylight type.

With this apparatus it was necessary to use a high-intensity source of illumination. A Bausch and Lomb 4.5-amp. a-c carbon arc illuminator was found to be practicable for this purpose. It produced sufficient illumination to take pictures at a speed of 32 frames per second and produced a picture on Kodachrome, daylight type film, free of chromatic aberrations and with good color fidelity. An undesirable feature of this instrument lay in its tendency to flicker and drift despite the spring-wound clockwork used on the carbon-feed mechanism.

A light meter was essential for the estimation of proper light intensities. One based on that of Clemens and Brar[6] using a phototube in an electronic circuit was employed. The circuit is given in Fig. 4. The phototube was covered with a light shield and fitted with a small window and adapter so that it could be used on the eyepiece of the beam splitter. This instrument is of the balanced circuit type operating on

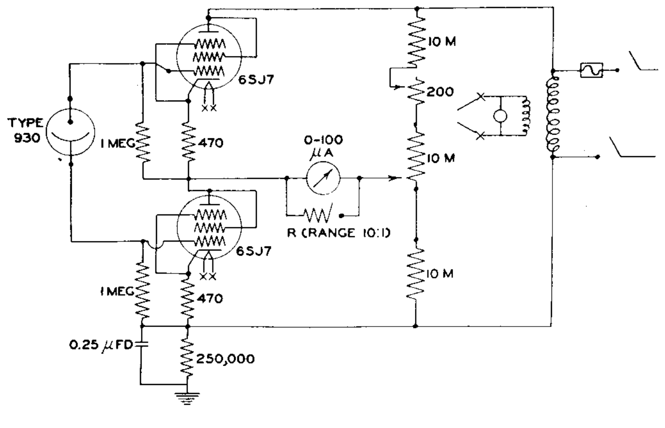

FIG. 4 — WIRING DIAGRAM FOR PHOTOTUBE EXPOSURE METER.

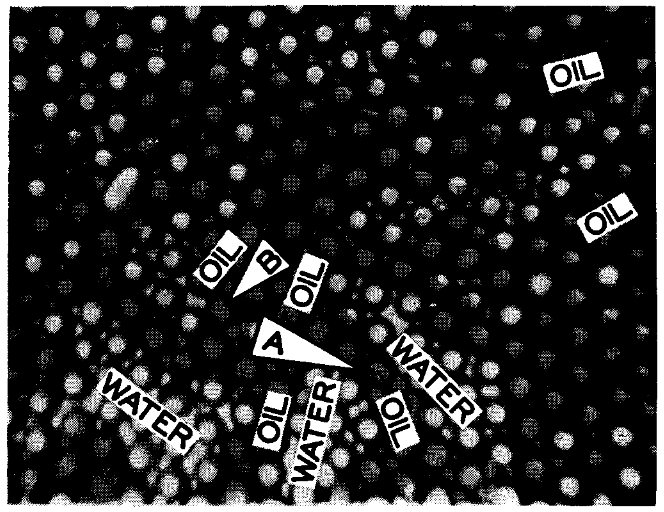

FIG. 5

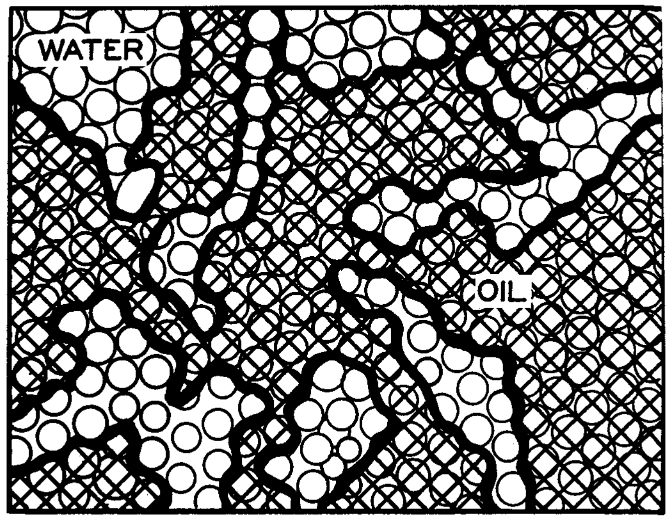

FIG. 5A

a 110-volt, 60-cycle line. The zero point is set by means of the variable resistance and potentiometer. The response follows from the disturbance in the balance caused by the phototube current. Calibration using a G.E. photo light meter as a standard showed the response to be linear with the intensity for a given source of illumination. For use in cinephotomicrography, the exposure meter was calibrated directly against film exposures.

OBSERVATIONS

Channel Flow

Channel flow is the name given to one of the flow regimes observed to prevail under certain conditions of simultaneous two-liquid flow. When water and crude oil (viscosity: 14 cp, specific gravity: 0.9, interfacial tension with water: six dynes/cm) were pumped through the observation flow cells at total velocities up to 1,000 ft per day, they were observed to move in channel flow.

This regime has several characteristics by which it may be described. Each fluid effects transport through its own network of interconnecting channels. The channels might vary in diameter from about one grain diameter to many. They are bound by liquid-liquid interfaces as well as liquid-solid surfaces and meander tortuously through the flow bed. It is probable that with the flow cells described above, each of the two flowing systems was transported through a single continuous network of channels.

For steady flow conditions, the channels maintained fixed geometries and positions throughout the flow bed. No movement was observed at the liquid-liquid interfaces at magnifications as high as 100X. With a change in saturation, the geometries of the channels were altered. An increase in oil saturation with a simultaneous decrease in water saturation was accompanied by a general growth in the diameters of the oil channels and a reduction in those of the water channels. There was a tendency for the channels to hold their positions in the flow bed. In the case of temporary flow disturbances the flow channels exhibited an elasticity whereby they tended to resume almost their exact starting configurations with the reestablishment of the original steady conditions.

By observing the movement of particles suspended in the flowing fluids, it was seen that the flow within any channel was essentially streamlined in nature. The moving particles delineated smooth lines of flow devoid of eddy currents despite the tortuosities of the channels. This was the type of behavior that was also observed in the flow of homogeneous fluids.

A photomicrograph showing a portion of the channel flow structure established in an observation flow cell is given in Fig. 5.* The oil and water channels are indicated in the photographs. They are distinguishable from each other by a difference in the darknesses occurring on either side of the oil-water interfaces. This is only that small portion of the flow bed included in the microscopic field. The matrix is an all-glass cell of a single layer of spheres (0.007 in. diam.) and the simultaneously flowing fluids are water and crude oil. The flow velocity of each of the fluids is about 350 ft per day. This phenomenon has been observed in other matrices including all-Lucite cells, glass-Lucite cells, and double-layered cells, as well as with other fluid systems including refined oils and brines with flow velocities ranging from 1.5 to 1,000 ft per day and flow ratios from 1:3 to 3:1.

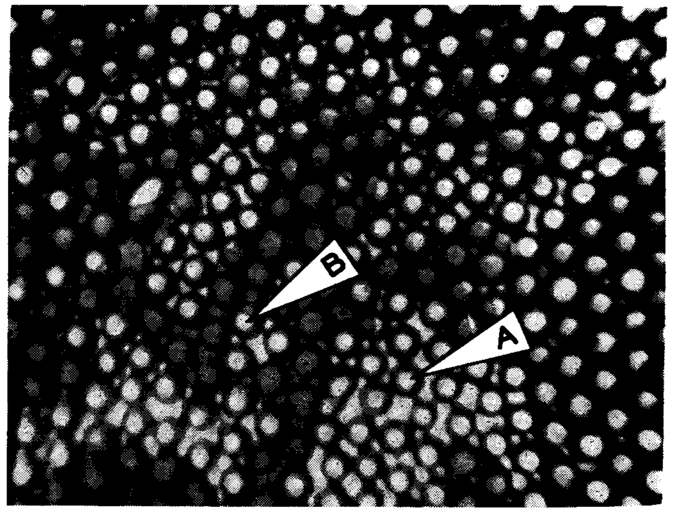

FIG 6

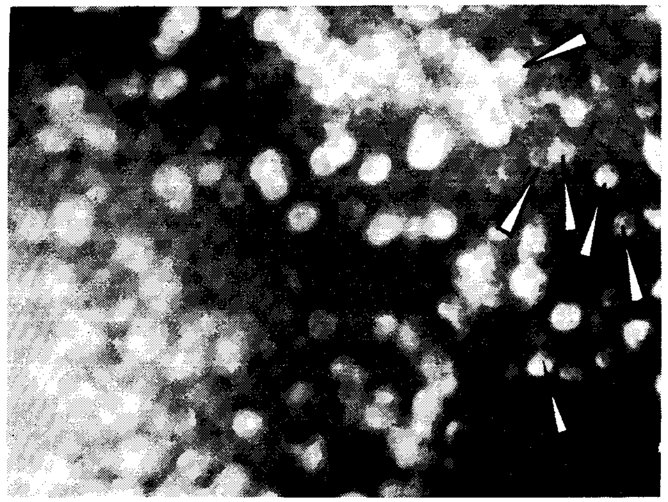

FIG. 7

Slug Flow

With a system composed of an all-glass observation flow cell flowing oil and water at less than 1,000 ft per day as noted above, a channel flow regime prevailed. However, increasing the total flow rate while keeping the flow ratio constant resulted in a change at some velocity less than 2,000 ft per day to a new flow regime in which slug flow was in evidence. By this it is meant that some of the transport was effected in the form of separate, isolated slugs or globules.

In an all-glass matrix, the oil phase formed the slugs while the water phase remained continuous. Fig. 6 is a photomicrograph of a system under slug flow. This is the same system and the same field shown in Fig. 5. The fluids, however, are flowing at a velocity of about 1,500 ft per day at a 1:1 ratio. To indicate differences in the flow structure two spheres have been labeled A and B respectively in the two figures. It is to be noted that in each case the sphere is under oil in Fig. 5 but not in Fig. 6, indicating that those parts of the oil flow structure have moved or disappeared during the existence of the slug flow regime. This phenomenon has been observed over ratios ranging from 1:3 to 3:1 and in cells of more than one layer of spheres. With an increase in total velocity past the point of slug flow genesis the frequency of slug formation and the number of slugs in the flow bed increased. Characteristic of these systems is the ease with which an oil globule or slug coalesces with another body of oil upon collision.

Flowing the same liquids under the same conditions in all-Lucite matrices, the oil appears as the continuous phase and the water as the slug-forming phase. If water slugs or globules are introduced into an oil stream, they will persist in slug flow resisting coalescence throughout their transport across the flow bed even upon strong collision with other water bodies. A photomicrograph of such a system is given in Fig. 7. The solid matrix is an all-Lucite one composed of a single layer of Lucite spheres (0.007 in. diam.) between two Lucite plates. Arrows indicate moving water globules.

Flooding Phenomena

"Flooding," here, is the term used to describe those systems in which only one fluid is being pumped into the observation flow cell. In an all-glass cell having an arbitrary initial water saturation with oil filling the remainder of the pore volume,

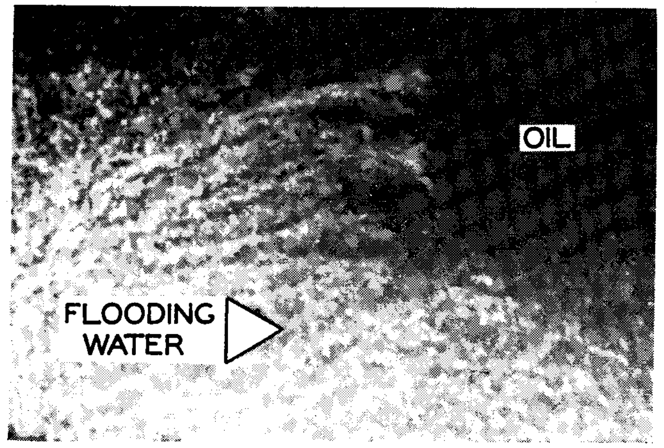

FIG. 8

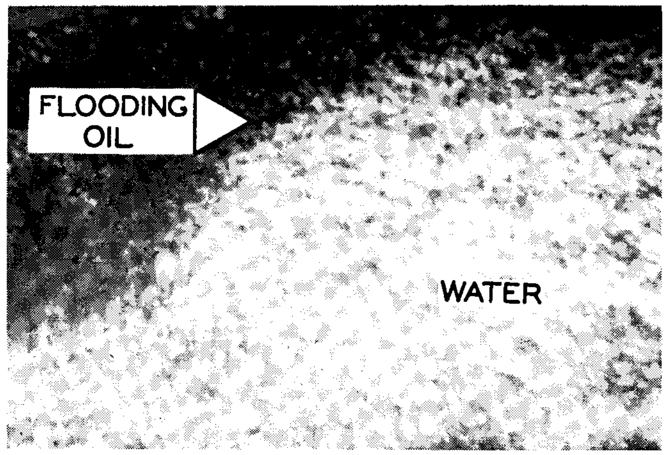

FIG. 9

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*A diagrammatic tracing of the photograph in Fig. 5 is given in Fig. 5A.

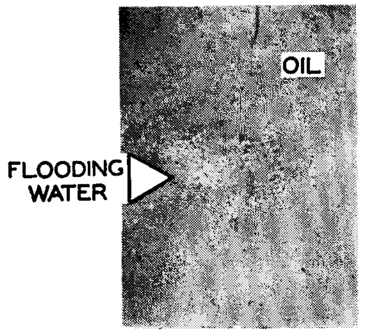

FIG. 10

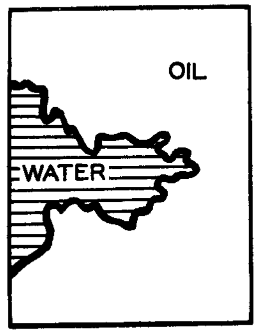

FIG. 10A

flooding with water results in a certain flood-front pattern. A stringy appearance is created by the water as it fingers through the flow bed, by-passing a considerable amount of oil. There is also a tendency for these fingers to branch out in dendritic patterns again by-passing oil.

A flood-front of this sort is shown in Fig. 8. This is a macroscopic view of an all-glass observation flow cell of a single layer. The velocity of water flow is about 1,500 ft per day. The dark areas are those occupied by oil while the light ones are those occupied by the flooding water. An arrow indicates the general direction of flood. The oil involved is the same as that whose properties are given above.

When a water-saturated cell is flooded with oil, a new type of flood-front pattern develops. In this case, the flood-front appears to be a circumferential band around the inlet port. This is seen in Fig. 9 where the system described in Fig. 8 is undergoing a flood by the oil at a velocity of about 1,500 ft per day. In a flood of this type the displacement mechanism appears to be more of a piston-like action with little tendency toward fingering and gross by-passing. It would be expected that this would result in more efficient displacements.

Floods were carried out with the same liquids in all-Lucite flow cells. These were of the same dimensions as the all-glass cells but presented a solid matrix or different surface properties, the Lucite being preferentially wet by the oil and the glass by the water under the conditions of the experimentation. Despite this difference, similar flood-front patterns developed as with the all-glass flow beds. Figs. 10* and 11 are photographs of a water flood and oil flood respectively in an all-Lucite matrix, both at velocities of about 1,500 ft per day. In all of these floods the transport of fluids took place through continuous phases without any formation of slugs.

Residual Formations

"Residual Formations" refer to those fluid formations left behind a flood front in the matrix of an observation flow cell. In water floods, the most apparent residual oil formations were those large volumes by-passed by the water. Depending upon conditions of flooding and the physical characteristics of the fluid system and porous matrix, these varied from very small to very large portions of the total void volume. They were continuous over many sphere diameters and sometimes over the length of the whole cell.

Almost always, smaller residual oil formations were also found in the flow bed. One form that these took is shown in Fig. 12. In this case the oil formation covering a few spheres has been left behind in flooding an all-glass matrix with water. Apparently held in place by capillary forces, these formations are not displaced by flooding rates as high as 10,000 ft per day. The liquids were the same in properties as those described above.

Another form of residual oil is shown in Fig. 13. This is a free spherical globule, usually no larger than a sphere of the matrix, occupying an insular region between the spheres. One of the interesting characteristics of these is that they are subject to rotation in place during water flooding. Such rotation has been observed in globules that were not entirely free but attached to some solid surface in the matrix. For a given globule, the rotation was always in the same direction even with intermittent water flooding. While a larger flooding velocity produced a higher speed of rotation, the velocity of the rotating globule appeared to be somewhat smaller than that of the flooding water. Some of the residual oil also remained behind in similar globules, smaller than the spheres of the matrix, which were attached to surfaces in the funicular regions and in which rotational movement was not observed.

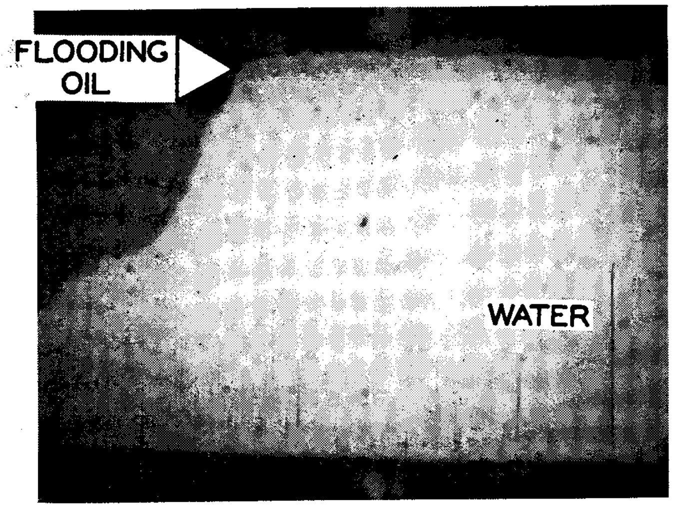

FIG. 11

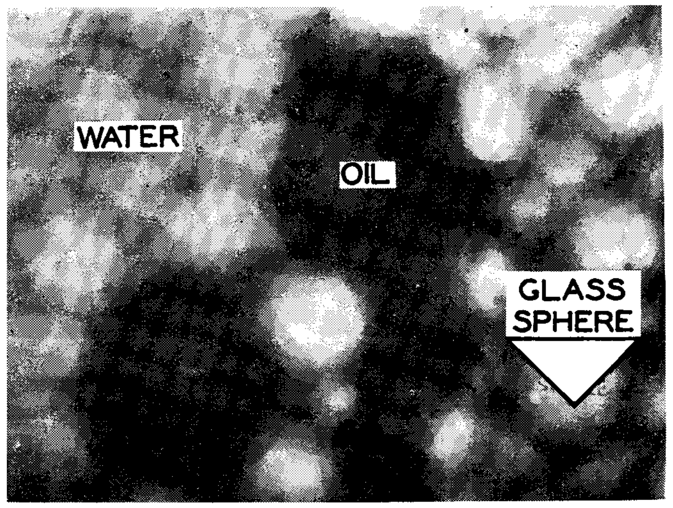

FIG. 12

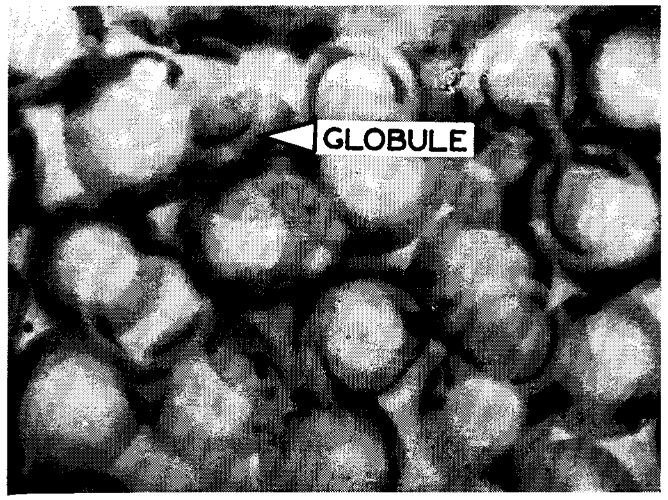

FIG. 13

In all-glass flow cells accommodating oil and water as described above, the predominating formation for the residual water was that of pendular rings. Most clearly observed were those that formed between the horizontal plates and the spheres of the flow matrix. However, they were found to form in a perpendicular plane between the spheres as well. Fig. 14 shows the intermediate step in the form of a "figure 8" as well as the final pendular rings formed during an oil flood. By suspending fine oil globules in the water phase, rotational movement has been observed in these pendular formations during flooding by oil.

In displacing water by oil in an all-Lucite flow cell, residual water remained behind as globules in the funicular regions rather than as pendular rings. Fig. 15 is a photograph of such formations in a single-layered Lucite matrix. These residual water formations were similar to some of the residual oil formations in all-glass cells during water floods.

DISCUSSION

These studies were, for the greatest part, exploratory in examining the possibilities of the visual approach in the investigation of microscopic mechanisms for fluid behavior in porous media. It is evident that with the development of the necessary techniques this approach is applicable to experimental systems which are somewhat idealized. Within such systems, as against more natural systems, some phenomena can be examined with considerable clarity and thoroughness leading to the eventual establishment of flow mechanisms for these particular systems. The most obvious idealizations are the single (or double) layer, the regular and uniform solid matrix, the use of flat plates in the flow bed and the use of processed fluids. Thereby, probable mechanisms are arrived at for natural systems which will grow in significance with the extension of investigations into systems more truly representative of petroleum reservoirs. Studies such as those described in this paper indicate a direction for such experimentation and further simplify the problem in providing definite phenomena to look for.

Channel flow as observed in the observation flow cells is consistent with developments in other directions. Rapoport and Leas[7] arrived at mathematical expressions defining the limits of liquid relative permeability in a liquid-gas system based on the postulation that the flow regime is that of channel flow or "parallel flow" as they term it. Comparing experimental data with theory they find satisfactory agreement.

In a paper by Geffen, Owens, Parrish and Morse[8] two points are of interest in this connection. Their saturation profiles for any one oil-water flowing ratio are different for different pressure gradients. However, the shapes of the profiles for all the pressure gradients are generally similar for the one flowing ratio. The second point involves the effect of saturation history upon relative permeabilities. They find that at a given saturation of brine, for example in an oil-brine system, the oil relative permeability curve is reversible with higher brine saturations. Upon reducing the brine to some lower value a new curve is arrived at which again is reversible but different from the previous curve. This hysteresis effect and the saturation profile variations may both be explained on the basis of a channel flow regime.

Wilson, Calhoun, and Chatenever[9] have found visual evidences of channel flow in synthetic cores. Flowing glycerine and melted paraffin through consolidated salt cores, and solidifying the wax, they found a flow structure composed of a network of interconnecting channels.

It is difficult to evaluate the significance of slug flow without additional data. The important factor in the genesis of slug flow is probably capillary pressure rather than velocity of flow. Further work is required in order to be able to estimate that portion of total flow that might be in the form of slug flow. It is indicated that in phases that tend to coalesce easily the slug flow regime will be less prevalent than in those where

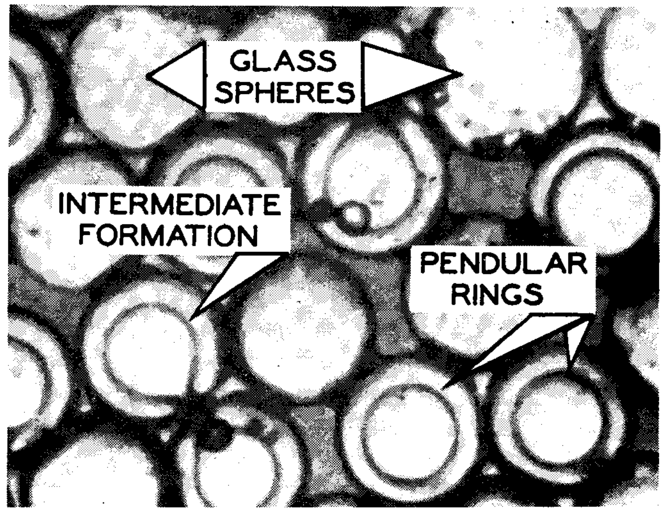

FIG. 14

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*A diagrammatic tracing of the photograph in Fig. 10 is given in Fig. 10A.

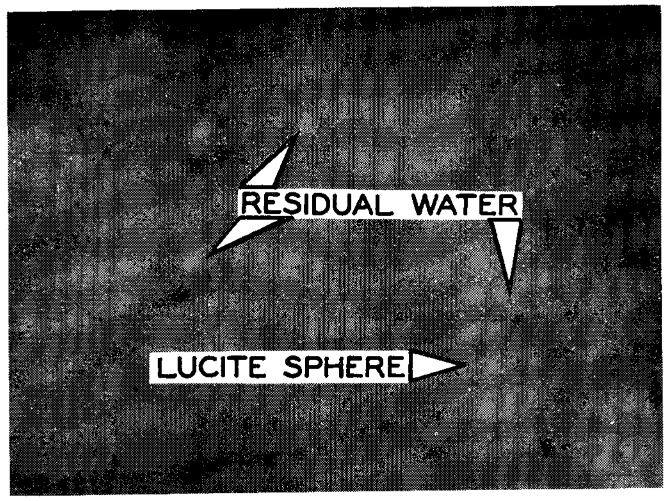

FIG. 15

there is a strong tendency not to coalesce. It is possible that this mode of fluid transport might have a bearing upon displacement phenomena as well as flow behavior. Thus, where by-passing is usually thought of in terms of sidetracking, a mechanism is introduced here in which a fluid may be by-passed by another flowing through it in globules or bubbles.

Of the flood-front patterns noticed in the flooding experiments, it would be expected that floods subject to the fingering mechanism would not be as efficient as those with regular linear fronts. It would be expected, too, that ultimate recoveries in the former case would be less although the relationships here are more subtle. As a consequence of the similarity of flooding behavior in glass and Lucite systems, preferably wet by water and oil respectively, it appears on the basis of these limited investigations that the wettability properties of the solid matrix may have relatively little effect upon the flood-front pattern. As a consequence of this, surface tension effects on flooding behavior might be relegated to a minor role. One relationship that suggests itself strongly in this connection is the ratio between the viscosities of the displaced and the displacing fluids. It is pertinent that flood-front characteristics have been studied here only over the length of a small observation cell; and it is possible that further ramifications may develop in cells of larger dimensions.

Most of the interest in residual oil formations derives from a desire to avoid them or, having formed them, to displace them. Again, it is as yet difficult to determine on the basis of these studies the relative importance of the various formations discussed. However, there are suggestions that any process that would favor the establishment of more numerous channels of flooding water would also favor smaller residual oil formations. It appears as if those that are given to rotation are probably the most difficult to displace by purely physical means. For those that are held in place primarily because of capillary forces, it would be expected that surface tension lowering agents would be efficacious in aiding displacement. Unlike the conditions attending flood-front phenomena, the wettability of the solid matrix is of definite consequence in residual formations. Thus in an all-glass water-wet cell none of the residual oil finds itself in the pendular regions. On the other hand, pendular rings are the most prevalent residual water formations in a matrix of this sort. This would be expected on the basis of Leverett's[10] work on capillary behavior. The movements within the pendular rings are noteworthy, as are those of the rotating oil globules in that they might have some bearing upon the dissipation of reservoir energies.

It is important to realize that the observations under discussion have been carried out in only a limited number of artificial systems. It is necessary, therefore, that the conclusions arrived at be confirmed by more extensive investigations before they are applied to natural petroleum reservoirs. One particular point that requires clarification, for example, is the apparent importance of surface tension in residual formations and the apparent lack of significance of this property in flood-front patterns. Current researches have already indicated significant possibilities and it is hoped that more work in this connection will be forthcoming.

ACKNOWLEDGMENT

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DRILLING FLUID FILTER LOSS AT HIGH TEMPERATURES AND PRESSURES

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ABSTRACT

This paper discusses the results obtained from high temperature, high pressure filter loss studies in which field samples of clay-water, emulsion, and oil base fluids were used. High temperature, high pressure tests of some premium priced emulsion and oil base drilling fluids show filter loss peculiarities that are not predicted by standard API tests. It is recommended that high temperature, high pressure filter loss tests be used to evaluate the performance of such fluids.

Apparatus is described which proved to be satisfactory for evaluating filter loss behavior over a wide range of temperatures and pressures.

INTRODUCTION

The petroleum industry spends large sums of money each year on chemical treating agents for lowering filter loss and on premium-priced low filter loss drilling fluids.

While it is an accepted fact that low filter loss is advantageous during drilling operations, it is questionable whether the present standard method of determining filter loss gives a reliable indication of the loss to be expected under bottom hole conditions. The purpose of this paper is to show that high temperature, high pressure filter loss tests should be used to evaluate filter loss behavior of fluids for deep drilling.

Concern over possible effects of filter loss on oil well drilling and well productivity dates back to the early 1920's. During the years 1922 to 1924, filtration studies were reported by Knapp,[1] Anderson[2] and Kirwan.[3] These studies were the first to be reported in the literature on this subject. No further information was published on the subject until 1932 when Rubel[4] presented a paper in which he discussed the effect of drilling fluids on oil well productivity.

In 1935, Jones and Babson[5] constructed the first laboratory tester designed to study the effects of temperature and pressure on the filter loss behavior of clay-water drilling fluids. In a discussion of their investigations, Jones and Babson[5] stated, "Performance characteristics of a mud can be evaluated with considerable reliability by a single test at 2,000 psi and 200°F. Exact correlation between the results of performance tests made under these conditions and the behavior of muds in actual drilling operations is of course impossible." Jones and Babson apparently were well aware that at best laboratory tests can give only qualitative answers to the question of what is the actual behavior of a drilling fluid when subjected to deep drilling conditions. Jones[6] presented a paper in 1937 in which he described a static filter loss tester to be used for routine filter loss tests. This instrument subsequently was adopted as the standard API filter loss tester.

In 1938, Larsen[7] developed a relationship between filtrate volume and filtrate time that is in general acceptance today. Larsen was cognizant of the danger of estimating bottom hole behavior from filter loss measurements at room temperature. He tried to predict the effect of temperature on filter loss by relating temperature effects through the temperature dependence of filtrate viscosity. This was undoubtedly an over-simplification of the temperature dependence of drilling fluid filter loss.

In 1940, Byck[8] published a summary of experimental results of filter loss tests made on six representative California clay-water drilling fluids. He concluded that "no existing method will permit even an approximate determination of the filtration rate at high temperature from data at room temperature. It is necessary to measure filtration at the temperature actually anticipated in the well, or to make a sufficient number of tests at various lower temperatures so that a small extrapolation of these data to the anticipated well temperature may be applied."

Byck's findings were presumably well accepted and recognized by drilling fluid technologists, and yet, they did not lead to wide adoption of high temperature drilling fluid filtration equipment. This is evidenced by the fact that no additional information has appeared in print on the subject since 1940.

Study of Byck's data shows that there was a useful consistency in them. The fluids did not show predictable losses at high temperatures, but they did line up at high temperatures in approximately the same order that they lined up at low temperatures. That is, if a fluid appeared to be a good fluid with relatively low loss at low temperatures, it would also be a good fluid with relatively low loss at high temperatures.

In the last decade, the above situation has changed. The drilling fluid art is markedly different from what it was. The outstanding change, as far as the present discussion is concerned, has been the adoption of wholly new types of drilling fluids. Oil base and emulsion drilling fluids have come into wide use. It is, therefore, necessary to re-examine previously satisfactory generalizations to see if they are still valid.

It turns out, as might have been expected, that Byck's explicit generalization, already quoted, is still true. Filter losses at high temperatures cannot be predicted from filter losses at low temperatures. However, no further generalizations are valid now. Fluids of different chemical types show different general behaviors. No longer do the fluids line up approximately the same at high temperatures as they do at low temperatures. They may line up entirely differently. Special fluids exhibiting very low loss at low temperatures may have losses as high as those of ordinary clay-water fluids at high temperatures. This fact is highly significant, because premium prices are being paid for the special fluids.

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