Determination of Relative Permeability Under Simulated Reservoir Conditions

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An apparatus for the determination of relative permeability under simulated reservoir conditions has been designed, constructed, and operated successfully. Complete water-oil relative-permeability data, with kerosene and simulated reservoir brine have been taken on four natural-sandstone cores at fluid pressures to 5,000 lb./sq. in. and overburden pressures to 10,000 lb./sq. in. One run was made at low pressure at a temperature of 160°F. for comparison with the results at low temperature. The apparatus is now being expanded so that gas-oil relative-permeability data may be taken, and crude oil containing gas in solution may be employed as the oil phase.

The results indicate that essentially the same water-oil relative-permeability data are obtained at fluid pressures of 5,000 lb./sq. in. as at 30 lb./sq. in. gauge. The application of overburden pressure causes a reduction in both water and oil effective permeability in about the same proportion as it affects the single-phase permeability. Consequently the calculated relative permeabilities are affected to only a moderate extent. The results of the one run at 160°F. were in good agreement with the values obtained at room temperature.

Laboratory determinations of relative permeability of oil-field cores are usually made at low pressure and room temperature by use of relatively pure fluids and solvent-extracted cores. There is general concern among both those who make the measurements and those who apply the data as to whether information obtained under such idealized conditions is truly representative.

The influence on relative permeability of two of the more obvious effects of high pressure and temperature—changes in viscosity and interfacial tension—was investigated and reported by Wykoff and Botset (*1*) in the first published paper to present permeability vs. saturation curves for two-phase flow in porous media. They found little effect on the relative-permeability behavior of a carbon dioxide-water system when sugar was added to the water to increase the viscosity of the water from 0.9 to 3.4 cp. or when amyl alcohol was substituted for water to decrease the surface tension from 72 to 27 dynes/cm. Leverett (*2*) made a systematic investigation of the effects of liquid viscosity and interfacial tension on the water-oil system. He found no significant variation in relative permeability to either oil or water for the system studied when the viscosity ratio was varied from 0.057 to 90.0. Reduction of interfacial tension from about 30 to 5 dynes/cm. by substituting amyl alcohol for the oil caused a moderate increase in relative permeabilities. Subsequent investigations (*3, 4*) of the effect of viscosity have been contradictory, and the problem appears to be still unsolved. If the effects of viscosity or interfacial tension were the only significant ones, it would be possible to take account of them by employing fluids having appropriate viscosities and interfacial tension in the laboratory tests. However, the multiphase flow behavior is so complex and little understood that there may well be other important factors. For example, change in wettability of the rock with pressure, such as was observed by Hough, Rzasa, and Wood (*5*) for stainless steel in a methane-water system, would drastically affect the relative-permeability behavior.

Therefore, it seemed that a direct approach to the problem by actual measurements of relative permeability at reservoir pressures and temperatures would be highly desirable. An apparatus was designed and constructed for this purpose, and the results of the first phase of the work, which involved a comparison of the relative permeability to kerosene and brine of several natural cores at ordinary pressures and at fluid pressures of 5,000 lb./sq. in., are reported in this paper.

APPARATUS

The apparatus employed in this work was designed to permit the determination of relative permeabilities at fluid pressures up to 5,000 lb./sq. in., core overburden pressures to 10,000 lb./sq. in., and temperatures to 300°F. In addition to the usual problems involved in high-pressure work, the following requirements had to be met: (1) the establishment and maintenance of constant fluid-flow rates as low as 0.1 and as high as 100 ml./hr., (2) the measurement of differential pressures of the order of 2 to 5 lb./sq. in. at total pressures of 5,000 lb./sq. in. by some instrument requiring only minute amounts of fluid for its operation, and (3) the determination of the amount of oil (or water) in the core being examined with an accuracy of about 0.05 ml.

The apparatus is shown in simplified form in Figure 1. Because of the rather large volumes of fluid involved, small temperature fluctuations could greatly affect the flow rates, and therefore nearly the entire equipment was installed in a constant-temperature air bath.

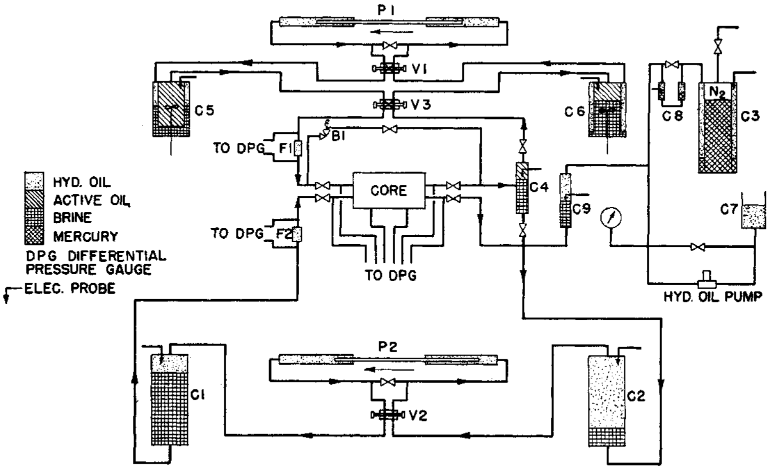


Fig. 1. Simplified flow diagram.

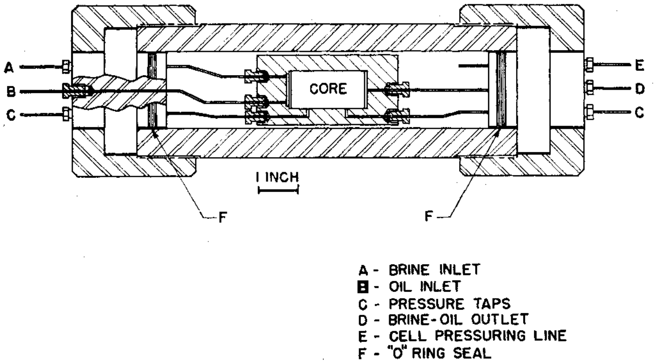


Fig. 2. Mounted core in overburden pressure cell.

In normal operation P2 (Figure 1) pumps hydraulic oil from C2 to C1, moving brine through the core at the set rate. Similarly, P1 pumps hydraulic oil from C6 to C5, establishing a constant oil flow rate through the core. The oil to be flowed through the core is separated from the hydraulic oil by a water seal into which a cylindrical baffle extends from the top of the vessel. The oil-brine mixture from the core is separated in C4, from which the oil passes to C5 and the brine to C2. The level of the oil-brine interface in C4 changes as the saturation of the core and the lines from the core to C4 vary. C4 is made just large enough to accommodate this change.

Pressure is maintained on the fluids in the core by compressed nitrogen in vessel C3. The nitrogen is separated from the hydraulic oil by a mercury seal into which a cylindrical baffle extends. Closing valve V4 with the probe in C8 just out of contact gives warning of any leak in the system when mercury contacts the probe.

Pumps

Each of pumps P1 and P2 consists of two opposed cylinders 16 in. long fitted with polished piston rods ¾-in. in diam. The seals at the ends of the cylinders were made removable so that the ¾-in. rods might be replaced by ⅜-in. rods for the lowest flow rates, if necessary. The rods are joined by a 16-in.-long screw, which is caused to move in either direction by a rotating nut, to which is attached a worm gear. The cylinders are attached to the opposite ends of a section of 4-in.-diam. tubing 34 in. long with the worm and nut housed midway between the cylinders. Thus the force needed to move the pistons is dependent on the differential pressure between the cylinders rather than on the total pressure, and there is no bending torque such as exists when the cylinders are mounted on a flat plate.

The oil pump is driven through a lathe "quick-change" unit combined with a specially built two-speed reducer. Ninety flow rates, increasing in steps of about 10%, are available covering the range from 0.152 to 152.3 ml./hr. The brine pump is driven by a simple unit having low- and high-speed shafts, on which speed is varied by means of change gears. By use of six pairs of gears, twenty-two flow rates increasing in steps of about 40% and covering the range from 0.0766 to 120.5 ml./hr. are available.

With the ¾-in. pistons, the pumps deliver 80 ml./stroke, and this quantity is nearly always sufficient to obtain one point on the relative permeability curve. Flow may be continued from C1 through the core to C2 by reversing P2 and the four-way valve V2 simultaneously. The volume of C1 is about 1 liter, which is adequate for several relative-permeability runs.

Because it was desirable to minimize the volume of radioactive oil in the system, a four-way valve was installed in the active oil lines, so that by reversing V3 at the same time that P1 was reversed, oil could be flowed through the core in the normal direction either from C5 to C6 or C6 to C5. The total volume of active oil in the system was about 150 ml. Because large volumes of oil must be flowed at relatively high rates to desaturate the core at the end of each run, the shifting of P1 and V3 at the end of each pump stroke was made automatic. Also, a by-pass relief valve B1, which could be set for any differential pressure up to about 40 lb./sq. in., was installed so that desaturation might be carried out at constant pressure.

Saturation Determination

The oil saturation of the cores was determined by a radioactivity method described previously (*6*). Iodine 131 in the form of iodobenzene was employed as the oil-phase tracer. Generally 75 mcurie. was used, and this quantity was sufficient for about 4 weeks' work. Vessels C5 and C6 were provided with motor-driven stirrers to facilitate mixing of the radioactive iodobenzene at the beginning of a run. Ten or more passes through the core were required to ensure thorough mixing; this operation was performed overnight automatically. The activity of the core was read at two positions: two ¼-in.-diam. holes ¾ in. deep and 1 in. apart were drilled into the 1-in.-thick wall of the overburden pressure cell, and additional lead shielding ½ in. thick was provided so that the activity reaching the counter through each opening was predominantly from that part of the core between one pressure tap and the middle of the core. Thus some indication of nonuniform saturation might be had; however, the data were generally employed only to determine the average saturation of the core. Continuous standardization of the counting equipment was achieved by counting a section of the oil inlet line before each traverse of the core. The counting apparatus was the same as that described previously (*6*). Auxiliary equipment was constructed to permit completely automatic scanning of the core and recording of the counting times.

Core Mounting

Cores *A* and *B* were mounted in Lucite with water-wet diaphragms and one pair of side taps in the manner described previously for low-pressure cores (*6*), except that the side-tap connections were drilled in from the ends. The mounting for cores *C* and *D* was simplified by omitting the water-wet membranes, and desaturation was accomplished by dynamic flow. The mounted core was placed in an overburden pressure cell with walls 1 in. thick, and connection made as shown in Figure 2.

Pressure Measurements

Two differential-pressure gauges (Wiancko type 3PDF20) capable of operating at absolute pressures to 5,000 lb./sq. in. were used in this apparatus. One was connected throughout each run to the core side taps; the other could be switched by means of a manifold to any of the pressure connections shown in Figure 1, including the core side taps. Both gauges were of the 0 to 20 lb./sq. in. range, and each gauge could be adjusted through a range and balance circuit to give full-scale deflection on a Foxboro Dynalog multipoint recorder for selected differential pressure ranges from 0 to 2 to 0 to 20 lb./sq. in. The differential pressure could be read with an accuracy of better than 1% in any of these ranges.

Filters, F1 and F2, were installed in the water- and oil-flow lines just ahead of the core. In addition to ensuring that no plugging material could reach the core, these were of value in checking the change in viscosity of the fluids when the fluid pressure was increased. The filters were cylinders of diatomaceous earth mounted in Lucite and sealed in stainless steel vessels.

Most of the valves were standard high-pressure needle valves; however, several sliding valves, such as V1, were built for special purposes. Such a valve can replace four ordinary valves and is easily adapted to automatic changing. The details of the valve are shown in Figure 3.

The design of an electrical probe that gave excellent service and could be installed in cramped quarters is shown in Figure 4. All the probes were connected in parallel to a sensitive relay with a toggle switch in each line.

The simple but highly successful seals employed on the stirring shafts in C5 and C6 are illustrated in Figure 5. Similar seals were used to connect ⅛-in. tubing to the various vessels.

EXPERIMENTAL PROCEDURE AND RESULTS*

The procedure employed on each core was generally as follows.

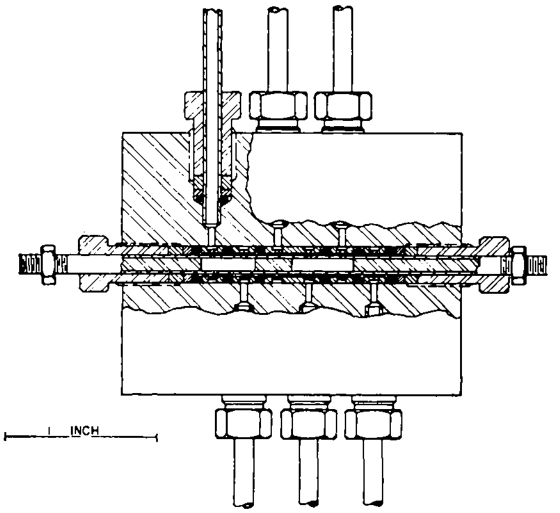
1. Two or more relative-permeability runs were made at 30 lb./sq. in. gauge fluid pressure, zero overburden pressure.
2. Two or more runs were made at 30 lb./sq. in. gauge fluid pressure, 5,000 lb./sq. in. gauge overburden pressure to determine the effect of overburden pressure.
3. Two or more runs were made at 5,000 lb./sq. in. gauge fluid pressure, 10,000 lb./sq. in. gauge overburden pressure to determine the effect of fluid pressure (same net overburden pressure).
4. Two or more runs were made at 30 lb./sq. in. gauge fluid pressure, 5,000 lb./sq. in. gauge overburden pressure to determine whether there had been any permanent change in the core.

The results for cores *A* and *B* were calculated for each run relative to the brine permeability determined under the same overburden pressure conditions. To do this it was necessary to measure the brine permeability both with and without overburden pressure before making the first relative-permeability run and to allow several weeks for the cores to recover their original permeabilities. It was noted on these cores and on other cores run in this laboratory (*7*) that the effect of overburden pressure on the oil permeability at interstitial water was very nearly in proportion to that upon the 100% brine permeability; and therefore on cores subsequently run the relative-permeability results were based on the respective oil permeabilities at interstitial-water saturation. The procedure employed on core *A* will be described in detail.

The core was mounted in Lucite with a Snow Floss diaphragm incorporated to permit desaturation by capillary pressure. The dimensions of the core are given in Table 1. The air permeability after mounting was 32 md., and the brine permeability was 16.8 md. without overburden pressure and 11.1 md. with 5,000 lb./sq. in. overburden pressure. The brine permeability had recovered to 13.9 md. within 24 hr., when capillary desaturation with kerosene was started.

When desaturation was complete, the core was placed in the apparatus, and 30 lb./sq. in. air pressure applied to C3. Kerosene containing about 50 mcurie. of radioactive iodobenzene was charged to vessel C5; the total volume of kerosene charged (about 150 ml.) was sufficient to give about 100 ml. below the probe in C5, when the probes in C4 and C6 were just in contact. After three

*Data have been filed as document 4795 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or 35-mm. microfilm.



←Fig. 3. Sliding 0 ring valve.

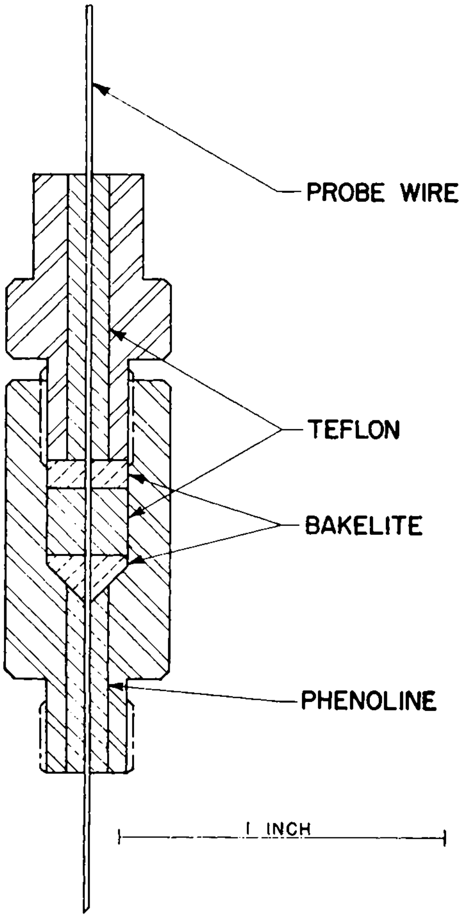


Fig. 4. Electrical probe.→

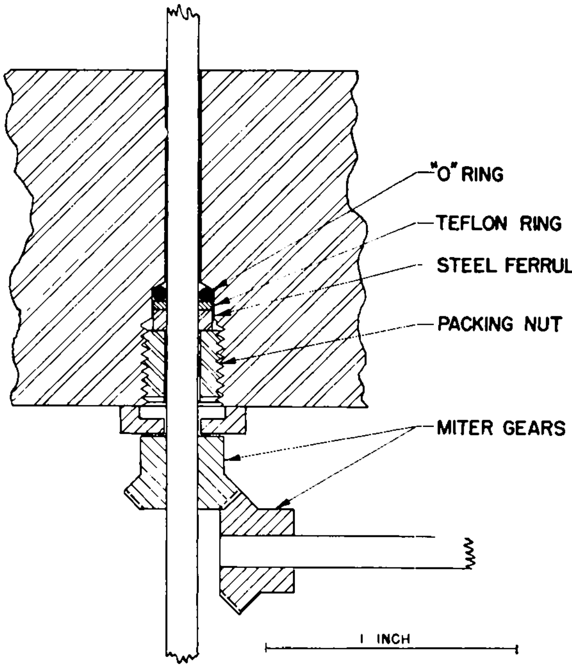


Fig. 5. Stirrer seal.

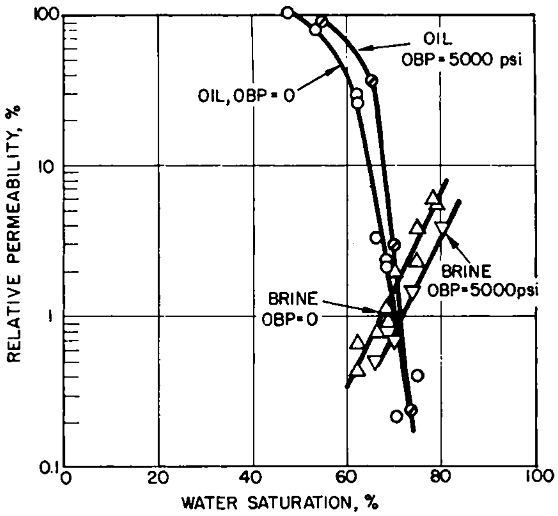


Fig. 6. Effect of overburden pressure on relative permeability of core *A*.

TABLE 1. PROPERTIES OF CORES TESTED

Core	*A*	*B*	*C*	*D*
Length, in.	2.186	2.12	2.32	2.579
Diameter, in.	1.018	0.95	0.873	0.945
Pore vol., ml.	6.54	6.53	5.53	6.09
Porosity, %	23.2	26.3	24.2	20.5
I.W., %	47.4	35.0	44.3	39.5
K_{air}, md.	30.1	142	81.1	31
K_w, md.	16.8	99	41.1	15.0
K_w at 5,000 lb./sq. in., md.	11.1	50		
K_{eo} at I.W., md.	17.4	104	39	20.1
K_{eo} at I.W., at 5,000 lb./sq. in., md.	9.7	49	22.1	14.7

passes through the core from C5 to C6, stirring before each pass, the radioactive oil appeared to be thoroughly mixed with the inactive oil in the core and lines. (This run was made before the reversing valve V1 was installed, and it was necessary to return the oil from C6 to C5 through the core by-pass valve between each pass. It was later found that three passes are not fully adequate.) While the oil was being mixed, the oil permeability was measured and found to be 17.4 md.

The next point on the relative permeability curve was obtained by reducing the oil rate to 4.68 ml./hr. and commencing to flow water at 0.254 ml./hr. The radioactivity measurements and the differential pressure reading between side taps on the core indicated that equilibrium was reached in about 11 hr. at a brine saturation of 62.5%. After 16 hr. of flow at these rates the oil rate was reduced to 0.950 ml./hr. and the brine rate increased to 0.915 ml./hr. to obtain the next point. About 9 hr. was required to reach equilibrium (68.7% brine). The rates were next changed to 0.158 ml./hr. oil and 2.032 ml./hr. brine. The brine saturation rose to 75.0% within a few hours. The oil flow was then stopped, and brine flow continued at 2.032 ml./hr. The pressure drop leveled off in about 12 hr., and no measurable additional oil was produced in an additional 12 hr. flowing at 2.032 and 16 hr. at 4.063 ml./hr. The results of the run are shown in Figure 6.

The core was desaturated by dynamic flow prior to the second run. As shown in Figure 6, the minimum brine saturation attained by dynamic flow was 53.3%, as compared with 47.4% obtained by capillary pressure desaturation, and the effective permeability to oil was 13.8 md. as compared with 17.4, but the relative-permeability curves were not altered significantly. (It is felt that the two lowest points on the oil curve are not accurate because the oil rates employed were below the value of 0.25 ml./hr., now thought to be the minimum practicable rate for the pump when ¾-in.-diam. pistons are used.)

The core was again desaturated by dynamic flow, and 5,000 lb./sq. in. overburden pressure was applied. The effective permeability was found to be 9.7 md., as compared with 13.8 md. without overburden pressure. This value represented a reduction of 30%. The relative permeability based on the original brine permeability without overburden pressure was 58%; however, it was equal to 87% based on the brine permeability with 5,000 lb./sq. in. overburden pressure. The pore volume of the core was decreased approximately 5% when the overburden pressure was applied, and, because the core was at interstitial water saturation at the time, only oil was squeezed out of the core, and the water saturation, expressed as percentage of pore volume, was increased from 52.2 to 54.8%. [The total change in pore volume of the core plus Snow Floss diaphragms, as measured by radioactivity readings taken before and after the application of overburden pressure, was 10%. The assumption, based on considerable overburden-pressure data (7) taken in this laboratory, was made that the change in pore volume of the core alone was 5%.] Because of this change in percentage of water saturation, the relative permeability is actually a little higher than the value obtained at the

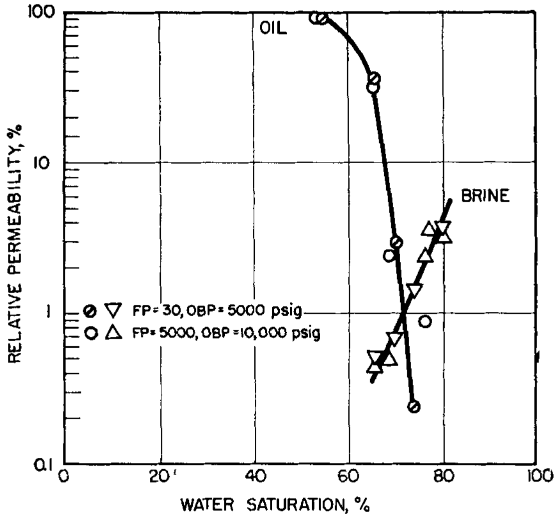


Fig. 7. Effect of high fluid pressure on relative permeability of core *A*.

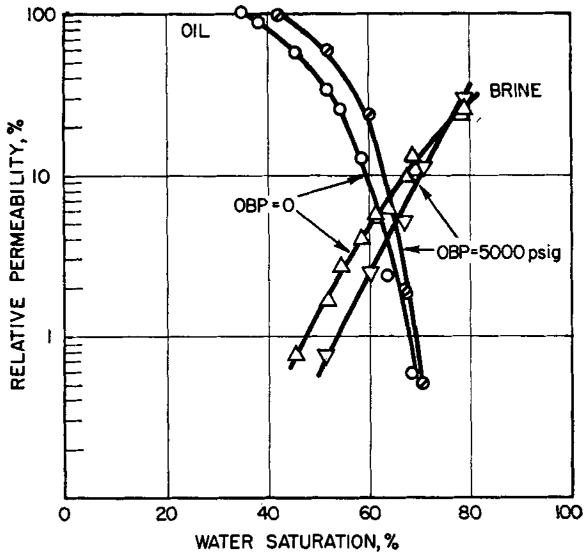


Fig. 8. Effect of overburden pressure on relative permeability of core *B*.

same water saturation, in percentage of pore volume, without overburden pressure. The complete relative permeability curves were then taken, approximately the same rates being used as were employed in the previous runs. The results are given in Figure 6. The oil relative-permeability curve is higher, and the water curve lower than the curves obtained without overburden pressure.

The overburden pressure was then slowly increased to 10,000 lb./sq. in. gauge. At the same time, pressure was applied to the fluids in the core, the difference between the overburden pressure and the fluid pressure being kept at approximately 5,000 lb./sq. in. during the process. *PVT* studies in this laboratory (*8*) on samples of kerosene similar to the oil employed in this work have shown that the effect of an increase in pressure from 30 to 5,000 lb./sq. in. gauge is to increase the viscosity by 58% and to increase the density by 3%. Measurements of the effective permeability of the core and of the filter F1 and of the radioactivity of the inlet cell before and after application of the fluid pressure agreed within experimental error with these values. Accordingly, they were employed in the saturation and permeability calculations. The effect of this pressure change on the viscosity of water is an increase of only 1% (International Critical Tables).

A relative-permeability run was then made at the elevated pressures, with somewhat lower oil-flow rates. A comparison of the results at high and low fluid pressure is given in Figure 7. Although the experimental errors are evidently larger in this apparatus than in conventional low-pressure equipment, it is nevertheless clear that the application of high fluid pressure had no significant effect on the relative-permeability behavior.

Core *B* was subjected to a similar study. This core was mounted with Aloxite distribution plates at each end and at the side pressure taps, and a Snow Floss diaphragm was built around the circumference of the core near one end for capillary desaturation only. Pertinent data on the core are given in Table 1. The effect of 5,000 lb./sq. in. gauge overburden pressure on the relative-permeability values is shown in Figure 8. The effect is approximately the same as observed with core *A*, except that relative permeabilities to brine at residual oil (calculated relative to the 100% brine permeabilities at corresponding overburden pressure) were little affected by the application of overburden pressure.

As the fluid and overburden pressures were being raised in preparation for the next phase of the study, the inlet oil line to the core ruptured, allowing the net overburden pressure on the core to rise abruptly to a value approaching 9,000 lb./sq. in. The overburden pressure was then dropped back to 5,000 lb./sq. in., and it was found that the permeability of the core had suffered a sharp decline. The effective permeability to oil at interstitial water saturation was now 19.3 md., as compared with 49 md. before. It seemed, however, to be very stable in this new condition, and two relative permeability runs at 30 lb./sq. in. gauge fluid pressure and 5,000 lb./sq. in. overburden pressure gave results in good agreement. The fluid pressure was then increased to 5,000 lb./sq. in., the overburden pressure to 10,000 lb./sq. in., and two runs were made at these pressures. The pressures were then dropped back to a fluid pressure of 30 lb./sq. in. gauge and an overburden pressure of 5,000 lb./sq. in., and a single run was made. All five runs were in good agreement (*see* Figure 9), and there was evidently no appreciable effect of high fluid pressure on the relative permeabilities. The core apparently suffered permanent mechanical change when the excessive overburden pressure was suddenly applied. This damage not only greatly reduced the effective permeabilities to oil and water, but changed the relative-permeability relationships (*compare* Figures 8 and 9).

Similar data are given in Figures 10, 11, and 12 for core *C*. Figure 10 shows an effect of overburden pressure quite similar to that observed on cores *A* and *B*. As with core *B*, some permanent change in the core took place when the fluid pressure and overburden pressure were first raised to 5,000 and 10,000 lb./sq. in. gauge, respectively, although this time there was no obvious cause (such as the breaking of a line, which occurred on core *B*). Relative-permeability curves taken before and after the first application of high fluid pressure are shown in Figure 11. The fluid pressure and overburden pressure were then dropped simultaneously to 30 and 5,000 lb./sq. in. gauge, and the relative permeabilities determined again. As shown in Figure 12, the results taken before and after the removal of the high fluid pressure agreed within experimental error.

The results for core *D* are given in Figures 13 and 14. The effect of overburden pressure was small, but in the same direction as on the other cores. The results at low and high fluid pressures agreed within experimental error.

Cores *C* and *D* were mounted without semipermeable pads and were desaturated initially, as well as between runs, by dy-

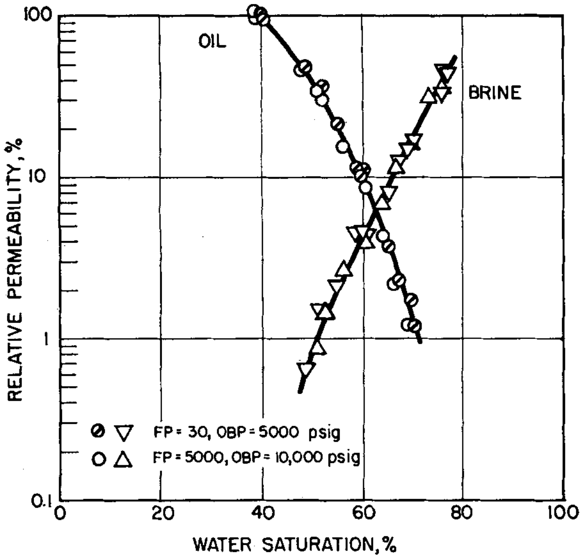


Fig. 9. Effect of high fluid pressure on relative permeability of core *B*.

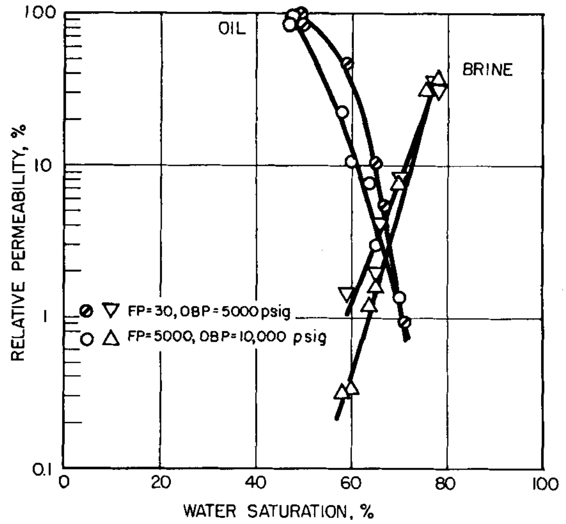


Fig. 11. Effect of first application of high fluid pressure on relative permeability of core *C*.

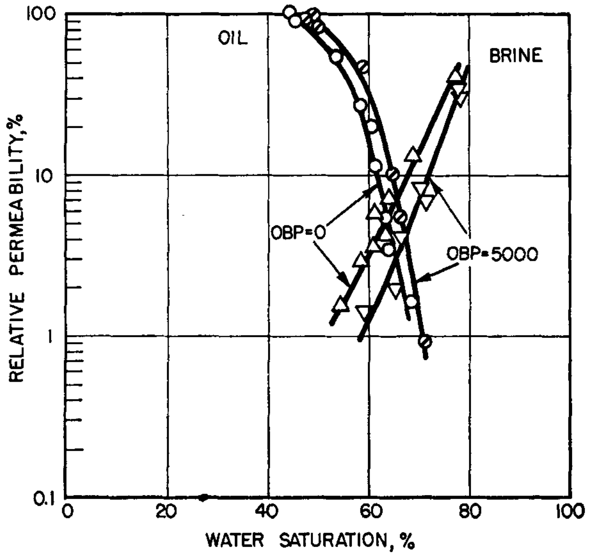


Fig. 10. Effect of overburden pressure on relative permeability of core *C*.

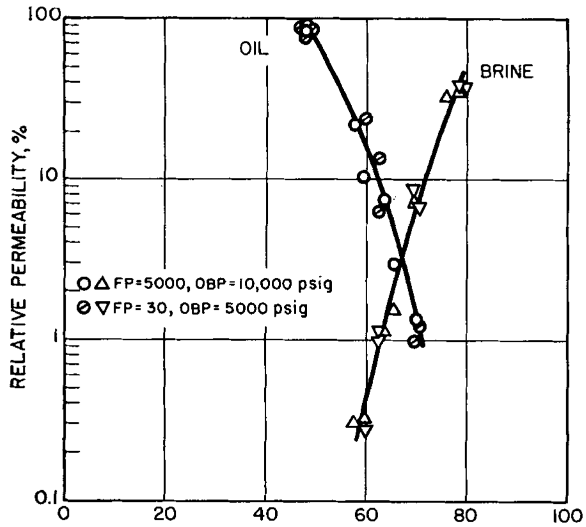


Fig. 12. Effect of removal of high fluid pressure on relative permeability of core *C*.

namic flow. The absence of compressible pads made it possible to determine the change in porosity by radioactivity measurements before and after the application of overburden pressure. The change for both cores was found to be 5% of the pore volume.

One run was made in this apparatus at elevated temperatures. Figure 15 shows a comparison of results of runs at low pressure on core *A* at 90° and 160°F. Although one point on the oil curve is out of line, this is probably the result of experimental error, and there is actually no significant effect of high temperature.

DISCUSSION OF RESULTS

The precision of these data is definitely less than can be obtained in conventional low-pressure equipment, but it is nevertheless clear that for the four cores studied here there was no significant effect of high fluid pressure as such on the relative permeabilities to oil and water. Although there is no real basis in the literature for predicting any appreciable effect, the mechanism of multiphase flow in porous media is so complex and little understood that actual experimental data are needed. It is possible that the drastic changes in cores *B* and *C* observed when the fluid pressure was first increased were a direct result of fluid pressure as such (for example, a change in wettability such as referred to above). However, the fact that the cores did not revert when the fluid pressure was removed would seem to indicate otherwise. The apparatus is now being modified so that gas may also be flowed, and a closer approximation to reservoir condition made.

Other work in this laboratory has shown some effect of a change in oil viscosity on effective permeability to water (*3*). However, these unpublished data indicate that the magnitude of the viscosity change caused by the application of 5,000 lb./sq. in. pressure to the oil employed in this study (from approximately 1.7 to 2.7 cp.) would change the relative permeability by an amount less than the experimental error. (It would shift the curve less than 1% on the saturation scale.) The effect of increasing the temperature to 160°F. on core *A* was to reduce the oil viscosity by 48% and the

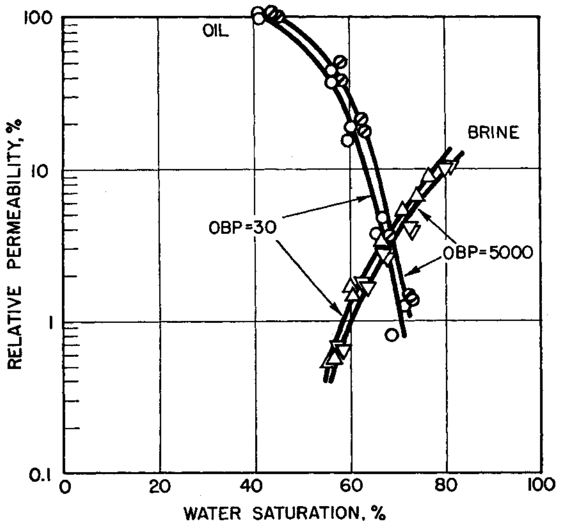


Fig. 13. Effect of overburden pressure on relative permeability of core *D*.

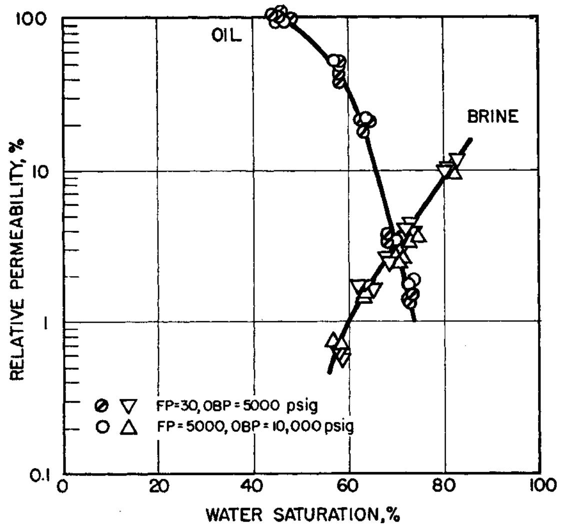


Fig. 14. Effect of high fluid pressure on relative permeability of core *D*.

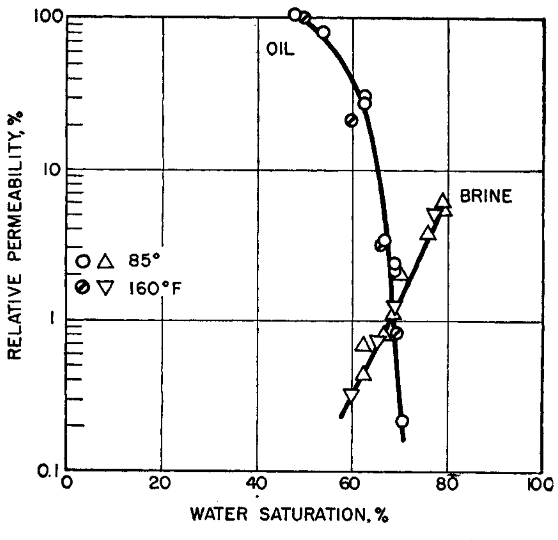


Fig. 15. Effect of temperature on relative permeability of core *A*.

brine viscosity by 50%, so that there was little change in viscosity ratio.

The application of overburden pressure reduced the effective permeabilities to oil and water to about the same extent as it did the single-phase permeability, and consequently the relative permeabilities were changed only moderately. The effect was, however, detectable in all cases. This is in contrast to the work of Fatt (*9*), who found no effect of 3,000 lb./sq. in. overburden pressure on relative permeability to gas in a gas-oil system. It might be expected that any distortion of a core sufficient to reduce the porosity by 5% would change the pore-size distribution significantly and thereby affect the relative-permeability relationships, but whether the expected change would be greater than the experimental error cannot be predicted in the absence of data. Some experiments to determine the change in pore-size distribution by capillary pressure measurements made with and without overburden pressure on the core are underway in this laboratory. Preliminary indications are that the effect is very slight.

It has been pointed out by Fatt (*10*) that the stress conditions in a Lucite-mounted core pressured by hydraulic oil may be different from those existing in a reservoir. The horizontal component of stress in reservoirs is probably less than the vertical component. This difference could influence in some degree the measurements of the effect of overburden pressure but should have no bearing on the conclusions regarding the effect of high fluid pressure.

ACKNOWLEDGMENT

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