Estimating Interstitial Water by the Capillary Pressure Method

BY O. F. THORNTON* AND D. L. MARSHALL,† MEMBERS AIME

(Galveston Meeting, October 1946)

ABSTRACT

Results of the determination of the interstitial water content of several core samples from oil reservoirs are presented. Data obtained by the capillary pressure method, which has recently been developed, are compared with water saturations measured in cores cut with oil-base mud and with values calculated from the electrical resistivity of the formation. The agreement between the capillary pressure and other methods, combined with the fact that similar agreement has been obtained by others, indicates that the capillary method properly applied yields results sufficiently accurate for most engineering purposes. In some cases, it may be possible to extend the utility of data obtained with the capillary pressure method by correlation of interstitial water saturation with more easily measured physical properties of the media.

INTRODUCTION

Several methods are in use for determining or for estimating the interstitial water saturation at given points within oil and gas reservoirs. The direct measurement of the water content of cores obtained with nonaqueous fluid in the hole is believed to be an accurate method under most conditions. The water saturation may be calculated by use of the resistivity curves of the electric log, but although this method is not applicable under conditions that exist in some reservoirs. Recently, a method has been developed and described wherein the interstitial water saturation of cores is measured at a capillary pressure such that conditions existing in the reservoir are simulated. The purpose of this paper is to present data obtained by use of this latter method, and to compare the results obtained with determinations made by other means.

METHOD

The theory underlying the capillary pressure method applied to petroleum reservoirs has been discussed adequately in the literature by Garrison, Leverett, and others. Briefly, and simply, capillary pressure is defined as the difference in pressure between two contacting fluid phases, such as oil and water. For the simplified sand, water and oil system illustrated in Fig 1, the pressure difference can be stated as follows:

\[
P_s = \gamma \left( \frac{1}{r_1} + \frac{1}{r_2} \right)
\]

where \(P_s\) is the capillary pressure in pounds per square inch, \(\gamma\) is the interfacial tension between oil and water in pounds per inch, \(r_1\) and \(r_2\) are the radii of curvature of the interface between oil and water in inches.

Capillary pressure varies in a given reservoir with depth because of the greater density of the water phase as compared with oil or gas. The following equation expresses the difference in pressure between two points:

\[
P_1 - P_2 = \frac{h \Delta \rho}{144}
\]

where \(P_1 - P_2\) is the capillary pressure difference in pounds per square inch, \(h\) is


* The Texas Company, Houston, Texas.
† The Texas Company, New Orleans, Louisiana.

References are at the end of the paper.
the vertical distance between the points in feet, and \( \Delta \rho \) is the difference in density between the water and oil or gas in pounds per cubic foot. If the capillary pressure at a laboratory under the capillary pressure existing at the depth from which the core was obtained, as computed from Eq. 2. The capillary pressure for the laboratory fluid system which is equivalent to that for the reservoir fluids at reservoir conditions may be computed from Eq. 1, so that the water saturation of the core as it is believed to have existed in the reservoir can be obtained by direct measurement.

**Procedure**

For the capillary pressure determinations described herein, core samples were selected from three wells in two Louisiana Gulf Coast reservoirs of Miocene age.

Well A, Fig 2, was drilled with conventional water-base mud to a depth of 8660 ft, where a string of 7-in. casing was set. The drilling fluid was then changed, and an oil-base mud was used in coring to the total depth of 8752 ft. The oil-base mud was replaced by the original mud before the hole was reamed so that the electric log obtained was comparable to that of other wells in the same reservoir. From representative samples of the cores recovered, determinations of water and oil saturations, salt content, porosity and permeability were made by conventional methods. Samples also were selected for capillary pressure determinations. Core samples also were obtained from two wells in another field. The cores were cut using water-base mud approximately three years prior to the capillary pressure determinations. The electric log of one of these wells designated as well B is shown in Fig 3.

The laboratory apparatus for the capillary runs was similar to that used by other investigators (Fig 4). It consisted of a metal cylinder, with a removable pressure tight cap through which pressure could be applied. The base of the cylinder was closed with a membrane which was permeable to water but impermeable to air at specified pressure differentials. Some of the mem-

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**Fig 1**—Illustrating curvature of water-gas interface (After M. C. Leverett).
branes first used were made of a thin layer of hydrated Wyoming bentonite on oilite bearing metal. Later, porous porcelain plates with high displacement pressures were used.

Potential

<table>
<thead>
<tr>
<th>Resistivity Meter Ohms</th>
<th>Interstitial Water Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0  2  4  6</td>
<td>0  20  40  60  80</td>
</tr>
</tbody>
</table>

T.D. 8752'

Fig 2—Log of well A, showing location of core samples (electrode spacing 16 inches).

Cores were cut to convenient size, extracted with carbon tetrachloride and acetone to remove oil, and dried to constant weight over anhydrous CaSO₄. The bulk volumes of the samples were measured, and the porosities were either determined with a gas-type porosimeter or assumed to be the same as those of duplicate samples previously analyzed. Some of the more friable samples were coated with cellulose acetate cement to prevent their crumbling.

The samples were saturated by placing them in water and by then applying a vacuum to the containing vessel. By this method, saturations of 80 to 90 pct of the porosity were obtained in a short time. It was found that water of sufficiently high ionic concentration to prevent hydration of clay particles should be used. Erratic results were obtained using a 5 pct sodium chloride solution, particularly with core samples containing large amounts of clay. In the measurements described herein, for-

mation water that had been filtered to remove iron oxides and treated to kill bacteria was used with satisfactory results.

After the samples were saturated and weighed, they were placed on the membranes in the core holders and a constant air pressure was applied through the opening in the top cover. When equilibrium was signified by constant weight of the core sample, the water saturation of the core was computed by difference between the dry weight and the weight of the partially saturated core.

The water phase was continuous from the core through the semipermeable plate, and the pressure on that phase was that of the atmosphere. The pressure difference between the air and water phase, or the
capillary pressure, was therefore equal to the gauge pressure of the air.

**Experimental Results**

Shown in Fig 5 are typical results of a series of equilibrium water saturations at various capillary pressures. The curves are similar to the desorption loops of the pressure saturation curves obtained by others\(^5,^6,^7\) consisting of a horizontal seat, a region of sharp curvature, and a vertical portion. The horizontal seat is approximately equivalent to the displacement pressure, below which pressure the core is saturated with water. In a reservoir, this may be thought of as the water level. For the vertical portion of the curve, very little change in saturation occurs for large changes in pressure, and an "irreducible" water saturation is approached. This corresponds to the productive zone of a reservoir. The region of sharp curvature corresponds to the transition in a reservoir from the water level to the oil or gas-producing zone.

Table 1 summarizes the results obtained from analyses of 20 samples from well A, taken at depths shown on Fig 2. The laboratory values of capillary pressure equivalent to the capillary pressures in the reservoir at the proper depths are shown. The capillary pressure at each depth was computed by means of Eq. 2, assuming...
the pressure at the water level of the reservoir (8773 ft) was equal to 1.5 psi. The densities of reservoir fluid and reservoir water were 31.8 and 67.4 lb per cu ft, respectively.

Since air was used rather than reservoir fluid in these experiments, it was necessary to compute the capillary pressure in the laboratory system which was equivalent to the "reservoir" capillary pressure. For this purpose it was assumed that the contact angle and radii of curvature were the same at a given water saturation for either the laboratory or reservoir fluid system. From Eq. 1, the correction factor by which the pressures computed as above from Eq. 2 should be multiplied is the ratio of the interfacial tensions of the two systems. From the data of Hocott, this factor was estimated as two and two thirds.

Fig 5 shows that the capillary pressure values calculated as above correspond to the vertical portions of the curves, or practically to the "irreducible" water saturation. In other words, the cores were taken from a distance sufficiently far above the water level to be outside the transition zone.

Values are shown in Table 1 for the interstitial water saturation of each core obtained: (1) by retort distillation at above 400°F; (2) by calculation from the salt content (obtained by titration) of the core and known salinity of the reservoir water; and (3) by the capillary pressure method.

The retort distillation values are higher than those obtained by the other two

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**Table 1.—Water Saturation, Well A**

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Permeability, Mds</th>
<th>Porosity, Pct</th>
<th>Distance Above Water Level, Ft</th>
<th>Laboratory Pressure, Psi</th>
<th>Interstitial Water Saturation, Pct of Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1) By Distillation</td>
</tr>
<tr>
<td>1</td>
<td>29</td>
<td>17.0</td>
<td>78</td>
<td>59</td>
<td>89</td>
</tr>
<tr>
<td>2</td>
<td>312</td>
<td>20.3</td>
<td>74</td>
<td>50</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>382</td>
<td>22.3</td>
<td>70</td>
<td>53</td>
<td>52</td>
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<td>4</td>
<td>518</td>
<td>28.1</td>
<td>66</td>
<td>50</td>
<td>29</td>
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<tr>
<td>5</td>
<td>250</td>
<td>23.0</td>
<td>61</td>
<td>47</td>
<td>53</td>
</tr>
<tr>
<td>6</td>
<td>263</td>
<td>16.0</td>
<td>54</td>
<td>41</td>
<td>73</td>
</tr>
<tr>
<td>7</td>
<td>2,536</td>
<td>27.2</td>
<td>51</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>23</td>
<td>20.0</td>
<td>48</td>
<td>37</td>
<td>82</td>
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<tr>
<td>9</td>
<td>319</td>
<td>25.7</td>
<td>43</td>
<td>33</td>
<td>44</td>
</tr>
<tr>
<td>10</td>
<td>1,830</td>
<td>31.1</td>
<td>40</td>
<td>31</td>
<td>19</td>
</tr>
<tr>
<td>11</td>
<td>550</td>
<td>27.1</td>
<td>37</td>
<td>29</td>
<td>47</td>
</tr>
<tr>
<td>12</td>
<td>1,490</td>
<td>27.2</td>
<td>35</td>
<td>27</td>
<td>44</td>
</tr>
<tr>
<td>13</td>
<td>1,118</td>
<td>31.0</td>
<td>33</td>
<td>26</td>
<td>30</td>
</tr>
<tr>
<td>14</td>
<td>1,730</td>
<td>32.0</td>
<td>32</td>
<td>25</td>
<td>47</td>
</tr>
<tr>
<td>15</td>
<td>540</td>
<td>27.9</td>
<td>31</td>
<td>24</td>
<td>35</td>
</tr>
<tr>
<td>16</td>
<td>1,048</td>
<td>28.0</td>
<td>30</td>
<td>24</td>
<td>36</td>
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<tr>
<td>17</td>
<td>410</td>
<td>27.5</td>
<td>29</td>
<td>23</td>
<td>38</td>
</tr>
<tr>
<td>18</td>
<td>1,060</td>
<td>27.4</td>
<td>28</td>
<td>23</td>
<td>33</td>
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<tr>
<td>19</td>
<td>2,238</td>
<td>29.6</td>
<td>24</td>
<td>20</td>
<td>36</td>
</tr>
<tr>
<td>20</td>
<td>1,120</td>
<td>30.9</td>
<td>22</td>
<td>19</td>
<td>32</td>
</tr>
</tbody>
</table>

Average ................................................. 43   36   35   -1.3
methods for some of the cores, but there is good agreement between the salinity and capillary methods. The higher values obtained by distillation probably are attributable to removal of bound water (called “water of crystallization” by some investigators) caused by the high temperature attained in the retorts. This bound water contains no salt, while the “capillary” water salinity should be the same as that of bottom water. It is believed the salt content of these core samples is a more reliable index of the interstitial water saturation than the values obtained by retort distillation.

![Graph](image)

**Fig 5—Typical pressure-saturation curves for well A.**

Table 2 summarizes results obtained by the capillary pressure method applied to core samples from well B (Fig 3), compared with results calculated from the long normal resistivity curves. The water level in the reservoir from which these core samples were obtained
was sufficiently far below the lowest core so that the capillary pressures corresponded with the vertical portion of the curve as described for well A.

Calculations were made from the electric log in the manner described by Archie,\textsuperscript{1} using measured values for water resistivity and formation factor. It was assumed there was no effect of invasion of mud filtrate upon the measured resistivity, but correction was made for the presence of the bore hole. The beds were thick enough so that the effect of formation thickness could be neglected.

**Discussion of Results**

The agreement between the capillary pressure and other methods shown herein, combined with the fact that similar agreement has been obtained by others, indicates that the capillary method properly applied yields results sufficiently accurate for most engineering purposes.

**Table 2.—Water Saturation, Well B**

<table>
<thead>
<tr>
<th>Depth, Ft</th>
<th>Resistivity Apparent</th>
<th>Meter X Ohms Corrected</th>
<th>Formation Factor</th>
<th>Interstitial Water Saturation, Pct of Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,162–10,172</td>
<td>10</td>
<td>9</td>
<td>10.0</td>
<td>19</td>
</tr>
<tr>
<td>10,187–10,195</td>
<td>24</td>
<td>18</td>
<td>7.3</td>
<td>11</td>
</tr>
<tr>
<td>10,195–10,210</td>
<td>32</td>
<td>23</td>
<td>7.3</td>
<td>10</td>
</tr>
</tbody>
</table>

* The resistivity of reservoir water was 0.031 meter X ohms at 20°C.

\textsuperscript{1} Average of five samples.

\textsuperscript{2} Average of four samples.

\textsuperscript{3} Average of seven samples.

**Table 3.—Use of Electric Log—Well A**

<table>
<thead>
<tr>
<th>Depth, Ft</th>
<th>Net Sand, Ft</th>
<th>Formation Factor</th>
<th>Interstitial Water Saturation, Pct of Porosity*</th>
</tr>
</thead>
<tbody>
<tr>
<td>8,665–8,668</td>
<td>3</td>
<td>9.3</td>
<td>26</td>
</tr>
<tr>
<td>8,692–8,693.5</td>
<td>1.5</td>
<td>9.3</td>
<td>43</td>
</tr>
<tr>
<td>8,697–8,705.5</td>
<td>7.5</td>
<td>9.3</td>
<td>37</td>
</tr>
<tr>
<td>8,707–8,716</td>
<td>9.0</td>
<td>9.3</td>
<td>37</td>
</tr>
<tr>
<td>8,721–8,724</td>
<td>3.0</td>
<td>9.3</td>
<td>34</td>
</tr>
<tr>
<td>8,724–8,727.5</td>
<td>3.0</td>
<td>9.3</td>
<td>39</td>
</tr>
<tr>
<td>8,729.5–8,730.5</td>
<td>1.0</td>
<td>9.3</td>
<td>37</td>
</tr>
<tr>
<td>8,731–8,736</td>
<td>5.0</td>
<td>6.9</td>
<td>21</td>
</tr>
<tr>
<td>8,737–8,739</td>
<td>2.0</td>
<td>6.9</td>
<td>30</td>
</tr>
<tr>
<td>8,740–8,745</td>
<td>5.0</td>
<td>6.9</td>
<td>24</td>
</tr>
<tr>
<td>8,745–8,752</td>
<td>7.0</td>
<td>6.9</td>
<td>27</td>
</tr>
</tbody>
</table>

Weighted average.......... | 31.5 |

* Values from salinity method, Table 1.
The capillary method is not applicable in many older fields for which sufficient core samples are not available for a representative portion of the reservoir. Also, the method is somewhat time consuming and cumbersome; although it is likely that use of the centrifuge method\(^7\) and other experimental short cuts will be developed and applied in the near future.

In some cases, however, interstitial water determined by the capillary method for one or two wells may, by correlation with some other measured physical property, serve as a basis for estimating average water saturation at other points in the same reservoir.

A plot of interstitial water versus specific permeability for samples from well A is shown on Fig 6, and for well B on Fig 7. The data for well A include the determinations made by the salt-content method for samples in addition to those shown in Table 1. Fig 7 includes data from well C, which is in the same reservoir as well B but across the structure approximately 1½ miles.

Both correlations show a general trend, although there is considerable scattering. The average curves shown on the two figures show different values for water saturations of cores with the same permeability, which emphasizes that permeability-water saturation curves should not be used indiscriminately to estimate water saturations in a given reservoir.

In some instances where interpretation of the electric log is difficult, the capillary method may be used to "calibrate" interpretation of the log. Table 3 shows results of such an application to well A, in which the reservoir consisted of interbedded sand, sandy shale, and shale (Fig 2). It was found that fair agreement between interstitial water content calculated from the electric log and that obtained by the capillary method could be obtained if the log was interpreted as follows: use the resistivity recorded with normal electrode arrangement and 16-in. spacing, assume no invasion, no bed-thickness correction, value for formation factor\(^1\) based on \(m\) of 1.5, resistivity of water equal to 0.30 ohm meters, and observed average porosities.

Electric logs usually are available for all wells and show the entire section, while core samples usually are not available from
many wells and core recovery seldom is complete. It is suggested therefore that the capillary pressure and electric log methods may be used together to advantage in determining the distribution of water in some reservoirs.

CONCLUSIONS

From the results herein and those of other investigators, it is concluded that the capillary method may be used to determine the interstitial water content of sands at points above the transition zone. No data are available for limestones or for points within the transition zone for sandstone reservoirs.

The range of utility of the capillary pressure method may be extended by use of correlations between interstitial water content and more easily measured physical properties of the media, such as permeability and electrical resistivity.

ACKNOWLEDGMENT

We wish to acknowledge the services of Messrs. C. B. Scotty and J. B. Glenville, who performed the laboratory measurements of interstitial water. Appreciation is expressed for the suggestions of Dr. W. V. Vietti, under whose supervision the work was done, and to The Texas Company for permission to publish the paper.

REFERENCES

5. M. C. Leverett: Trans. AIME (1941) 142, 152.

DISCUSSION

E. F. STRATTON*—Mr. Thornton and Mr. Marshall are to be complimented for their significant contribution to our limited, but growing knowledge, of the capillary-pressure technique for determining interstitial water. It has been suggested elsewhere that the interstitial water existing in an actual reservoir might be higher, owing to processes of oil accumulation, than the "irreducible" water obtained from capillary-pressure measurements. The comparison of results obtained by the several methods for determination of interstitial water indicates that the capillary-pressure procedure does duplicate reservoir conditions.

The electric log resistivity curve in many uniform reservoirs with bottom water shows a very sharp change from the oil or gas zone to the water-bearing portions. This would indicate that the "transition" zone is short. On the other hand, vertical changes in the physical properties, for example permeability, of the reservoir may serve to lengthen the transition zone appreciably.

The agreement between determinations of interstitial water by the capillary-pressure method and by electric-log analysis demonstrates that the latter technique can be used in many cases to obtain data quickly and at low cost.

The short-spacing resistivity values and the lack of correction factors for the mud, the borehole, and bed thickness in the electric-log analysis of well A, should not be considered a general application. Conditions existing in this well undoubtedly were favorable for their technique; the procedure used for well B is certainly to be preferred.

G. FANCHER*—The authors are congratulated for an excellent paper on a timely subject of great practical importance, as well as theoretical interest.

We have had some experience with the capillary-pressure method of determining connate water at the University of Texas, employing methods and apparatus like those of Thornton and Marshall, and have found the methods reliable and useful for teaching purposes. We have had little opportunity to check the methods because we do not core wells and have available cores obtained while using oil-base muds. Our cores come from here and there, from friends, and usually

* Schlumberger Well Surveying Corporation, Houston, Texas.

* University of Texas, Austin, Texas.
we know little about them, but they serve our purpose of instruction and experimentation. Curiously, the first sample run in our laboratory by the capillary-pressure method was a very old piece of Woodbine sand cored during the boom in the East Texas field. We also had Woodbine salt water from the East Texas field available. Enjoying typical beginners’ luck, we found from the capillary-pressure curve a connate water saturation of 16.5 pcf, a value agreeing nicely with that determined from the electrical log by Archie of 15 pcf and the commonly accepted value of 17 pcf from analytical determinations.

The authors apparently had difficulty developing a connate water saturation greater than 90 pcf by the technique of immersing samples in water and pulling a vacuum on the submerged samples. We have had little difficulty developing water saturation of 95, 98, and even 99 pcf by applying a high vacuum to the dry samples for an hour or so and then introducing sufficient water into the evacuated flask to cover the samples before removal of the vacuum. Of course, this point is academic in that, as Hassler shows, a saturation of 85 to 90 pcf is sufficient to yield reproducible results upon desaturation in capillary-pressure tests. Nevertheless, if saturations greater than 85 to 90 pcf are wanted, they can be obtained.

We agree with the authors that these tests should be made with salt water from the particular formation, if possible, and, in any event, with water of equal salinity.

Although the explanation attributing the consistently higher connate water saturation by the retort method to bound water is plausible, Dr. Hill in a comprehensive investigation of various methods of determining fluid saturations at Penn State found that so-called “water of crystallization” saturation ranged only from 1.4 to 2.5 pcf for samples of the Bradford sand, a notoriously dirty sand, ranging in porosity from 10.6 to 17.6 pcf, and in connate water saturation from 12.5 to 38.7 pcf.

The authors have demonstrated the value of the capillary-pressure method in determining the connate water saturation above the transition zone. Although the method is tedious, the practical suggestion to employ the capillary tests to calibrate interpolation of parameters more easily and speedily measured is excellent, and we can look forward, I believe, to further development of these ideas. I believe capillary-pressure tests offer so valuable a check that soon they will be routine in core-analysis work. The challenging problem now is the transition zone. First, we need reliable information as to the actual thickness of such zones. If, in general, the transition zone is thin, we need not worry. If, as is likely, it may approach in thickness the oil-bearing zone of irreducible connate water content, to say nothing of the producing zone that is entirely a transition zone, research workers must get busy on accurate determinations and correlations of contact angles; a baffling subject, to say the least.

J. E. Sherborne*—The paper by Thornton and Marshall is a significant contribution to petroleum technology, for it supplements previous papers in substantiating that the capillary-pressure method of determining interstitial water yields results that are representative of conditions actually existing within large portions of our oil-bearing reservoirs. It would appear that sufficient determinations have been made by Messrs. Thornton and Marshall and others over a wide enough range of conditions to justify the wide-spread use of this procedure as a standard laboratory test for the determination of interstitial water.

The fact was noted with interest that the writers obtained erratic results when the water used in the testing by this procedure was of low ionic concentration. It has been the experience in our laboratory that the final equilibrium saturation is affected by the ionic concentration of the brine used. In fact, for most of the samples investigated, there is a distinct shift to a lower equilibrium saturation with an increase in brine saturation. In our experience, however, the shifting has been uniform, so that a family of uniform curves is obtained rather than a series of erratic points. The samples we have examined in this manner, however, all contained rela-

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* Union Oil Company of California, Santa Fe Springs, California.
tively large quantities of argillaceous material. The writers' discussion, relative to a comparison between the water saturation of the cores, as obtained by the various methods, is interesting. As is to be expected, the value to be obtained by retorting is somewhat higher than that obtained by the capillary method, but apparently no correction was made for the bound water, which undoubtedly was driven off in the retort process. For precise comparisons, the ASTM method of determining water saturation has been used in our laboratory rather than the retort, since with this method bound water is not liberated and rather close comparisons have been obtained. It has not been possible to obtain reasonable interstitial water values from salinity determinations for the great majority of California cores examined.

It has been our experience that, for the type of cores and fluids encountered under California conditions, cleaning with carbon tetrachloride sometimes apparently does not suffice to remove all of the adsorbed material from the surface of the grains, and it has been found that a further leaching with dioxan has been helpful.

As the authors point out, the procedure is time consuming if enough points are obtained to establish the shape of the capillary-pressure curve; however, it would appear to be their experience, and that of others, that for the large part of the oil-bearing reservoir, under commonly encountered conditions, a value obtained at a sufficiently high pressure so that the saturation will be on the flat part of the curve approaching the "irreducible saturation" would be all that would be necessary. Thus, the choice of some suitable standard pressure, such as for example 30 or 40 lb, would probably in most instances yield a good engineering answer and would materially speed the analysis.

It is hoped that this excellent paper will stimulate more universal use of this method of obtaining much needed information on interstitial water.

**Paul Weaver**—In this paper, mention is made that some core samples contained a large amount of clay (p 71). It would seem that much more information could be obtained for comparison with future observations if the cores tested by various methods in the laboratory were photographed so that the type of distribution of sand grains and the distribution of the clay in the core could be seen graphically.

In discussing the reservoirs that are sandstones, mention is frequently made of the sand being "dirty" or "clean," referring apparently to varying amounts of clay in the sand. Not only the amount of such clay is significant as regards both horizontal and vertical permeability, but also its distribution, because in some sands it forms definite layers separated by sand of fairly uniform and large grain size. In other sands, it is distributed in the space between the sand grains. A record of the type of clay distribution, therefore, would aid in interpreting permeability measurements of cores.

**J. M. Robinson**—The authors are to be commended for a direct examination of the important problem of determination of the interstitial water saturation of oil sands. The capillary-pressure method for estimating the interstitial water saturation of oil sands is a valuable tool in reservoir studies.

The correlation between permeability and interstitial water saturation must be used with care, as stated by the authors. It has been noted that in such a correlation, increase in the number of data available tends to increase the spread of the points until the relationship becomes merely a trend.

It was reported that saturations of from 80 to 90 pct of the pore space were obtained when saturating the core samples with formation water in capillary-pressure tests. This is in agreement with results in laboratory flooding tests on fresh core samples, in which tests, total saturations vary from 85 to 95 pct of the porosity.

**N. Van Wingen**—Messrs. Thornton and Marshall's paper is of particular interest in that it presents additional field data com-

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* Chief Geophysicist, Gulf Oil Corporation, Houston, Texas.  
† Richfield Oil Corporation, Los Angeles, California.
paring the results of various methods for estimating interstitial water saturations. It is to be hoped that others will feel similarly prompted, as only the availability of numerous data of this nature for many reservoirs of several types will establish definitely whether or not the minimum saturation values, as obtained by the capillary method, can be considered to be representative of true reservoir interstitial water values. In other words, the point to be established is whether oil reservoirs in general are in such a state of capillary equilibrium that their interstitial water content is truly "the irreducible minimum."

Another important consideration in this regard is the formation of an adequate concept regarding the thickness of transition zones. Thin transition zones are suggested on the basis of the work of Katz, Monroe and Trainer as they conclude that the magnitude of water-oil interfacial tension in most reservoirs may have been generally overestimated. In support of this contention, it is of interest to note the results of Thornton and Marshall's well A, where comparable saturations for various methods were obtained to within 22 ft of the oil-water interface. It would be of interest if the authors could similarly identify the position of the water level in their well B.

O. F. Thornton (author's reply)—The water level in the sand of well B is at a depth corresponding to 10,230 ft, or 20 ft below the lowest core sample analyzed.