Waterflood Relative Permeabilities in Composite Cores

By: J.D. Huppler
Esso Production Research Co. Houston, TX, USA

When cores longer than about 3 in. are desired for waterflood testing, it is common to assemble a composite core from a set of short core pieces. Long composite cores reduce the importance of capillary effects such that lower flooding rates can be used. Composite cores are also useful where end effects would invalidate results from tests on individual short cores. The assumptions made in using such a composite core for waterflood testing are that all the core sections: (1) have nearly identical relative permeability curves, (2) are homogeneous and isotropic, and (3) have nearly identical connate water and residual oil values. It is further assumed that there is good contact between sections and that the flooding rate is high enough to make capillary pressure effects unimportant in all core sections.

When these assumptions are met, we can make several assertions based on analysis of the one-dimensional, two-phase flow equations. The water-saturation distributions throughout a flood are the same in a composite core as in a single homogeneous core having the average properties of the composite, no matter what ordering of core sections is used in the composite. (If the porosites of the segments have much variation, one must first multiply lengths in the jth segment by $\phi_j/\phi_{composite}$ to normalize the porosity-length product.) Production histories are also the same for any ordering of core segments. Thus experimental waterflood relative permeability ratios may be quite accurate for any ordering.

The individual-phase relative permeability curves calculated from composite waterflood data may be in error. Neglecting capillary pressure and assuming a one-dimensional displacement, we have at any point in the core:

$$-k\left(\frac{dP}{dx}\right) = \frac{(q/A)}{\left(\frac{k_{ro}}{\mu_o}+\frac{k_{rw}}{\mu_w}\right)} \quad . \qquad (1)$$

The right-hand side of Eq. 1 is generally saturation dependent, so the pressure gradient at each point and the pressure drop across each core section depends upon the saturation distribution within that section. If the right-hand side of Eq. 1 decreases with increasing water saturation, then placing tighter-than-average core sections near the outlet end causes ΔP across the core to be too large. Hence, pressure distributions within the composite, and pressure drop across the composite, depend upon the arrangement of the individual sections and will differ from corresponding values in the homogeneous core. Therefore, calculated relative permeabilities, which depend upon ΔP across the core, will depend upon the arrangement of individual sections.

We suggest that the core sections should be ordered such that the harmonic-average permeability between sections is as close as possible to the over-all average permeability for the composite. Also, those sections having average permeabilities that are closest to the over-all permeability should be located near the end of the composite, where the pressure gradient is greatest.

For n segments of similar length, a satisfactory ordering scheme that effects the desired arrangement of permeabilities is as follows:

1. Start ordering at the end of the composite where the pressure gradient will be most important (the outlet end if, after water breakthrough, ΔP across the core decreases with time).
2. Let the harmonic-average permeability of all sections through the jth section be:

$$k_j = \sum_{i=1}^{j} L_i \Big/ \sum_{i=1}^{j} \frac{L_i}{k_i} \qquad (2)$$

where L_i are section lengths.

3. Order the sections so that:

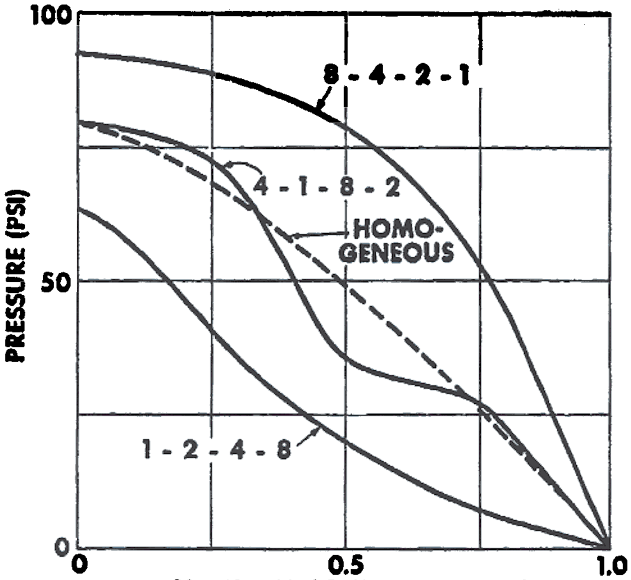

Fig. 1—Pressure distributions in composite cores with different orderings of section permeabilities, after injection of 0.83 PV.

$$F = \min\left[\frac{k_n}{n}\left(\sum_{j=1}^{n}\frac{1}{k_j}-\frac{1}{k_n}\right)\right]. \quad (3)$$

As new sections are added, this intuitively plausible scheme keeps the average permeability of the partially assembled composite closest to the over-all composite permeability. It weights most heavily the permeabilities near the end of the composite where the pressure gradient is most important.

To test the validity of the proposed ordering scheme, waterflood simulations were performed using one-dimensional, two-phase difference equation approximations to describe immiscible water-oil displacement. The difference equations, which were implicit in water pressure and capillary pressure, were solved using a Newtonian residual iteration scheme[1] with the alternating direction iteration procedure (ADIP).[2] For each simulation, the permeability and porosity distribution of the heterogeneous core to be studied was specified; fluid flow characteristics of the system, including a single set of input relative permeability curves, were stipulated. Then the waterflood simulation was performed. From the resulting fluid production and pressure drop data, a set of "waterflood" relative permeability curves was calculated using the standard computational procedure applicable to homogeneous cores.[3] With this procedure, the waterflood relative permeability curves should closely match the input curves for homogeneous systems. Since the same set of input relative permeability curves was used for all rock sections, deviations of the waterflood curves from the input relative permeability curves gave an indication of the effects of heterogeneities.

TABLE 1—ORDERING OF COMPOSITE CORE SECTIONS

Ordering of Section Permeabilities	F (from outlet end)
1-2-4-8	0.43
8-4-2-1	0.49
4-1-8-2	0.136

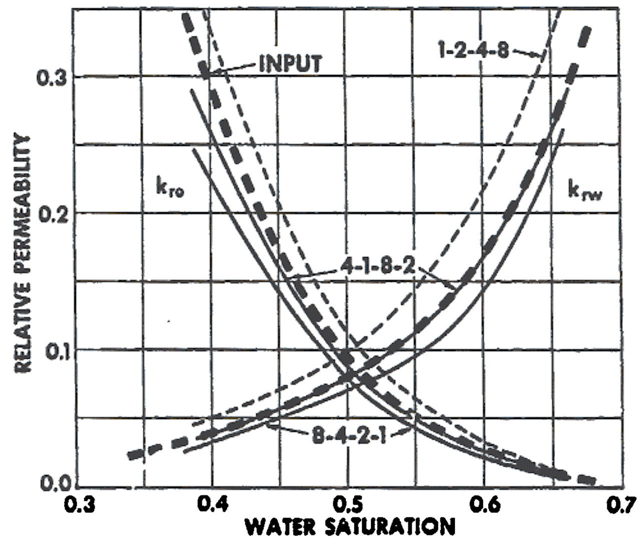

Fig. 2—Waterflood relative permeabilities from simulated waterfloods of composite cores with different orderings of section permeabilities.

Waterflood simulations were performed for a composite of four strongly water-wet core sections equal in length and having permeabilities in the ratios 1:2:4:8. Each section met the requirements for a valid composite section as listed above. Simulations were performed at a stabilized flooding rate using a 20:1 oil/water viscosity ratio, with the sections ordered as shown in Table 1. For comparison, flow through a homogeneous core with the harmonic-average permeability of the composite core ($k = 2.13$) was studied.

Results of the simulated waterfloods on these cores showed that saturation distributions and production curves were similar for all cases but that the pressure distributions (Fig. 1) were different. Calculated relative permeability curves (Fig. 2) were high for the 1-2-4-8 arrangement, low for the 8-4-2-1 arrangement, and nearly correct for the 4-1-8-2 arrangement. The F values calculated using Eq. 3 and listed in Table 1 support the proposed ordering criterion, since accurate relative permeabilities were obtained from the simulated waterfloods where the ordering of core sections gave low F values. Results of further composite core studies indicated that experimental relative permeability errors of less than 15 percent could be expected for $F < 0.2$.

References

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3. Johnson, E. F., Bossler, D. P. and Naumann, V. O.: "Calculation of Relative Permeability from Displacement Experiments", *Trans.*, AIME (1959) **216**, 370-372.

J. D. Huppler, SPE-AIME
Esso Production Research Co.
Houston, Tex.