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OBTAINING RELATIVE PERMEABILITY DATA USING A COMBINATION OF STEADY-STATE AND UNSTEADY-STATE COREFLOODS

by

J. L. Shafer, E. M. Braun, A. C. Wood III, and J. M. Wooten

Exxon Production Research Company
Houston, Texas

ABSTRACT

Oil-water relative permeability curves are commonly measured on core samples in the laboratory by either steady-state or unsteady-state fluid displacement techniques. Experimentally, the unsteady-state waterflood is the simpler technique; however, the valid interpretation of unsteady-state data depends on the flood being unaffected by viscous fingering and core heterogeneity. If such non-ideal effects are significant in an unsteady-state waterflood, the calculated relative permeability curves can have serious errors. A second drawback of the unsteady-state method is that it fails to provide data near irreducible water saturation.

By combining the steady-state and unsteady-state techniques in a single experiment, we have been able to obtain relative permeability data that would not be available from either technique separately. In the combined experiment, steady-state measurements are made by pumping oil and water through the core simultaneously. The steady-state measurements are followed by an unsteady-state waterflood, without returning the core to low water saturation.

Three examples of applying these techniques are presented, each illustrating a different advantage of combining steady-state and unsteady-state measurements.

INTRODUCTION

Neither the steady-state (SS) method nor the conventional unsteady-state (USS) waterflood methods provide relative permeability data at all saturations that will exist in the reservoir during its productive life. The steady-state technique is limited in the data it provides near residual oil saturation, whereas unsteady-state waterflood tests do not provide relative permeability data near irreducible water saturation.

To obtain steady-state measurements near residual oil saturation requires pumping oil and water simultaneously through the core at very low oil fractional flows; however, there are two difficulties associated with achieving uniform low oil fractional flows. The first of these is due to limitations of the pumping system in accurately controlling the oil flow rate. The second problem is caused by non-uniform oil entry into the core face; at a very low rate, it may enter as pulses, which can adversely affect the pressure drop across the core.

In the case of the unsteady-state waterflood, no relative permeability data are obtained before water breakthrough. As a result, no data are obtained near the irreducible water saturation. Also, valid interpretation of unsteady-state test data requires the core to be homogeneous and the fluid displacement to be uniform. If these conditions are violated, significant errors in calculated relative permeability values may result.

To obtain relative permeability information over a wide range of water saturations, we have used steady-state and unsteady-state techniques in combination. Measurements were conducted on both single plugs and composite cores.

THEORETICAL BACKGROUND

Buckley and Leverett (1942) and Welge (1952) presented equations for the speed at which a plane of constant saturation moves during two-phase flow in a porous medium. These equations are most commonly applied to the case in which the porous medium is initially at irreducible water saturation. However, as discussed by Craig (1971), the same equations are also applicable to situations in which the water is mobile at the start of the flood. One such situation occurs when an unsteady-state waterflood test is conducted following two-phase steady-state flow of oil and water.

Buckley and Leverett's equation for the distance moved by a plane of constant saturation as a result of water injection is

$$\Delta u = \frac{Q_T}{\phi A} \frac{df_D}{dS_D} \quad .$$

It is important to note that the initial water saturation does not appear in this equation. Therefore, at any position in the swept portion of a waterflooded core, the saturation is a function of the fractional flow curve and the amount of water injected, but not of the initial water saturation. It follows that two identical cores, one initially at irreducible water saturation and the other at a higher water saturation, will have the same saturation profile in the swept region after injection of equal volumes of water. The same holds true for the fluid pressure as a function of position.

Of course, in the unswept area ahead of the displacement fronts, the two cores will have different saturations, equal to their respective initial saturations. Thus, the saturation profiles in the two cores do not become identical until the injected water has affected the saturations along the entire length of both cores.

The Johnson-Bossler-Naumann (1959) (JBN) method is widely used for deriving relative permeability results from the saturation and pressure drop data measured during unsteady-state corefloods. Given the insensitivity of saturation profiles and pressure gradients to the initial water saturation, it follows that the results obtained from the JBN method are also insensitive to the initial water saturation. Indeed, nowhere do Johnson, Bossler, and Naumann state that proper application of their method requires the core to be in a given saturation condition at the start of a flood.

Figure 1 illustrates typical average saturation data that would be obtained in USS waterfloods of two identical cores, one initially at irreducible water saturation and the other following steady-state two-phase flow. For the first core, the curve starts at point A, the irreducible water saturation. Before breakthrough of the injected water, the slope of the curve is one, representing one volume of oil produced for every volume of water injected. Breakthrough occurs at point B, where the oil fraction in the produced flow stream (and thus the slope of the curve) drops sharply. With further water injection, there is a further continuous decline in oil fractional flow.

For an USS waterflood following steady-state flow, the curve starts at point C, representing an intermediate water saturation. The slope of the curve from point C to point D (breakthrough) is less than one and equal to the fractional flow of oil used during the steady-state portion of the test. At breakthrough, there may or may not be a discrete change in slope, depending on whether a displacement front forms during the flood. This is discussed further by Craig

(1971). Following breakthrough, the slope of the curve decreases continuously, representing a declining fraction of oil in the fluid produced from the core.

The part of the curve beyond point B represents the portion of each flood in which the entire core has been affected by the injected water; the curves for the two cores overlay in this region. JBN analysis of this portion of the curve would yield the same relative permeability data for the two floods.

EXPERIMENTAL RESULTS

The use of a combination of steady-state and unsteady-state coreflood techniques is illustrated by three cases using preserved core plugs; properties of the cores and fluids used in these measurements are summarized in Table 1.

Case One

In this example, the primary purpose of the test was to obtain steady-state relative permeability data. Multi-point steady-state tests at reservoir conditions are expensive and experimentally difficult; however, the addition of the USS waterflood portion of the test required no additional experimental steps. The only additional effort was the gathering and analysis of transient pressure drop and oil production data during the period of water-only injection at the end of the steady-state test.

Measurements were conducted on a 95 millidarcy composite core made up of seven carbonate core plugs. In the steady-state portion of the test, oil and water were pumped simultaneously through the core at a series of flow rate ratios, ending with 3% and 0% fractional flow of oil. The fluids were recirculated in a closed system, and saturations were measured by material balance, based on the interface level in an oil-water separator (Braun & Blackwell, 1981). After conditions in the core had equilibrated at 3% oil fractional flow, the oil pump was turned off and water-only injection was begun. Because the pumps used in this test were limited in their ability to maintain very low flow rates, it was impractical to make measurements at a non-zero fractional flow less than 3%. Early in the water-only injection period, oil was produced from the core at a fractional flow of 3%, but the fractional flow later declined monotonically, reaching a value of 0.01% after 236 pore volumes of water injection. The final steady-state k_{rw} point shown in Figure 2 was derived from the average conditions in the core after 236 pore volumes of water injection, even though oil production was continuing at a very slow rate.

Following the combined SS/USS test, the core was returned to irreducible water saturation, and a conventional unsteady-state test was performed. The resulting JBN-derived results agree well with the steady-state and unsteady-state portions of the previous test, but do not provide data near irreducible water saturation.

Figure 2 shows the results of the steady-state and unsteady-state measurements conducted on this core. Following the 3% oil fractional flow measurement (the last steady-state k_{ro} point shown in the figure), a saturation change of nearly 20% PV was achieved by water-only injection, i.e., 0% oil fractional flow. The transient oil production and pressure drop data obtained during this step were analyzed by the JBN technique. The results of this analysis (shown by the solid curves in Figure 2) defined the relative permeability characteristics of the core at saturations between those obtained at the final two steady-state points (3% and 0% oil fractional flow). The unsteady-state k_{ro} data in this region were especially valuable, providing an indication of the curve shape as k_{ro} approached zero near residual oil saturation; no information about the curve shape in this region was available from the steady-state data.

Case Two

Although the addition of an unsteady-state waterflood at the end of a multipoint steady-state test may produce more complete relative permeability curves, it is also very time and equipment intensive, and thus expensive. In contrast, the conventional unsteady-state waterflood is a more convenient and less costly way to obtain relative permeability information. The addition of steady-state relative permeability measurements at one or two saturation points prior to the start of the unsteady-state waterflood can provide relative permeability information at water saturations less than the saturation at waterflood breakthrough. If these steady-state measurements are obtained with a once-through flow of the oil and water, less sophisticated equipment is required than with a recirculation system.

This SS/USS combination was used in analyzing cores from a reservoir with a large oil-water transition zone. In this case, the unsteady-state waterflood method provided relative permeability data over only a limited saturation range, which was smaller than the range of saturations that exist in the transition zone. However, by obtaining at least one steady-state relative permeability measurement at a high oil fractional flow, some definition of the relative permeability curves at low water saturations was obtained.

Figure 3 shows the results of oil-water relative permeability tests conducted on a 0.12 millidarcy single shaly siltstone core plug. The relative permeability results were obtained by steady-state measurements at two fractional flows, followed by an unsteady-state waterflood.

In the steady-state measurements, oil and water were pumped simultaneously through the core at two different oil fractional flow values, 80% and 20%. To avoid modifying our conventional waterflood apparatus, the fluids were pumped through the core without recirculation until steady-state flow was achieved, as indicated by a constant pressure drop across the core.

Pumping the oil and water once-through required a different approach to determine the saturation/material balance than was used in Case One; namely, brine-phase tracers were used to determine the effective water saturation. From step to step in the experimental procedure, the injected brine was switched between a brine containing an iodide tracer and one containing bromide. The produced brine was analyzed by ion chromotography to determine the water content of the core at various points in the test. The core plug pore volume and the water saturation at residual oil saturation at the completion of the waterflood were determined by Dean-Stark extraction.

Oil production during the USS waterflood portion of the test was monitored in an oil-water separator. The initial produced fractional flow of oil at the start of the waterflood was 20%, the same as the second steady-state data point. The final oil fractional flow was 0.2% at the end of the waterflood after 5.9 pore volumes of brine injection.

As shown in Figure 3, the steady-state and USS waterflood data are consistent, with each technique defining different portions of the relative permeability curves. The first steady-state data point, at an oil fractional flow of 80%, helps to define the relative permeability curves at saturations occurring in the transition zone of the reservoir. In a conventional USS waterflood, breakthrough would have occurred at a higher water saturation, leaving this region of the relative permeability curves undefined.

Case Three

Another situation in which a combination of SS and USS relative permeability data is useful occurs with unfavorable oil-water mobility ratios. This can result in viscous fingering, which causes early waterflood breakthrough during USS tests and produces unreliable relative permeability results. Steady-state measurements, on the other hand, are considered to be relatively free of viscous fingering effects. The addition of at least one steady-state relative permeability data points therefore assists in defining the relative permeability curves at low water saturations.

Figure 4 shows the results of oil-water relative permeability tests conducted on a 4560 millidarcy composite core made up of four sandstone core plugs. The relative permeability results were obtained by steady-state measurement at one fractional flow, followed by an unsteady-state waterflood.

The oil-water viscosity ratio for this example was 131. Such an unfavorable oil-water mobility ratio can result in viscous fingering, particularly at the high flow rates required to obtain a measurable pressure drop across this high permeability core. In the steady-state test, oil and water were pumped simultaneously through the core at 2% oil fractional flow. As in Case Two, the fluids were pumped through the core without recirculation until steady-state flow was achieved, as indicated by a constant pressure drop across the core.

Oil production during the waterflood portion of the test was monitored in an oil-water separator. The fraction of oil in the produced fluid at the start of the waterflood was 2%, the same as the steady-state data measurement. The final oil fractional flow at the end of the waterflood after 53 pore volumes of brine injection was 0.12%.

Again, the steady-state and the unsteady-state data are consistent and complementary. Viscous fingering effects are not apparent, possibly because of the low oil fractional flow at the start of the waterflood. The steady-state measurement confirms the validity of unsteady-state data obtained at unfavorable oil-water mobility ratio.

CONCLUSIONS

The measurement of relative permeability data by a combination of steady-state and unsteady-state waterflood techniques offers a number of benefits. Adding an USS waterflood to the end of a steady-state experiment provides the following advantages.

1. The range of relative permeability information is extended without increasing the complexity of the steady-state experiment.

2. The shape of the k_{ro} curve near residual oil saturation is defined.

The addition of one or two steady-state relative permeability measurements prior to the start of an USS waterflood offers the following advantages.

1. The range of relative permeability information is extended to water saturations less than the saturation at breakthrough in an unsteady-state waterflood.

2. The steady-state data provide a check on the validity of the USS waterflood data. This is of particular value with an unfavorable oil-water mobility ratio, which could cause viscous fingering in USS tests.

3. Steady-state data are obtained without increasing the complexity of the conventional USS waterflood experiment.

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NOMENCLATURE

Δu = distance moved by plane of constant saturation

Q_T = volume of water injected

ϕ = porosity

A = cross-sectional area

f_D = fractional flow of the displacing phase

S_D = saturation of the displacing phase

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TABLE 1

Summary of Rock and Fluid Properties

Case #	Core Material	Configuration	Perm (md)	Viscosity Ratio (o/w)
1	Carbonate	Composite	95	1.68
2	Shaly siltstone	Single Plug	0.12	9.3
3	Sandstone	Composite	4,560	131

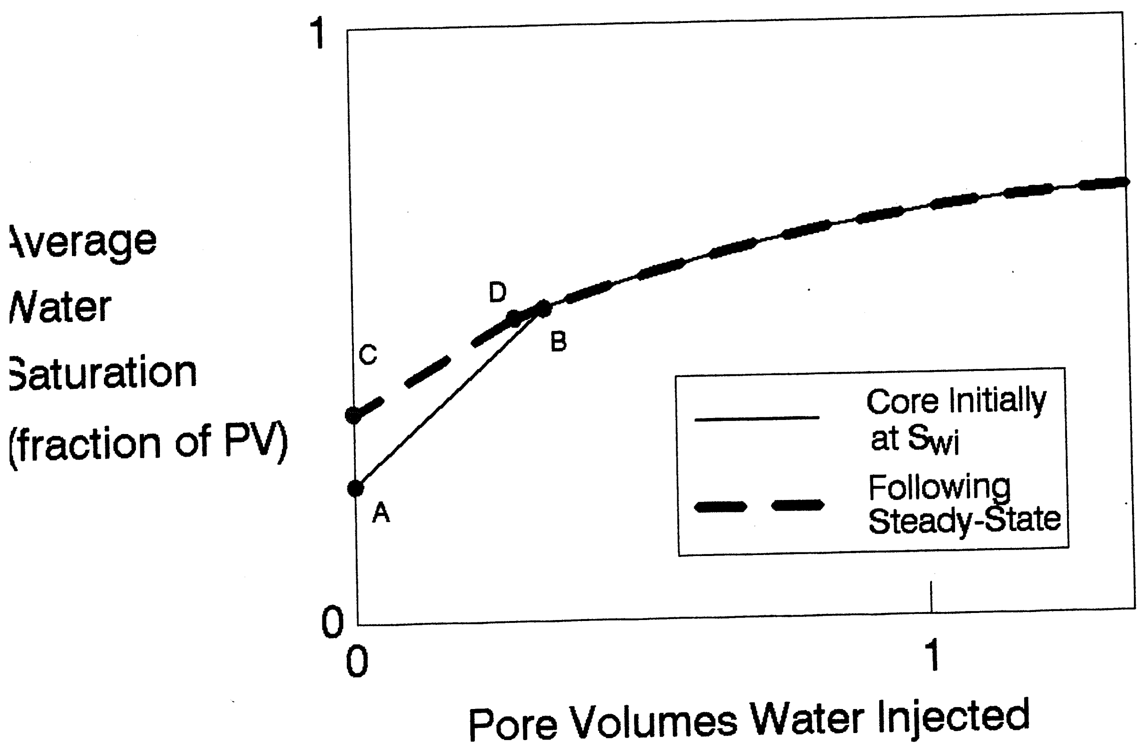

Figure 1. Water saturations during USS waterfloods starting at irreducible water saturation and after steady-state flow.

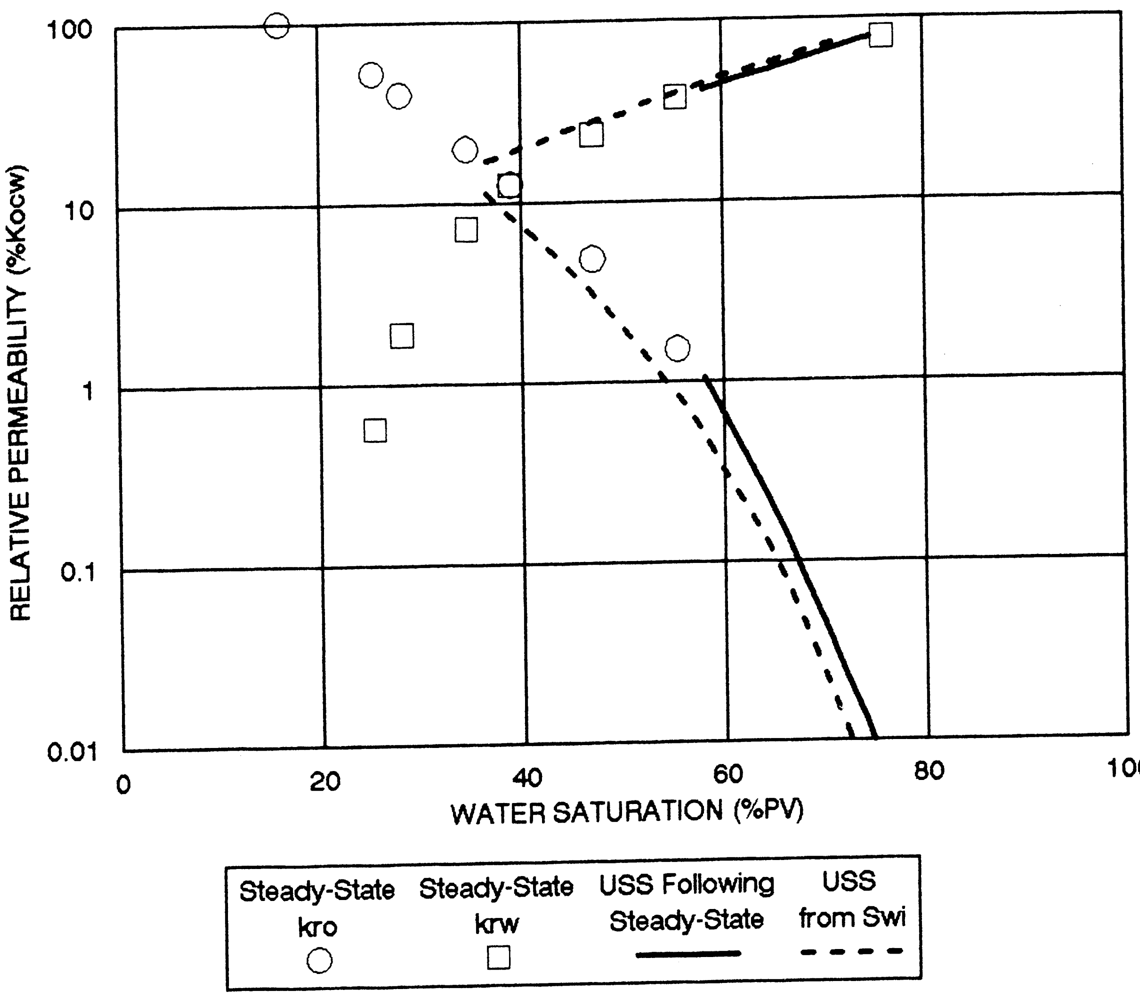

Figure 2. Steady-state and USS waterflood results for carbonate core.

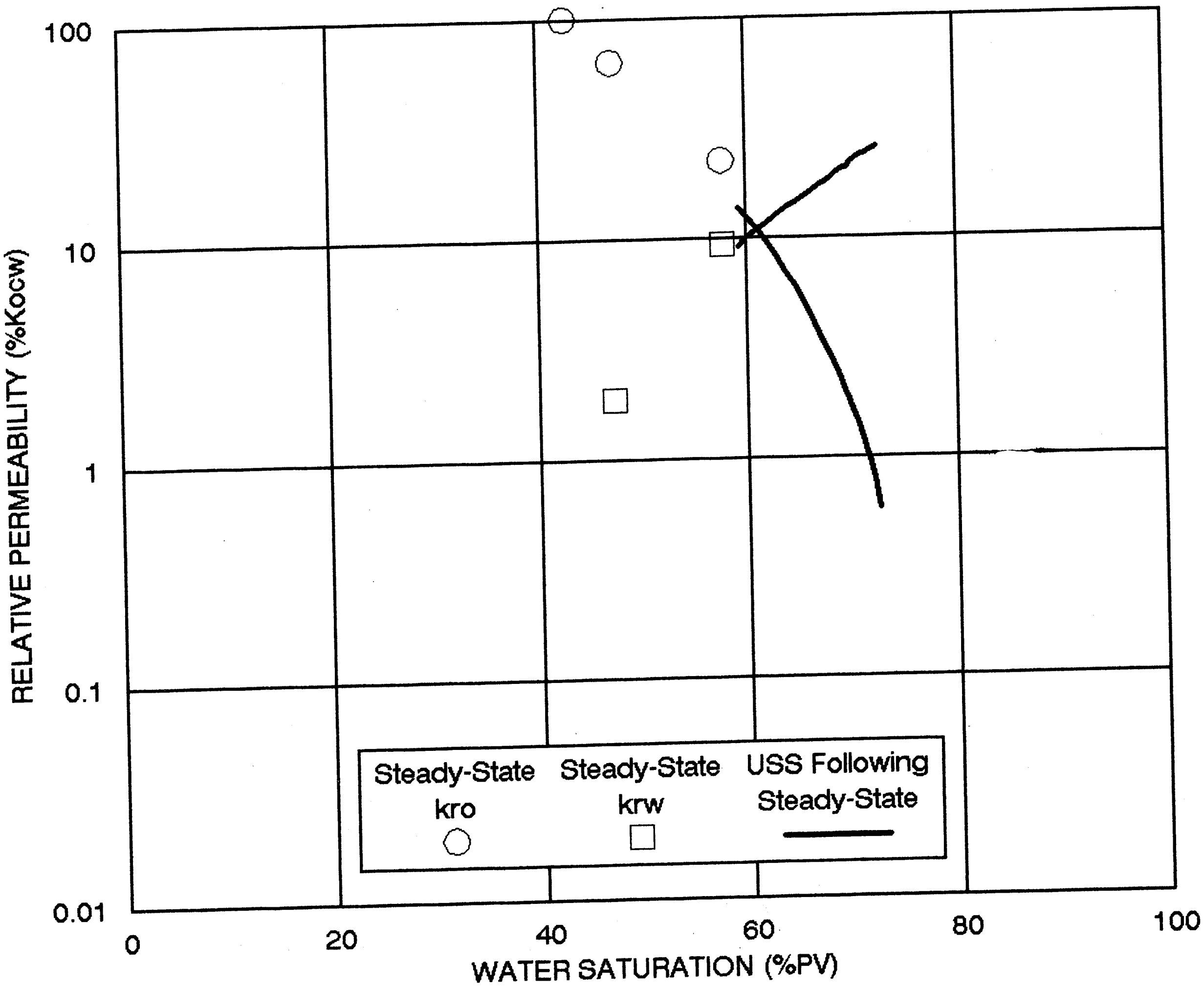

Figure 3. Steady-state and USS waterflood results for shaly siltstone core.

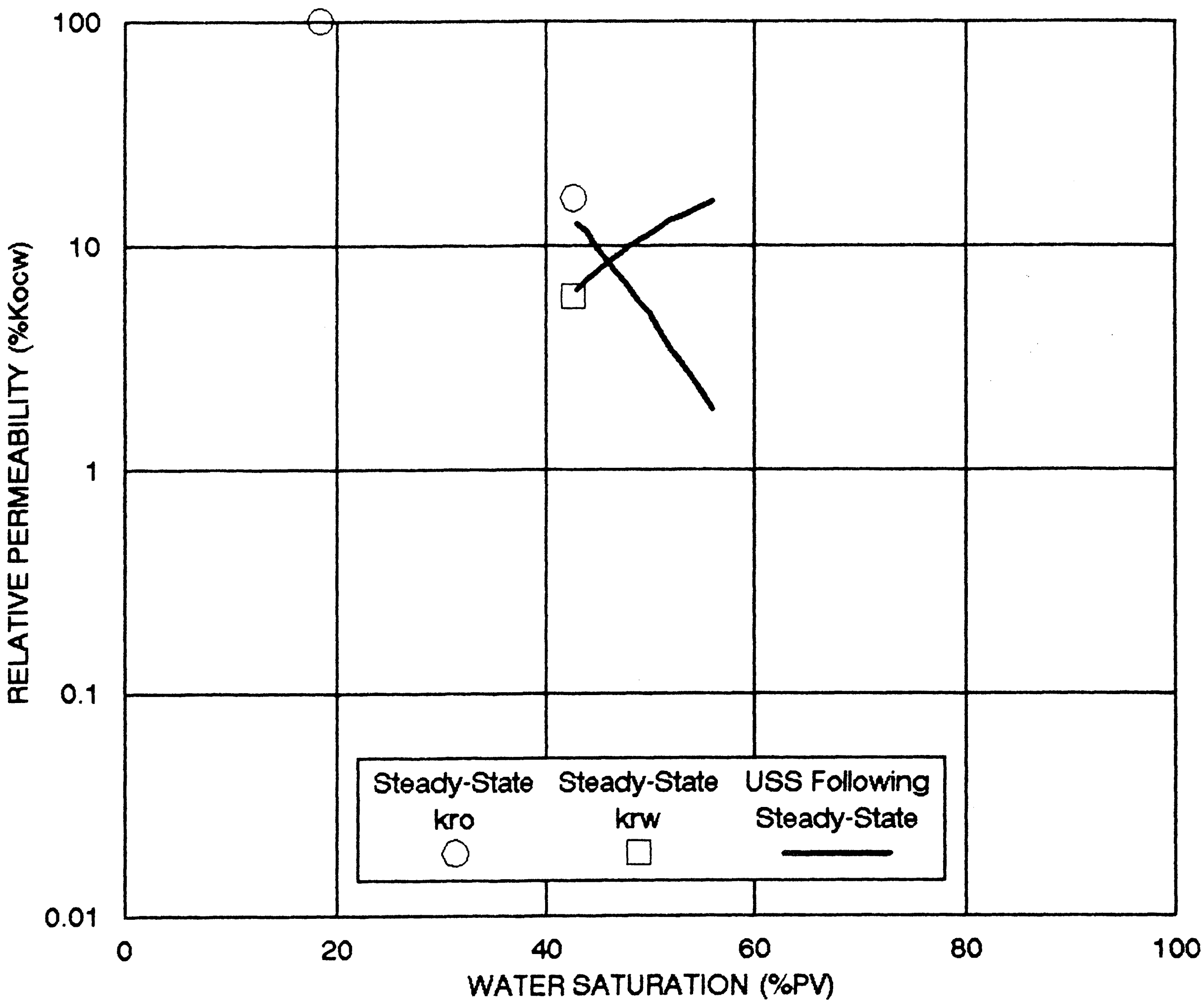

Figure 4. Steady-state and USS waterflood results for sandstone core.