The Integration of Capillary Pressures and Pickett Plots for Determination of Flow Units and Reservoir Containers

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Summary

This paper shows how to construct lines of constant capillary pressure, process speed, pore-throat aperture, and height above the free water table on a Pickett plot. The integration of these properties allows the determination of flow units and reservoir containers and illustrates the important link between geology, petrophysics, and reservoir engineering.

The concept of flow (or hydraulic) units and reservoir containers has been used in the oil industry with a good deal of success during the past few years. The process or delivery speed k/ϕ can be used in many instances to define a flow unit. Correlation of flow units between wells helps to establish reservoir containers and forecast reservoir performance.

We show that a Pickett crossplot of effective porosity vs. true resistivity should result in parallel straight lines for intervals with constant process speed k/ϕ. The slope of the straight lines is related to the porosity exponent m, the water-saturation exponent n, and constants in the absolute permeability equation. From the straight lines, it is possible to determine capillary pressures and pore-throat apertures directly for each flow unit at any water saturation. Pore throats at 65% water saturation compare very well with Winland r_{35} values. The method has not been published previously in the literature.

Building lines of constant k/ϕ allows the display of complete capillary pressure curves on the Pickett plot, including regions that are and are not at irreducible water saturation. Previous empirical methods for determining the absolute permeability of a given interval assume that the water saturation is at irreducible conditions. This paper presents a technique that allows us to estimate absolute permeability even if the interval contains moveable water.

The use of this technique is illustrated with previously published data from the Morrow sandstone in the Sorrento field of southeastern Colorado and carbonates from the Mission Canyon formation in the Little Knife field of North Dakota. We conclude that flow units can be determined reliably from the integration within one single log-log graph of Pickett plots, capillary pressures, pore-throat apertures, and Winland r_{35} values.

Introduction

Pickett plots[1,2] have long been recognized as very useful in log interpretation. The Pickett plot has been extended throughout the years to include many situations of practical importance, including naturally fractured reservoirs,[3–5] shaly formations,[6] reservoirs with irreducible and moveable water,[7,8] formations with variable permeabilities,[8,9] and reservoirs with significant variations in pore-throat apertures.[10,11]

This paper shows how to determine flow units by incorporating lines of constant process speed k/ϕ on a Pickett plot. A schematic of this approach is shown in **Fig. 1,** where P_{c1} and P_{c2} are constant capillary pressures, r_1 and r_2 are constant pore-aperture radii, and $(k/\phi)_1$ and $(k/\phi)_2$ are constant process or delivery speeds. The correlation of flow units between wells helps to define reservoir containers.[12]

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Theory

Well-log signatures, capillary pressures, Winland r_{35} pore throats, and/or process (or delivery) speed k/ϕ help to define a flow unit. Hartmann and Beaumont[12] have defined a flow unit as a reservoir subdivision characterized by a similar pore type. They define a container as "a reservoir system subdivision consisting of a pore system made up of one or more flow units, which respond as a unit when fluid is withdrawn." The work presented in this paper is based on those definitions. The same parameters mentioned earlier are built on the Pickett plot to facilitate the determination of flow units.

Pickett Plot

Archie's[13] basic formation evaluation equations can be combined as proposed by Pickett[1,2] to obtain

$$\log R_t = -m\log\phi + \log(aR_w) - n\log S_w. \quad (1)$$

Eq. 1 indicates that a crossplot of ϕ vs. R_t on log-log coordinates should result in a straight line with a negative slope equal to m for intervals with constant values of aR_w, n, and S_w.

Archie's equation poses the limitation that it would tend to give unrealistically large values of water saturation in shaly formations. To alleviate the problem, it is better to prepare the Pickett plot using a shale correction (A_{sh}) to the resistivity (R_t), as explained by Aguilera.[6] This is based on the observation that all equations for evaluation of shaly formations published in the literature, no matter how long they are, become $S_w = I_{sh}^{-1/n}$.

Permeability

An empirical equation that has been found to give reasonable estimates of permeability throughout the years has the form[14]

$$k^{1/2} = 250\,\phi^3/S_{wi} \quad (2)$$

for the case of a medium-gravity oil. For a dry gas at shallow depth, a constant approximately equal to 79 is used in place of 250. Water saturation in Eq. 2 is at irreducible conditions. The optimum situation is when core data are available and the constants in Eq. 2 can be calibrated to better fit a particular reservoir. In that case, the permeability equation is written as follows:

$$k^{1/c4} = c_2\phi^{c3}/S_{wi}. \quad (3)$$

Eq. 3 can be solved for irreducible water saturation S_{wi} and incorporated into Eq. 1 to obtain

$$\log R_t = (-c_3 n - m + n/c_4)\log\phi + \log[aR_w(c_2^{-n})(k/\phi)^{n/c4}]. \quad (4)$$

Eq. 4 indicates that a crossplot of R_t vs. ϕ on log-log coordinates should result in a straight line with a slope equal to $(-c_3n-m+n/c_4)$ for intervals at irreducible water saturation with constant aR_w and constant k/ϕ. Extrapolation of the straight line to 100% porosity yields the product $[aR_w(c_2^{-n})(k/\phi)^{n/c4}]$.

Capillary Pressure, Pore-Throat Radius, and Height Above the Free Water Table

Aguilera[10,11] has presented equations and methods to construct lines of constant capillary pressure, pore-throat radius, and height above the free water table on a Pickett plot. The lines are valid between water saturations of 30 and 90%. Aguilera[11] presented

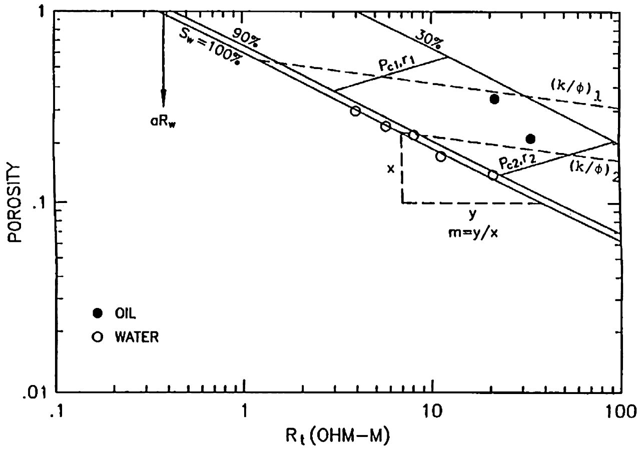

Fig. 1—Schematic of Pickett plot showing lines of constant process speed (k/ϕ), constant capillary pressure, and constant pore-throat radius.

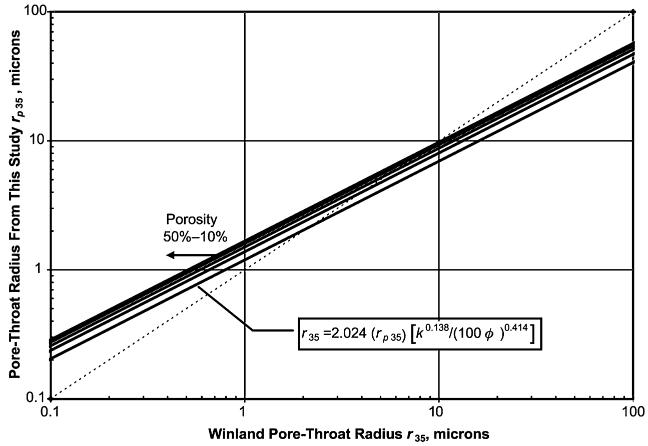

Fig. 2—Comparison of Winland r_{35} pore-throat radius and r_{p35} from this study.

examples from a high-porosity sand/shale sequence in the Gulf Coast of North America and a limestone reservoir in the Lansing Kansas City oil field. Similar equations and the same general philosophy are followed in this paper.

The significant difference is that in Ref. 11, the capillary pressure on the Pickett plot was valid only at irreducible water saturation. A different graph was displayed in that paper to show the complete capillary pressure curve, which included zones that were not at irreducible water saturation. In the present study, the complete capillary pressure (including zones that are and are not at irreducible conditions of water saturation) is built on the Pickett plot. This permits estimating values of permeability even for intervals that contain moveable water.

Furthermore, in the present study, we construct lines of constant process speed k/ϕ, which were not included in Aguilera's[11] previous paper.

Winland r_{35} Values

H.D. Winland of Amoco developed an empirical equation that has proved most valuable as a cutoff criterion to delineate commercial hydrocarbon reservoirs in stratigraphic traps. The equation is[15,16]

$$r_{35} = 5.395(k^{0.588}/100\phi)^{0.864}. \quad (5)$$

Kwon and Pickett[17] published an empirical correlation to generate capillary pressure curves. From their data, Aguilera[11] developed the following equation for calculating pore-throat radius at 35% mercury saturation:

$$r_{p35} = 2.665[k/(100\phi)]^{0.45}. \quad (6)$$

For practical values of pore-throat apertures, Eqs. 5 and 6 provide similar results. This is significant because the research was carried out independently at different times, and the data sets were from different formations. Winland's correlation was developed with data from formations ranging in age from Ordovician to Tertiary, including Simpson, Delaware, Tensleep, Nugget, Cotton Valley, Muddy, Mesaverde, Terry, First Wall Creek, Frontier, Montrose, Vicksburg, and Frio sandstone.[16] Kwon and Pickett's[17] correlation was developed with data from more than 2,500 sandstone and carbonate samples from the Aux Vases, Hoover, Dakota, Nesson, Judith River, Lodgepole, Nisku dolomite, Morrow and Keyes, Hunton, Granite wash, Venango, Cypress, Mission Canyon, Cherokee, Bartlesville, Stony Mountain, Swift, Muddy, Tar Springs, Minnelusa, Red River, Desmoines, Devonian, Benois, Trenton limestone, Silurian, and Edwards formations.

Fig. 2 shows a comparison of pore-throat apertures at 35% mercury saturation, ranging between 0.1 and 100 microns and calculated with the use of Eqs. 5 and 6. The relation between r_{35} and r_{p35} is given by

$$r_{35} = 2.024\, r_{p35}[k^{0.138}/(100\phi)^{0.414}], \quad (7)$$

where permeability is in millidarcies and porosity is a fraction.

Clastics Application

The techniques developed in this paper are illustrated first with data from the Morrow sandstone in the Sorrento field of southeastern Colorado **(Figs. 3 and 4),** presented originally by Hartmann and Coalson.[18] Published data have been included in this paper to allow the reader a comparison with alternate methods presented in the literature. The example illustrates the important link between geology, petrophysics, and reservoir engineering.

Fig. 5 shows the Pickett plot developed in the present study. The water-saturation lines are reproduced from Hartmann and Coalson's plot.[18] The negative slope of the constant water-saturation lines (m) is 1.8. Lines of constant mercury-air capillary pressure ranging between 6.06 and 200 psi, pore-throat apertures (r_p), and heights above the free water table (h) are determined as explained by Aguilera[10,11] with the use of the following equation:[17]

$$P_c = A[k/(100\phi)]^{-c1}, \quad (8)$$

where constant A is given by[10,11]

$$A = c_5 S_w^{-c6}. \quad (9)$$

Eq. 9 was developed empirically with published data from more than 2,500 sandstone and carbonate samples from 30 formations in North America. It has been shown to be valid between 30 and 90% water saturation.[11]

The following constants, discussed previously in this paper, were used to prepare Fig. 5:

- Archie's equation: $m=1.8$, $n=2.0$, $a = 1.0$, $R_w=0.04$.
- Permeability equation: $c_2=250$, $c_3=2.1$, $c_4=2.0$.
- Capillary pressure equations: $c_1 = 0.45$, $c_5 = 19.5$, $c_6 = 1.7$.

All these parameters are specific to the Morrow sandstone. For other reservoirs, Archie's parameters m, n, a, and R_w would be determined conventionally. Constants c_1 through c_6 are general for medium-gravity oil. However, for better results, it is recommended that local calibrations be performed, whenever possible, with core data. Based on these constants, the slope of the constant capillary pressure lines in Fig. 5 is calculated to be +1.8 from the following equations:

$$P_c \text{ slope} = -m + nc_7/c_8, \quad (10)$$

$$\text{where } c_7 = (1 - c_3 c_4)c_1 \quad (11)$$

$$\text{and } c_8 = (-c_6 + c_4 c_1). \quad (12)$$

To draw a line of constant capillary pressure, determine R_t for an assumed porosity from the equation[11]

$$R_t = \phi^{(-m+nc7/c8)} a R_w (P_c^{1/c8} c_2^{c4\,c1/c8})^{-n} / [(100^{c1} c_5)^{1/c8}]^{-n}. \quad (13)$$

For example, for an aR_w of 0.04 and a porosity of 0.2062, a value of R_t equal to 34.3 ohm-m is calculated when P_c is equal to

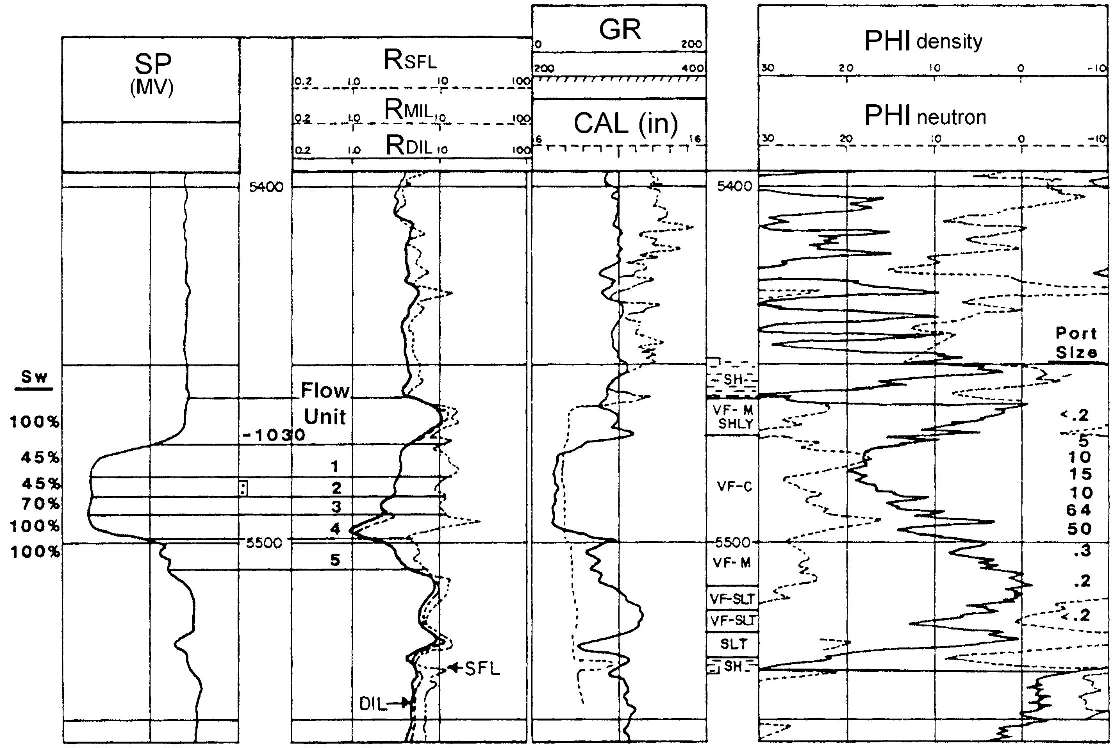

Fig. 3—Logs of a well in the Sorrento field of southeastern Colorado showing five flow units in the Morrow sandstone (after Hartmann and Coalson[18]).

50 psi. Graph a control point on the Pickett plot corresponding to $\phi = 0.2062$ and R_t equal to 34.3. This is represented by the black triangle shown in Fig. 5. Draw a straight line through this control point with a positive slope equal to 1.8. This straight line corresponds to a constant capillary pressure of 50 psi. The same procedure is followed to draw lines for other capillary pressures of interest.

Another way of drawing the constant capillary pressure line is by calculating two values of R_t from Eq. 13 at two assumed values of porosity and drawing a straight line between the two points. For example, a new assumed porosity of 0.08 calculates an R_t of 6.24 ohm-m. This point is represented by the black square shown in Fig. 5. The straight line connecting the triangle and the square corresponds to a capillary pressure of 50 psi. This straight line is valid for water saturations ranging from 30 to 90%.[11]

The Pickett plot in Fig. 5 also shows pore-throat apertures and heights above the free water table, calculated with the following basic data: $(\rho_w - \rho_o) = 0.271$, $\sigma_h = 35$ dynes/cm, $\Theta_h = 30°$, $\sigma = 480$, and $\Theta = 140°$. For these data, the pore-throat radius is r_p~$108.1/P_c$, and the height above the free water table is h~$0.705\ P_c$.

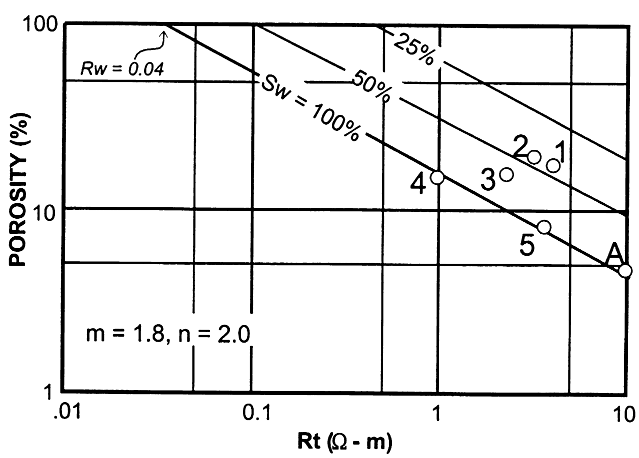

Fig. 4—Pickett plot of Morrow sandstone showing five flow units (after Hartmann and Coalson[18]).

To draw lines of constant k/ϕ on Fig. 5, use the following procedure:

- Select the line you want to draw [e.g., $k/\phi = 20{,}000$ md (porosity as a fraction)].
- Assume a porosity (e.g., $\phi = 0.2062$).
- Calculate R_t from Eq. 4. Using the basic data, $aR_w = 0.04$ ohm-m, $m = 1.8$, $n = 2.0$, $c_2 = 250$, $c_3 = 2.1$, and $c_4 = 2$. In this case, a true resistivity $R_t = 34.3$ ohm-m is calculated.
- Graph the point corresponding to $\phi = 0.2062$ and $R_t = 34.3$ on the Pickett plot. This is represented by a black triangle in Fig. 5.
- Draw a straight line through the triangle with a slope equal to $(-m\ -c_3 n\ +\ n/c_4) = (-1.8 - 2.1\times2 + 2/2) = -5$. This straight line is valid for a constant process speed of $k/\phi = 20{,}000$ md (porosity is a fraction). Lines for other process speeds of interest are drawn in the same form.

Zones 1 through 5 are characterized by distinct process speeds. Consequently, each one can be treated as a separate flow unit, as suggested by Hartmann and Beaumont.[12] Correlation of similar flow units between wells defines a reservoir container.

Fig. 6 shows an air-mercury capillary pressure for Flow Unit 2 generated with the use of Eqs. 8 and 9. The process speed for Flow Unit (Zone) 2 is approximately 2,000 md (porosity is a fraction). Control points A, B, C, D, and E display values of water saturation, capillary pressure, pore-throat radius, and height above the free water table.

The pore-throat radius at 35% mercury saturation (65% water saturation) is $r_{p35} = 10.30$ microns (from Eq. 6). The pore-throat radius from the Winland equation is $r_{35} = 13.62$ microns (Eq. 5). From a practical point of view, both numbers give us the same information. Both equations classify the pore size of Flow Unit 2 as megaports (a port size larger than 10 microns) based on the following classification suggested by Coalson *et al.*:[19] megaports (r_{35}>10 microns), macroports (r_{35} between 2.5 and 10 microns), mesoports (r_{35} between 0.5 and 2.5 microns), microports (r_{35} between 0.1 and 0.5 microns), and nanoports (r_{35} between 0.01 and 0.1 microns).

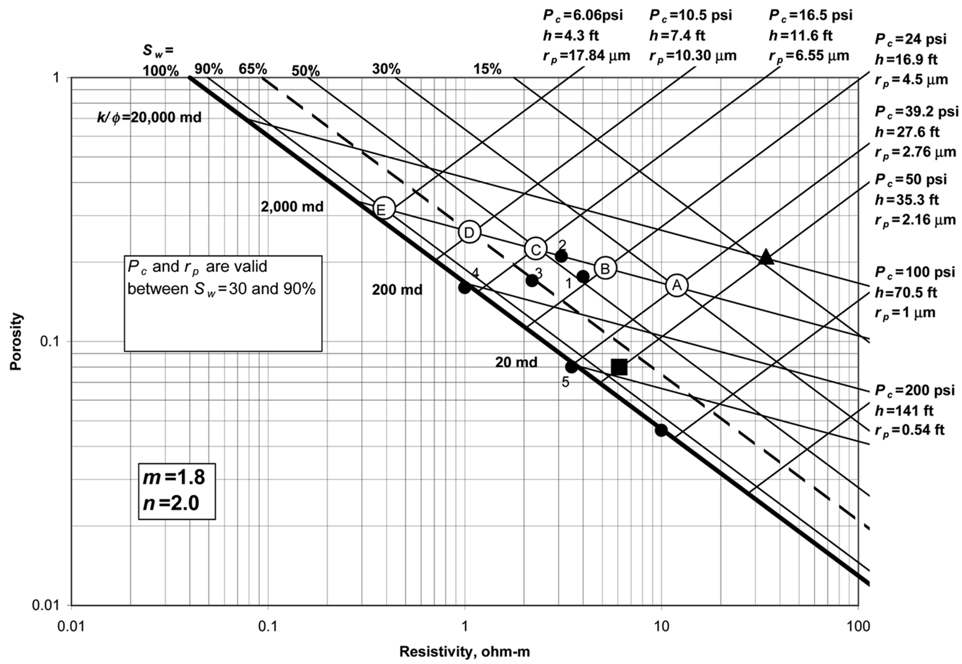

Fig. 5—Pickett plot of Morrow sandstone showing lines of constant water saturation, process speed (k/ϕ), capillary pressure, pore-throat radius, and height above the free water table.

Fig. 6 shows the complete capillary pressure curve for Flow Unit 2 ($k/\phi = 2{,}000$) going all the way to 100% water saturation (i.e., it includes water that is not at irreducible conditions). The same complete capillary pressure is shown in the Pickett plot displayed in Fig. 5 at a process speed k/ϕ equal to 2,000. For ease of comparison, control points A, B, C, D, and E are also included in Fig. 5. For example, Point A shows a capillary pressure of 39.2 psi at 30% water saturation in both Figs. 5 and 6. Point B shows a capillary pressure of 24 psi at 40% water saturation. The other control points (C, D, and E) also compare exactly in Figs. 5 and 6.

Based on the previous discussion, the capillary pressure (10.5 psi) and the pore-throat radius ($r_{p35} = 10.30$ microns) at 65% water saturation (35% mercury saturation) can be read directly from the Pickett plot. This corresponds to Point D in Figs. 5 and 6 and is approximately equal to Winland r_{35}, as discussed previously.

Zone 2 has a water saturation of approximately 45%. It was perforated and tested at approximately 100 BO/D and 300,000 scf/D with zero water. This zone was initially at irreducible water saturation. The capillary pressure from Figs. 5 and 6 is approximately 18 psi at 45% irreducible water saturation.

For Point E, the Pickett plot shows a capillary pressure of approximately 6.06 psi at 90% water saturation (moveable water). By plotting the capillary pressure line on the Pickett plot, as described in this paper, the limiting assumption of irreducible water saturation used in Aguilera's[11] previous work is removed.

The absolute permeability calculated for a zone located at Point E in Fig. 5, based on a porosity of approximately 0.31, is $k = (k/\phi) \times \phi = 2{,}000 \times 0.31 = 640$ md. This value is correctly calculated despite the fact that the water saturation ($S_w = 90\%$) is not at irreducible conditions. For this case, the permeability calculated from Eq. 3, which assumes an irreducible water saturation, is lower (564 md).

In addition to capillary pressure for a process speed (k/ϕ) of 2,000, Fig. 6 also shows curves for process speeds of 200 and 20, as well as the height (h) above the free water table. Results compare favorably with the capillary pressures presented in the Pickett plot, displayed in Fig. 5.

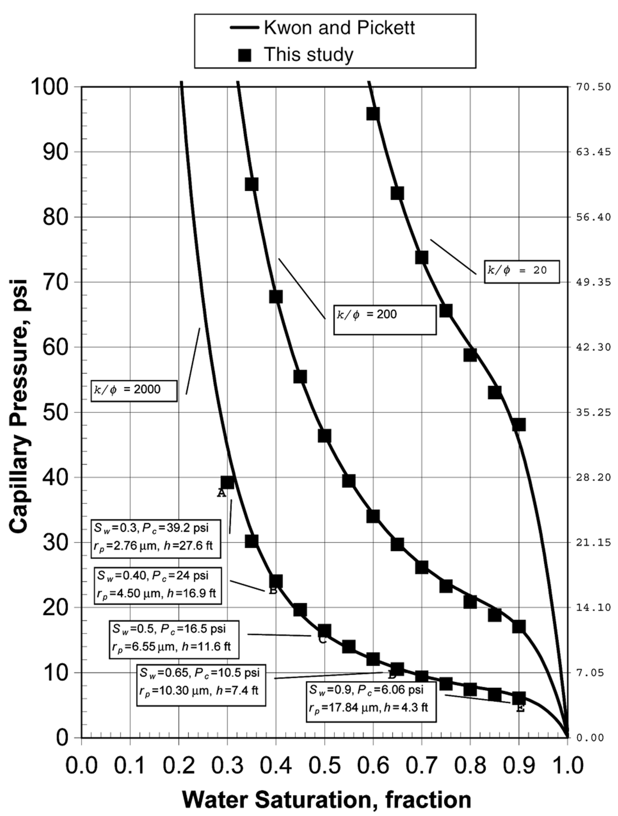

Fig. 6—Calculated air-mercury capillary pressures from Eqs. 8 and 9 (black boxes) for three flow units show a good comparison with results from Kwon and Pickett[17] (black continuous solid lines).

Carbonate Application

The second application deals with the Mission Canyon formation in the Little Knife field of North Dakota. The data were published originally by Martin *et al.*[20] **Figs. 7 and 8** show Pickett plots for wells Leo Klatt 3-19-48 and Kadrmas 1. The plots incorporate lines of constant water saturation, process speed k/ϕ, capillary pressures, pore-throat radii, and height above the free water table.

The Pickett plots were generated as explained in the previous application with the following basic data:

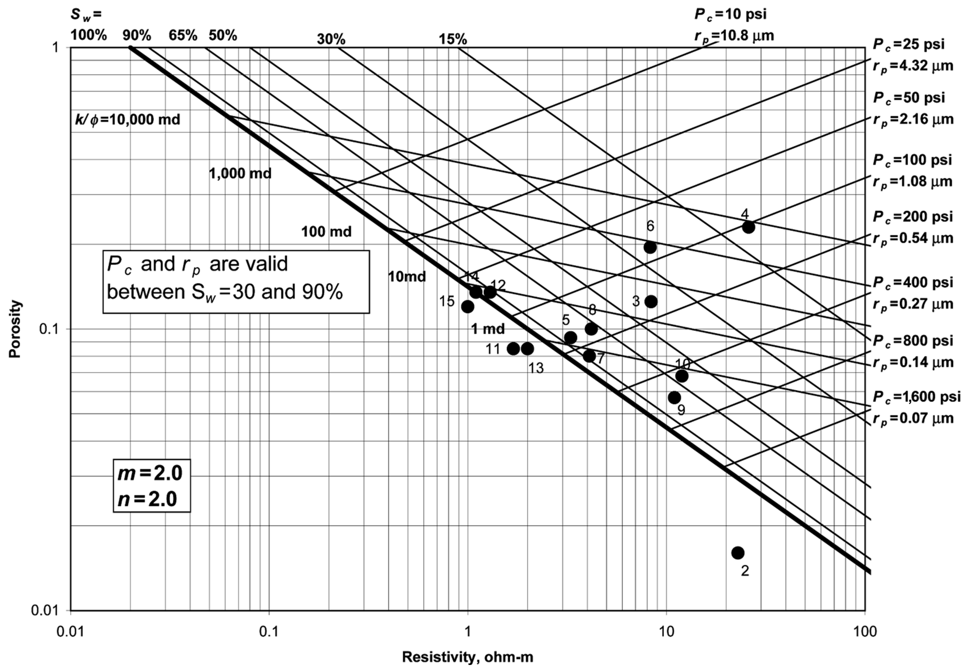

Fig. 7—Pickett plot for Well Leo Klatt 3-19-4B, Mission Canyon dolomitic grainstone, Little Knife field, North Dakota (flow units after Martin *et al.*[20]).

- Archie's equation: $m=2$, $n=2.0$, $a=1.0$, $R_w=0.02$.
- Permeability equation: $c_2=400$, $c_3=3.0$, $c_4=2.0$.
- Capillary pressure equations: $c_1=0.45$, $c_5=19.5$, $c_6=1.7$.

Lines of constant process speed k/ϕ were calculated with the same procedure used in the previous application.

Well Leo Klatt 3-19-48 tested initially at 485 BO/D. The well accumulated 979,000 STB of oil between July 1977 and May 1993. Well Kadrmas 1 was tested on October 1987. The well died during DST 1 while recovering only 2 L of oil and water cushion in 30 minutes.

The wells considered in Figs. 7 and 8 are characterized by distinct Pickett plots. In the Klatt well (Fig. 7), which recovered 979,000 STB of oil, Flow Units 3, 4, and 6 have low water saturations, high values of process speed k/ϕ, and reasonable pore-throat apertures (r_{p35}). Zone 4 is composed of megapores (r_{p35}>10 microns), Zone 6 of macropores (r_{p35} between 2.5 and 10 microns), and Zone 3 of mesopores (r_{p35} between 0.5 and 2.5 microns). On the other hand, the Kadrmas well (Fig. 8), which recovered only 2 L of oil and water cushion during a DST, shows that all the intervals have very high water saturations and lower values of process speed k/ϕ than the Klatt well. Pore-throat apertures at 35% mercury saturation (65% water saturation) read from the Pickett plots are also larger in the Klatt well.

Summarizing the evaluations shown in the Pickett plots presented in Figs. 7 and 8 help in determining flow units and distin-

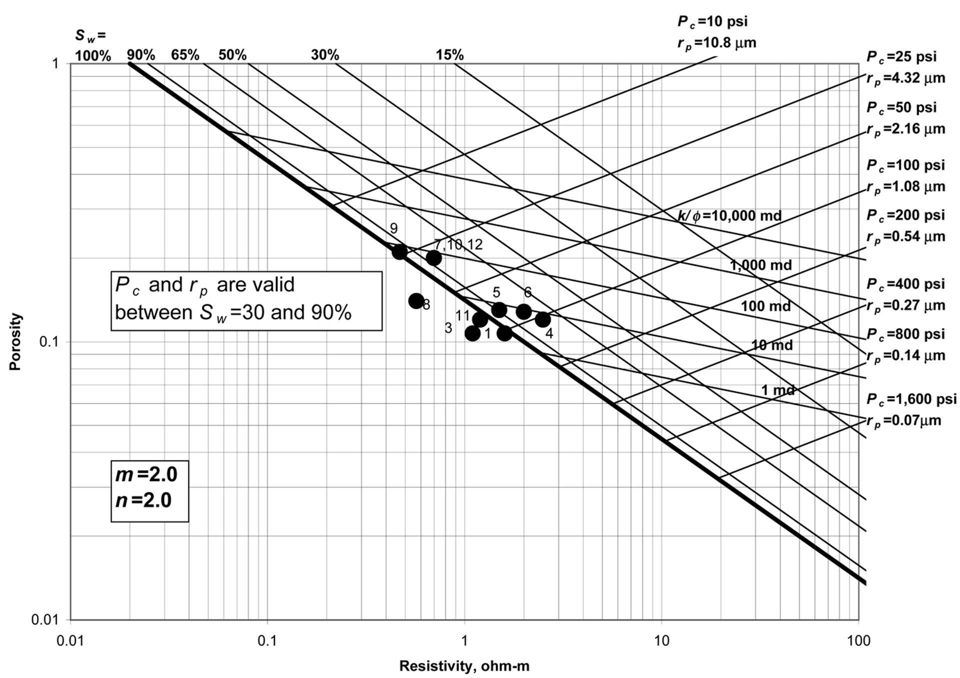

Fig. 8—Pickett plot for Well Kadrmas 1, Mission Canyon dolomitic grainstone, Little Knife field, North Dakota (flow units after Martin *et al.*[20]).

guishing a good well from a dry well. They also are useful for defining stratigraphic traps.

Conclusions

1. A new method has been developed for defining flow units and reservoir containers by integrating capillary pressures and Pickett plots.
2. A log-log crossplot of porosity vs. true resistivity should result in a straight line for intervals with constant process speed k/ϕ. The same straight line defines a complete capillary pressure curve for each flow unit.
3. Absolute permeability can be estimated from the Pickett plot developed in this study even if water saturation is not at irreducible conditions.
4. The technique allows for a direct reading from the Pickett plot values of pore-throat radius r_{p35} at 65% water saturation (35% mercury saturation). These radii compare very well with Winland r_{35} values.
5. More significant results can be obtained if the empirical equations presented in this study are calibrated with cores.
6. Integrating process speed k/ϕ, permeability, capillary pressures, pore-size classes, and geometry of the pores on a log-log graph of porosity vs. resistivity makes the Pickett plot one of the most formidable formation evaluation tools yet devised.

Nomenclature

a = constant in formation factor equation
A = constant in Eq. 8 for a given S_w
A_{sh} = shale group for miscellaneous models
c_1 = exponent in capillary pressure equation (Eq. 8; e.g., 0.45)
c_2 = constant for oil or gas in permeability (Eq. 3; for example, 250 in the case of some medium-gravity oils, and 79 in the case of a dry gas at shallow depth)
c_3 = exponent of porosity in an equation to calculate permeability (Eq. 3; for example, 3.0).
c_4 = nth root of permeability in Eq. 3 (e.g., 2.0 or square root)
c_5 = constant in Eq. 9 to calculate A (e.g., 19.5)
c_6 = exponent of water saturation in Eq. 9 to calculate A (e.g., 1.7)
c_7 = $(1 - c_3c_4)(c_1)$
c_8 = $(-c_6 + c_4c_1)$
F = formation factor
h = height above free water table, ft
I = resistivity index
I_{sh} = resistivity index of shaly formation
k = absolute permeability, md
m = porosity exponent
n = water saturation exponent
P_c = capillary pressure (mercury injection), psi
r_{35} = Winland pore-throat aperture corresponding to a mercury saturation of 35%, microns
r_p = pore-throat aperture radius, microns
r_{p35} = pore-throat aperture from this study for a mercury saturation of 35%, microns
R_o = formation resistivity of zone 100% saturated with water, ohm-m
R_t = true formation resistivity, ohm-m
R_w = water resistivity, ohm-m
S_{wi} = irreducible water saturation, fraction (unless stated otherwise)
S_w = water saturation, fraction (unless stated otherwise)
Θ = air/mercury contact angle
Θ_h = water/hydrocarbon contact angle
ρ_h = hydrocarbon density, g/cm^3
ρ_o = oil density, g/cm^3
ρ_w = water density, g/cm^3
σ = air/mercury interfacial tension, dynes/cm
σ_h = water/hydrocarbon interfacial tension, dynes/cm
ϕ = effective porosity, fraction (unless stated otherwise)

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SI Metric Conversion Factors

B/D × 1.589 873	E–01	=	m^3/d
cp × 1*	E–03	=	Pa·s
dyne/cm × 1.0*	E+01	=	mN/m
ft × 3.048*	E–01	=	m
in. × 2.54*	E+00	=	cm
psi × 6.894 757	E+00	=	kPa

*Conversion factor is exact.

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