REVIEW OF THE WINLAND R35 METHOD FOR NET PAY DEFINITION AND ITS APPLICATION IN LOW PERMEABILITY SANDS

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NET PAY - WHAT IS IT AND WHY IS IT IMPORTANT?

Net pay is the thickness of the porous, permeable interval containing commercial hydrocarbon saturations. The thickness of net pay compared to the total pay zone thickness is known as the "net-to-gross" ratio. This is an important factor in hydrocarbon volumetric calculations of reserves, and the design of facilities. Net pay definition is particularly difficult in low permeability gas reservoirs, since sands which are typically excluded as being "tight" may, in fact, contribute significantly to gas movement.

- With no net pay cut-off, gas reserves may be over estimated. This might mean daily contract quantities are not met, with the consequent implication of financial penalties.

- With a net pay cut-off that is too high, gas reserves would be under estimated. This could lead to the production facilities being designed for too short a lifetime, with possible consequent loss in gas reserves.

Given the importance of net pay definition, it is still surprisingly arbitrary being normally defined by a single porosity or permeability value. Rarely is information found in the literature about the basis of net pay cut-off. Dake (1994) made an apt statement on the subject:

"Application of petrophysical cut-offs is a somewhat arbitrary exercise and is highly subjective in that the practitioner in his office makes decisions about fluid movement in reservoirs without the slightest resort to any quantitative technique." Laurie Dake, in The Practice of Reservoir Engineering, 1994.

THE WINLAND R35 METHOD

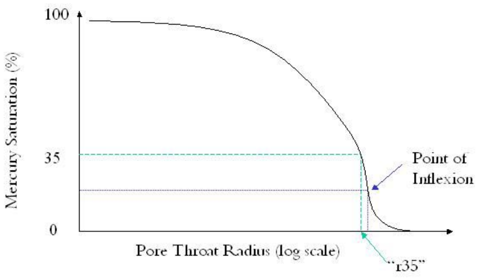
Dale Winland of Amoco developed the following empirical equation:

$$\log R35 = 0.732 + 0.588 \log K_{air} - 0.864 \log \varphi_{core} \qquad [1]$$

where R35 is the pore aperture radius corresponding to the 35th percentile of mercury saturation in a mercury porosimetry test, K_{air} is the uncorrected air permeability (in mD), and φ is porosity (in %).

The equation was originally defined from mercury porosimetry measurements on some 300 samples from the Spindle Field in Colorado. Winland correlated porosity and permeability to pore throat radii corresponding to different mercury saturations and found that the 35th percentile gave the best correlation.. The 35th percentile was taken to approximate the modal class of pore throat size where the pore network becomes interconnected forming a continuous fluid path through the sample. More accurately, the above is only true at the pore throat size corresponding to the point of inflexion of the pore throat size versus mercury saturation plot (Katz, 1986).

Figure 1: Schematic Mercury Intrusion Curve



The R35 method can used as a tool to assign flow units, and also as a net pay cut-off to exclude very low porosity-permeability, using a slightly more scientific approach than simply selecting a certain porosity, permeability and/or gamma ray/Vshale cut-off.

Winland used an R35 value of 0.5µm as the definition of net pay for the Spindle Field due to evidence he had seen of dry wells having an R35 of <0.5µm and producing wells with R35>0.5µm. The value of 0.5µm has since been used in other reservoirs to define pay.

OBJECTIVES OF THE STUDY

This method of net-pay definition is not widely used and the UK Department of Trade and Industry (DTI) were interested in assessing its value for wider use in defining net pay for low permeability gas sands. The study set out to answer two key issues:

1. Pittman (1992) suggested there may not be a modal pore throat size in low permeability samples and hence no point of inflexion on the semilog plot illustrated in Figure 1. Therefore the R35 method may be inappropriate for low permeability samples.

2. R35 values are *calculated* from a correlation rather than *measured* on the particular rock type in question. We consider the correlation could change markedly for different rock types, therefore giving different cut-off points.

EXPERIMENTAL INVESTIGATION

Forty samples were selected from two wells of a Sherwood Sandstone reservoir in Morecambe Bay. The samples were grouped by their facies (fluvial. Aeolian, sheetflood), permeability (<5md or >5md) and well number (A or B).

Mercury intrusion tests were carried out on all 40 samples up to 60,000psi. Well A raw data is shown in Figure 2.

Correlations of R35 and R(inflex) to the poro/perm data were made for the 40 Sherwood sandstone samples for comparison to the original Winland Equation.

Pore throat sizes were derived from the Washburn Equation:

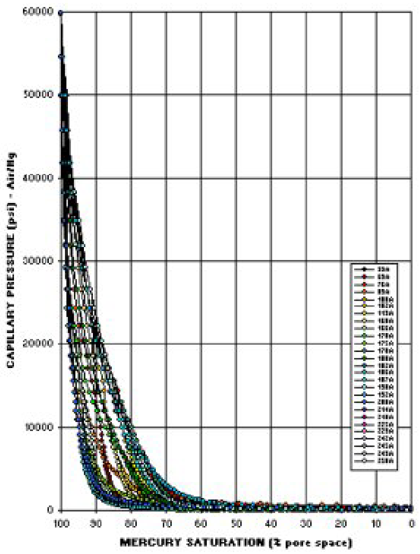
$$P_c = 2\gamma \cos\sigma / r \quad [2]$$

where Pc is the mercury/air capillary pressure, γ is the mercury/air interfacial tension (480 dynes/cm), σ is the mercury/pore wall contact angle (140°) and r is the pore throat radius.

R35 was read off for each sample from semi-log plots as illustrated in Figure 1. All samples tested showed a point of inflexion.

The point of inflexion cannot be accurately read from a plot in the format of Figure 1 so this was obtained from a plot of δ(Pc)/δ(Hg sat) versus Hg saturation, and pore throat radius versus Hg saturation on the same graph, Figure 3.

Figure 2: Mercury Intrusion Data for Well A

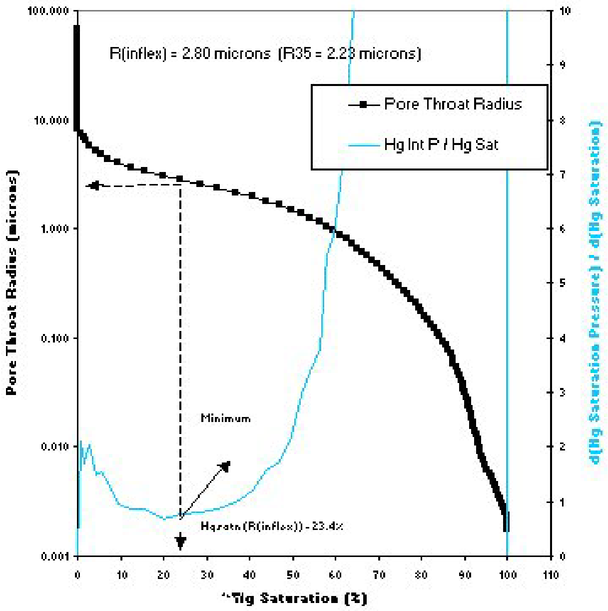


In most cases the mercury saturation corresponding to R(inflex) did not equal 35%. This data is shown for Well A data in Table 1.

Tables 1: Core Properties for Well A

Sample Number	Porosity	Kh	R35	R(inflex)	Hg Sat at R(inflex)
	%	MD	Microns	Microns	%
33	9.3	0.20	0.370	0.47	22.6
63	9.4	6.36	5.150	6.30	24.3
76	10.0	11.00	0.230	0.40	14.3
83	5.7	0.04	0.160	0.17	29.0
100	12.6	2.25	2.230	2.80	23.4
102	4.1	0.25	0.480	0.55	26.0
119	11.6	1.52	0.780	0.52	16.0
160	11.6	2.55	1.710	2.10	21.6
166	7.4	2.75	0.690	1.00	19.0
170	11.5	18.00	8.400	11.00	23.7
178	10.0	24.00	2.930	5.30	18.0
180	12.9	61.00	3.070	5.00	19.7
182	14.4	28.00	2.510	1.80	45.2
186	17.7	48.00	1.340	1.40	32.0
187	12.0	0.60	0.410	0.53	23.3
190	10.0	6.80	0.870	1.05	25.0
192	6.9	0.40	0.240	0.27	28.0
208	9.4	0.20	0.480	0.51	27.6
214	7.6	1.54	2.730	2.80	33.3
225	10.3	0.66	0.500	0.61	26.0
229	7.0	0.05	0.120	0.16	20.3
242	12.2	0.19	0.573	0.61	28.3
245	11.0	0.07	0.186	0.22	23.7
249	11.0	0.25	0.480	0.46	31.3
250	10.0	0.22	0.292	0.38	24.4

Figure 3: Determination of R(inflex)



REGRESSION ANALYSIS

A linear regression correlation was made of measured pore throat radius against calculated pore throat radius to derive v a Winland type equation specific to the particular rock type:

$$\mathrm{Log}R(x) = a + b \log K - c \log \varphi \quad [3]$$

where R is the pore throat radius and x is the mercury saturation.

Correlations for x = 35% for all sub-groups and x = saturation of the inflexion point, for a selection of sub-groups are shown in Table 3.

Table 2: Linear Regression Coefficients

Sub-group	**X = 35%**				**X = saturation of inflexion**			
	A	**b**	**c**	**r^2**	**a**	**b**	**c**	**r^2**
Well A	-0.1509	0.4026	-0.0102	.5952	0.1434	0.4384	-0.2374	.6286
Well B	-0.2365	0.4026	-0.1544	.6469	-0.3754	0.3843	0.0559	.7055
Fluvial	0.6805	0.4608	-0.8345	.6495				
Aeolian	0.6495	0.7356	-0.7647	.8530				
Sheetflow	-0.5687	0.4038	0.2597	.5160				
<5 mD	0.0055	0.4737	-0.1919	.5663	-0.0999	0.4703	-0.0193	.6572
<5 mD quartz	-0.3378	0.4831	0.2667	.6753	-0.3797	0.5062	0.3639	.7461
> 5mD	0.8192	0.4669	-1.0441	.2530				
Winland	0.7320	0.5880	-0.8640					

As can be seen, correlation coefficients were obtained that were quite different to those of the Winland Equation. As the R35 method currently involves calculating R35 values from the standard Winland equation for *any* reservoir, the relevant issue was whether the new “rock type specific” correlations would have a significant effect on the derived cut-off.

CUT-OFF DETERMINATION

The method used by a UKCS operator (which first caught the attention of the DTI) was to calculate R35 from the standard Winland equation (equation [1]) and then individually plot the calculated R35 against porosity and permeability. The permeability cut –off plot is shown in Figure 4 for the <5mD sub-set.

Net pay permeability cut-off was then read off from the best fit line through the data using the 0.5μm threshold value defined by Winland. This gave a permeability cut-off of 0.48mD. Similarly the porosity cut off was 7.8%.

The same data is plotted in Figure 5 but this time with R35 (and R(inflex)) calculated from the rock type specific equations (equation [3]).

Figure 4: Permeability Cut-off Plot
<5mD Samples: R35 by Winland Equation

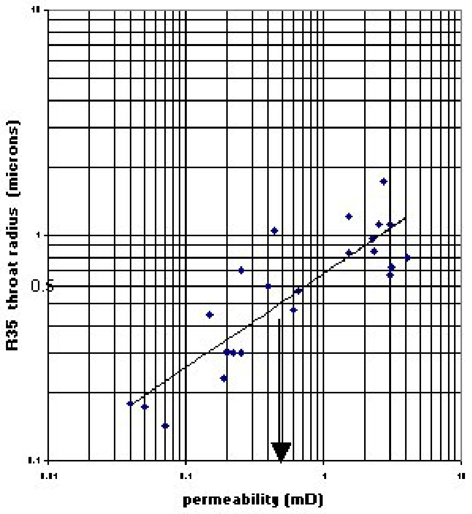
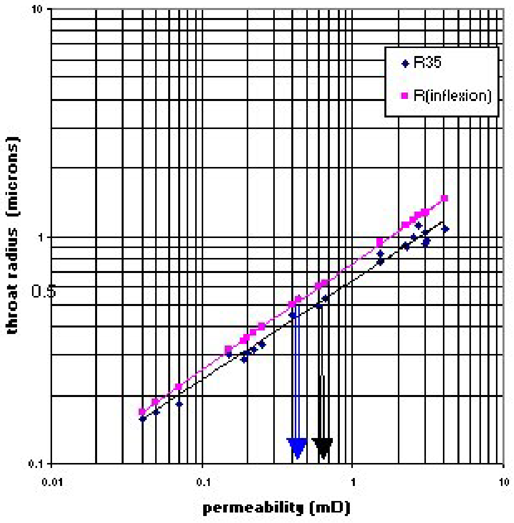


Figure 5: Permeability Cut-off Plot
<5mD Samples: new correlations



In this case the permeability cut-off was 0.57mD, and porosity cut-off was 11.1%. If R(inflex) was used, the permeability cut-off was 0.41mD, and the porosity cut-off was 9.0% .

Note: The use of the Winland Equation for some of the subsets was simply not applicable as negative cut-offs were predicted.

CROSS-PLOT ANALYSIS

Another method of defining the cut-off porosity and permeability is via a cross-plot. By rearranging Winland's equation, permeability can be calculated for a given pore throat radius over a range of porosities:

$$\log K = [\log R - a - c \log(\varphi)] / b$$

where R is the net pay threshold

In this way a graph of porosity versus permeability can plotted showing lines of *isopore-throat radius*. This was performed with isopore-throat lines derived from the Winland correlation and the new rock specific correlations (R35 and R(inflex)) for a selection of subgroups.

The actual poro/perm data was then super-imposed on both the cross-plots and samples lying below the 0.5 micron line would be deemed to be non-pay and those above would be pay.

In this way a combined porosity/permeability cut-off can be defined. The Winland and new R35 rock specific correlation cross-plots for the <5mD sub-group are shown in Figures 6 and 7.

Figure 6: Isopore Throat Radius Cross Plot
<5mD Samples: Winland Equation

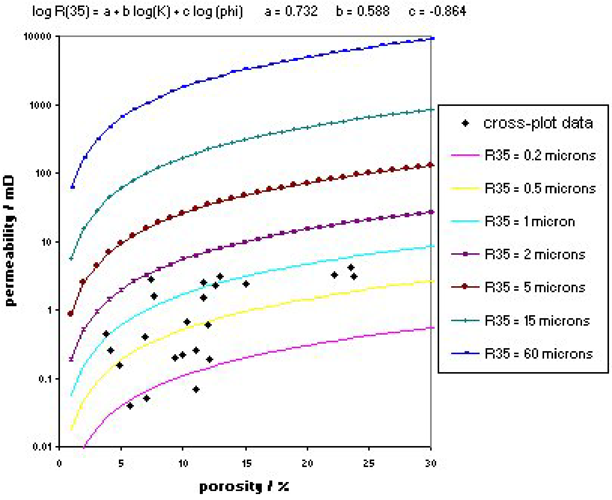
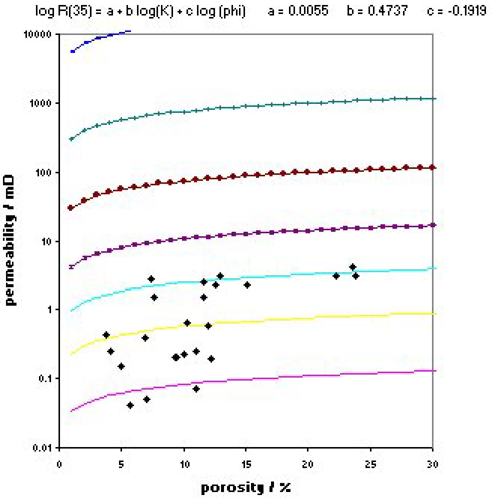


Figure 7: Isopore Throat Radius Cross Plot
<5mD Samples: New Correlation



As can be seen in Figures 6 and 7, there are small differences between the Winland 0.5µm isopore-throat radius line and the rock specific 0.5µm isopore-throat radius line, but, for this core, the cut-offs defined by each relationship exclude almost exactly the same core.

The large effect on cut-off values that would occur if a *different isopore throat* size was used is evident from Figures 6 and 7.

CONCLUSIONS

1. Mercury intrusion measurements were made on 40 samples in total. Of these 24 samples had a permeability of < 5mD and 14 of these were < 1mD. All samples showed a point of inflexion on the plot of mercury saturation versus pore throat radius (semi-log scale). Therefore it can be concluded that there is a dominant modal class of pore aperture size in the low permeability samples and so the R35 method can at least be physically applied to low permeability gas sands.

2. Small but potentially significant differences were seen in porosity and permeability cut-offs depending on whether the rock specific relationships or the Winland Equation were used.

3. The differences noted in conclusion 2 are relatively small compared to the differences that would occur if a completely pore throat size were chosen as the cut-off i.e. the 0.5 µm isopore-throat radius line is relatively insensitive to the correlation used.

4. The more pertinent question is whether 0.5µm should be used as the cut-off threshold for tight gas reservoirs.

FURTHER WORK

Previous studies for the DTI have shown that low permeability core of just a few micro-darcies may produce gas, providing it is in reasonably close contact with higher permeability layers.

This earlier work implied that permeability cut-offs in UKCS gas reservoirs were often too high.

In most reservoirs there is a distribution of “good” and “poor” quality rock. Depending on the reservoir architecture, a significant contribution of the gas production may originate from the poor quality rock. This is possible as, in a depletion gas reservoir, gas can flow relatively easily from poor rock to good rock, from which it can flow to the well and be produced.

This, together with the findings of the present study have prompted further work for the DTI to investigate guidelines for selecting permeability cut-offs in heterogeneous reservoir types, where poor quality sand is connected to good quality sand in a number of architectures.

The Winland analysis says little about flow potential and used in isolation from methods to quantify the relative permeability of tight gas sands (e.g. special core analysis laboratory measurements) may lead to erroneous estimates of net-to-gross. Also, it does not account for reservoir architecture effects, and so should be treated with caution.

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