Water Saturation & Productivity Estimates from Old Electrical Survey Logs of Clean & Shaly Sections Otis P. Armstrong P.E. April 17 2005

Abstract:
Here is a method for analysis of Electrical Survey Logs where Rxo and/or other porosity tool runs are not available. The basic equations are:

$S_w = \{(R_i/R_t)[Z + (1-Z)/(10^{(\alpha SSP/K)})]\}^{(5/\alpha 8)}$	Eq.1
$[Z^{2.62}(10^{(SSP/K)}-1)+Z^{1.62}](1-2Z)^2 - Rmf/[(Ft/Fa)2.5Ri] \equiv g(Z)=0$	Eq2
$F_t/(F_a) = \exp[0.0307(\alpha - 1)SSP]$	Eq3
$F_t = \{F_t/(F_a\}[Ri\ (1-2Z)^2]/(R_z)$	Eq4
$R_z = R_{mf}/\{(10^{(SSP/K)})Z + (1-Z)\}$	Eq5
$\alpha = ASP/SSP$	Eq6

Using these equations requires only input of information available from ES log and header, (Depth, D, temperature, T, at depth, bit diameter, d, mud resistivity Rm, at Tf, bed thickness, e, R16, and R64 or R18-8) and the use of invasion charts. Alternatively, one may use the spreadsheet for calculations, which includes regressions for Ri/Rm =f(R16/Rm, & R64/Rm or R19/Rm) and Rt estimation.. The spreadsheet method was tested against 34 actual logs and found to have a standard error of +/- 10%. The spreadsheet compares log evaluation data of others, Pirson, Asquith, and Hilchie for hard and soft formations both with and without shale for either sand or carbonate sections. The spreadsheet also contains 18 data sets for productivity estimates of either gas or oil from clean or shaly sands, using Pirson's' methods. Permeability, K, sand estimated for either sands by Wiley-Rose or carbonates from Armstrong's Equation. Details of the methods' equations and comparisons follow in the text.

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Problem Statement

Many old wells were surveyed using only the ES tool, R16,R64,R18-8, and SP. These ES logs have neither GR, nor Microsurvey nor other porosity tools. The Tixier RM analysis method for ES log is useful only for clean hard rock formations. The Doll-Schlumberger equation can be used only when a micro-survey tool is run for Rxo determination and Pirson's ES method of analysis is somewhat cumbersome. Expensive time consuming neural network systems are available to rework these old logs but presently have long lead and development times.. The method developed here-in is a ratio method and requires only inputs available from an ES log, running with a few seconds on a downloadable spreadsheet. The spreadsheet is downloadable from www.oiljetpump.com.

Background:[12,15,40,41]

Evaluation of old ES logs without Rxo is based on invasion charts which correct R16 values to Ri. The invaded zone is an intermediate zone between the flushed zone and the undisturbed zone, expressed for water-wet-rocks in standard terms as:

$Ri = RzF/(1-ROS)^2. = RzF/(Si)^2$ & $R_{xo} = R_{mf}F/(S_{xo})^2. = R_{mf}F/(1-ROS)^2.$ Eon. 6

Z is a mixing factor and is solved by Equation 2, the derivation of which is listed in the appendix. Rz is a mixed zone water resistivity given by

$1/Rz = z/Rw + (1-z)/Rmf$ or $Rmf/Rz = zRmf/Rw + (1-z)$ Eon. 7a, b

re-arrangement allows elimination of Rw/Rz by:

$Rw/Rz = (z + (1-z)Rw/Rmf)$ Eq.8

Eliminate F in the flushed zone to arrive at $Sw/Sxo = \sqrt{((Rxo/Rt)/(Rmf/Rw))}$ and for the invaded zone, $Sw/Si = \sqrt{((Ri/Rt)/(Rz/Rw))}$. Pirson observed for water wet rock that Si and Sxo are about the same value, which allows elimination of Si or Sxo by Si or $Sxo = Sw^{r}$ or $(Sw/Swi)^{2} = (Sw)^{8/5}$ if Doll's 0.2 factor is used. For clean water wet rocks the ratio equations differ only by the ratio of (Ri/Rxo)(Rmf/Rz), which should be =1.

Relation of Swi or Swx to Sw

Various proposals have been made to relate either Swi or Swx to Sw as follows:.

1. Tixier for Paleozoic rocks proposed $Swi = \sqrt{Sw}$, with z=0.075 intermediate porosity sands and 0.05 for intermediate porosity carbonates, {The Tixier equation is (Sw) = {(Ri/Rt)[z + (1-z)/(10^(SSP/K))], from which it is seen that water saturation is directly proportional to the ratio, (Ri/Rt), for a given rock type & SSP. However the method does not work for high porosity formations, Ri/Rm<10. }
2. Doll for general rocks $Swi=S^{0.20}$,
3. Wylie proposed $Si = (1+Sw)/2$ and
4. Birdwell, low permeability formations seen in older nomographs is $Si = S^{0.33}$.

Pirson favored using ROS. But of these, only the Doll exponent, 0.2, has found regular acceptance. Doll's exponent was used to arrive at Equation 1, via eq.8 & 7, details of the derivation are found in the appendix.

Pirson advocated use of invasion charts to solve F chapter 7 & 8 with Eqn's #6-a and #7, see Pirson examples 7.1, Fig 7-12, 8.1, Fig 8-14 and 14.2 Fig14.14. Pirson's method relies on prudent selection of ROS and z., Pirson pp 257 and 57. Here, it is proposed to use ROS = 2z and to then solve both F & Z simultaneously, details of the derivation are found in the appendix. The alternative is to base ROS on oil or gas gravity. This was discarded because such information is not recorded on Log header. If the analyst has confidence in type and gravity of the HC zone, they may wish to use an ROS value in lieu of 2Z.

Shaly Sections

Alpha indicates shale as ASP/SSP, at 1 is zero shale and zero for 100% shale. The static SP is SSP = -Klog(Rmf/Rw), where K is a mild function of formation temperature, detailed in appendix. Doll proposed modification of the ratio equation in Rxo form by the term of alpha and has been regularly accepted. What is proposed here is to use Doll's alpha term in the Ri form of the ratio method. In either case, Rxo or Ri, when alpha equals one (clean formations) the Doll form reverts to the clear ratio method, and there is no loss of functionality by including Doll's alpha term in a generic solution to Sw via the ratio form. Calculation of shaly section porosity is done by Pirson's Ft/Fa method. Again, no functionality is lost in clean sections, for Pirson's equation gives Ft/Fa = 1 when alpha equals 1.

Use of Invasion Charts

This method uses invasion charts (R16/Rm-R64/Rm and R16/Rm-R19/Rm) to solve for Ri and Di/Dh. An exact calculation of Rt from both the long normal and lateral may not be available from ES logs. Either because the zone is too thin for correct response from R64 or a zone may be overlaid by a high resistivity streak, producing a blind spot in the lateral curve. This may be surmounted by solving Di/Dh using a plot of Ri from the lateral and normal charts vs. Di/Dh. Obtain an intersection of the Ri/Rm curves by changing the unknown deep resistivity, and both Ri/Rmud and Di/Dh are solved. Another alternative is to estimate invasion diameter and both Ri and Rt may be solved using the known deep resistivity chart.. A final alternative is to use Ri/Rm from the regressed equation of Figure 5.14, Pirson[5]., given on the program plot as Ri/Rm(Di/dh=22). Additional details are found in the appendix and spreadsheet. If no correction for bed thickness is required use Rs=Ra in the spreadsheet.

ROS - Oil Wet Rocks

Oil-wet and partially oil-wet rocks represent an exceptional class of rocks, with differences pointed out here for why the user should exclude them from this calculation. Pirson, p294 cites the Athbaska Tar sands as an oil wet system and partly oil-wet systems as: Wilcox of OKC and Sims and Springer at Sholem-Alechem, OK, the Tensleep at Little Buffalo and Elk basins Wyoming, many Permian Basin limestone and dolomites and the Dollard and Instow fields of Canada. Such situations are typically recognized by very low Sw when calculated with n=2. A value of n =3 for Springer sand and n =4 in the Tensleep is proposed by Pirson.

He notes on pg294, "a pronounced ROS gradient is within the flushed and invaded zones .. .. accordingly it is no longer justified to assume the same degree of ROS in the flushed and invaded zone proper .. flushed zone ROS is much less than 20-30% and much more in the invaded zone, on order of 50-75%, 70% recommended average, ... since water based muds contain surface active chemicals, the flushed zone may be rendered water wet, where n=2 may apply in the flushed zone but not in the invaded zone. Additionally calculation of kro and krw are different than those used in the spreadsheet.

The ratio of Ri/Rt is determined from Invasion charts. However, before using invasion charts, correction for both borehole diameter and bed thickness must be applied. Typically, neither Long Normal R64") nor Long Lateral (R18'8" or R19) need be corrected for borehole conditions.

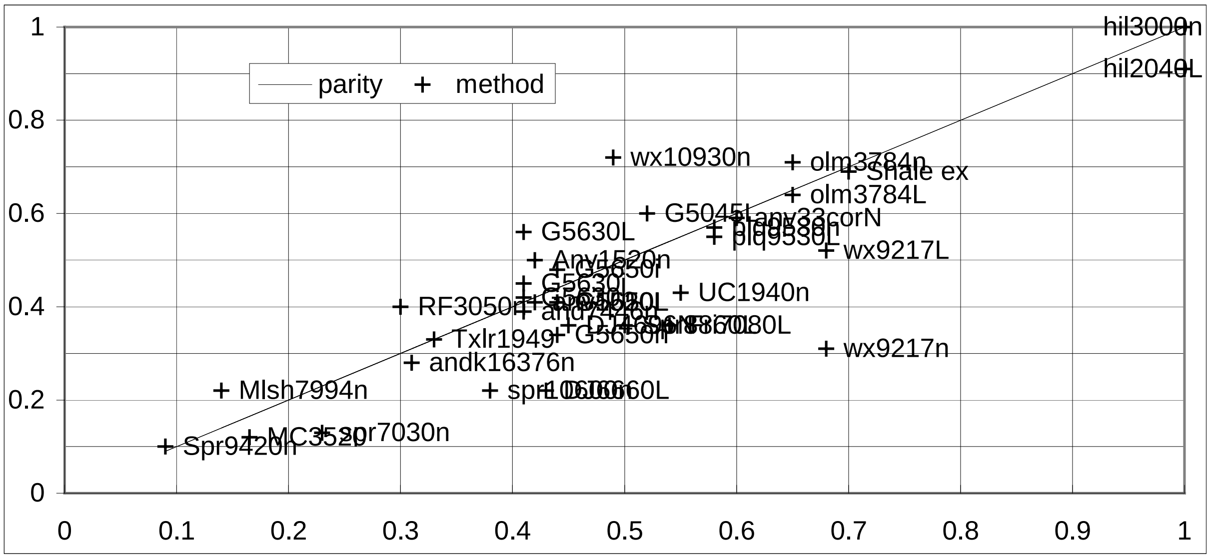
Results

The results of this calculation routine are compared in below graph. The RR to parity is 80% with error of estimate of +/- 10%. One reason for the variation is the difference in Doll's ratio method, Eq,1 and Pirson's Ratio method for cases of shaly formations i.e.:

$$(Ft/Fa)(1-ROS)^2 Ri/Rz=F=S^2 Rt/Rw \Rightarrow S=\sqrt{\{(Ri/Rt)(Ft/Fa)(1-ROS)^2[Z+(1-Z)/(10^{(SSP/K)})]\}}$$

The difference according to Pirson, World Oil part2,pg5, is that Doll's Equation, Eq.1, "calculates the free water not bound to clay," while his method gives total water both bound and free, from which Pirson subtracts the hydrated water, $H = 1-\alpha+SSP*(0.36*\alpha^3-\alpha^2+0.64*\alpha)/34$.

In the case where the formations are clean, the difference is [(1-ROS)/Sw^0.2]^2. In other words, how well does Sw^0.2 approximate (1-ROS). When using ROS one must use ROS =0 for formations devoid of HC, while systems using a power term for Si or Sxo naturally arrive at (1-ROS) =1. Hence the selection of (Sxo=S^0.2) system for spreadsheet calculation.



e/AM	e/AO	R16/Rs	R19/Rs	CF16	CF19	R19c	R16c	R16/Rm	R16c/Rm	R19c/Rm
2.25	0.16	1.40	1.75	1.25	1.40	4.90	5.25	2.69	2.56	2.51
Rm	Rmf	R16	R19	e,"				Ri/Rm	Rt/Rm	Ri/Rt
1.95	1.31	4.20	3.50	36				2.25	2.50	0.90
	SSP	ASP	alpha	T,F	K	H	Ft/Fa	FreeW	Ft	Swdoll
	-50	-35	0.70	121	-76	0.63	1.60	0.07	5.37	0.56

The preceding Table represents the method using this variant of Doll's Equation. Data of the Table is from an ES of the upper cretaceous shaly glauconitic Olmos sand of BigFoot Field, Frio County Texas, at MD of 3787 feet presented by Pirson[12].

Water saturation as calculated by modified Doll equation (presented above) was 56%. Pirson[12] commented, "this is one of the most shaly oil producing sands known . . . at this location the Olmos sand produces clean oil, even though the water saturation is 65% as determined by core analysis".

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Appendix 1

Relation of Z to ROS and Porosity, derivation of Z(porosity)

Formulations for solution of Z vary widely, but typically tend to relate Z to porosity. Some formulations listed by Pirson are: 1/F, $1/F^{1.41}$, and by tabulation to right:

por, v/v	<10	10/15	15/22	18/25	>25
k, md	<10	10/100	100/500	0.5-1k	>1k
Di/Dh	10	5	3	2	2
z	0.025	0.05	0.075	0.10	0.15

A simple formulation of z is just (por/2-0.01). Tixier’s Rocky Mountain, RM, method used Z=0.075 for medium porosity sands and 0.05 for medium porosity carbonates. Tixier’s RM is not applicable to high porosity carbonates nor unconsolidated nor high porosity sands.

To have a general solution requires simultaneous solution of both Z and porosity. The below table summarizes values for z listed by Pirson. A regression of F verses z was made using an averaged F of Humble formula and inverse squared porosity. The regression fit was rr=0.94 with equation of $F = 1/(2.5Z^{1.62})$.

por v/v	0.075	0.125	0.185	0.21	0.28	0.14	0.21	0.28
z(Ri)	0.025	0.05	0.075	0.1	0.15	0.05	0.075	0.1
Ref. page	257	257	257	257	257	57	57	57

Appendix 2

ROS Values in Water Wet Rocks

Pirson, pg 57 gives the following generalizations about ROS, “Residual oil and gas saturations are postulated for lack of better information, but they are assumed using rock properties as a guide.. Low porosity, <15% and k< 3md, it is possible that no invasion exists, if k<5,100md>, ROS depends on filtrate loss ie, <10cc/30min ROS =30% heavy oils and 20% light oils, if filtrate loss exceeds 10cc/30min, 20% low API, and 10% light oil. If porosity >15% & k <100md, ROS=20%, if k>100md, ROS expected to be 30%, and in case of gas, 30% ROS should be assumed in most cases.”

Pirson, page 122, lists ROS for various API ranges. Asquith repeats the table on p44. Pirson's API-ROS values regressed with 95% confidence to:

ROS= [1-2API/100]/3, if gas use 0.30

An alternative for ROS is to use mixing factor, as follows:
Pirson, pg 257, lists z as a function of porosity, which can be regressed to z = por/2-0.01 re-arranging to 2Z = por v/v - 0.02, from part 1, use the generalization, ROS = por - 0.02, substitution gives the formulation of :
2Z=(ROS+0.02)-0.02 => **ROS = 2Z** Eq. 2d
It is elected to solve Z in Eqn. 2c and 2b using the substitution of 2d unless more specific information is available to better characterize ROS.

Appendix 3

Derivation of simultaneous solution equation for solving Z with Invasion charts

Pirson's gives: $F=(Ft/Fa)(Ri/Rz)(1-ROS)^2$ & with $F = 1/(2.5Z^{1.62})$ it is possible to solve Z as follows:

$(1/F)(Ft/Fa)(1-ROS)^2 = Rz/Ri$, but $1/F=2.5Z^{1.62} \Rightarrow 2.5(Ft/Fa)Z^{1.62}(1-ROS)^2 = Rz/Ri$

and $1/Rz = z/Rw +(1-z)/Rmf$ and substitute for Rz gives

$2.5[\mathbf{Z}/Rw+(1-\mathbf{Z})/Rmf](\mathbf{Z}^{1.62})(Ft/Fa)(1-ROS)^2 = 1/Ri$

take both sides by Rmf/2.5 and collect common **Z** terms =>

$[Z(Rmf/Rw -1)+1](Z^{1.62})(Ft/Fa)(1-ROS)^2 = Rmf/(2.5Ri)$

arrange to:

$[Z^{2.62}(Rmf/Rw - 1)+ Z^{1.62}](1-ROS)^2 -Rmf/[(Ft/Fa)2.5 Ri] \equiv \mathbf{g}(Z) =0$ Eq.2

For solution of Z use Newton method of $Z_{i+1}=Zi-(gi/g'i)$ and Z1=Rmf/Ri

Solve g' using $g' = dG/dZ = \partial G/\partial Z + \partial G/\partial(1-ROS)\ \partial(1-ROS)/\partial(ROS)(dROS/dz)$

if ROS = 2Z then $(dROS/dz) =2$ & $\partial(1-ROS)/\partial(ROS) = -1$

$dG/dZ = \partial G/\partial Z -2\partial G/\partial(1-ROS) = \partial G/\partial Z -2*2*[Z^{2.62}(Rmf/Rw - 1)+ Z^{1.62}](1-ROS)$

$dG/dZ = \partial G/\partial Z -2\partial G/\partial(1-ROS) = \partial G/\partial Z -4[Z^{2.62}(Rmf/Rw - 1)+ Z^{1.62}](1-ROS)$

$\partial G/\partial Z = [2.6Z^{1.6}(Rmf/Rw - 1)+ 1.6Z^{0.6}](1-ROS)^2$

$dG/dZ = [2.6Z^{1.6}(Rmf/Rw - 1)+ 1.6Z^{0.6}](1-ROS)^2 \; -4[Z^{2.62}(Rmf/Rw - 1)+ Z^{1.62}](1-ROS)$

$dG/dZ = [2.6Z^{1.6}(Rmf/Rw - 1)+ 1.6Z^{0.6}](1-2z)^2 \; -4[Z^{2.62}(Rmf/Rw - 1)+ Z^{1.62}](1-2z)$

arrived at by substitution of ROS = 2Z & g' = dG/dZ

$g' = (1-2Z)\{[2.6Z^{1.6}(Rmf/Rw- 1)+ 1.6Z^{0.6}](1-2Z) -4[Z^{2.6}(Rmf/Rw- 1)+ Z^{1.6}]\}$,dist.(1-2Z)

Recap:

$g' = \{[2.6Z^{1.6}(Rmf/Rw- 1)+ 1.6Z^{0.6}](1-2Z)^2 - 4(1-2Z)[Z^{2.6}(Rmf/Rw- 1)+ Z^{1.6}]\}$	Eq. 2a
$g(Z) = [Z^{2.62}(Rmf/Rw - 1)+ Z^{1.62}](1-2Z)^2 -Rmf/[(Ft/Fa)2.5 Ri] \equiv 0$	Eq.2

in event ROS is not dependent on Z, as used by Pirson, then **g**(Z) and g' simplify to

$g' = [2.6Z^{1.6}(Rmf/Rw - 1)+ 1.6Z^{0.6}](1-ROS)^2]$ Eq.2c

$\mathbf{g}(Z) = [Z^{2.62}(Rmf/Rw - 1)+ Z^{1.62}](1-ROS)^2 -Rmf/[(Ft/Fa)2.5 Ri] \equiv 0$ Eq.2b

Appendix 4 Ancillary Equations used in the algorithm:

Shoulder & Bed Thickness Effects:

Corrections for R16 and R19 are made from Guyod[40] Charts 10-6 and 6-19, correction for R16 borehole effect from Figure 2 Pirson[12] .

Normal Sondes Correction for Bed thickness, R16 or R64:
IF{e<1.5*AM, err, Rn[1+LN(Rn/Rs)/(e/AM-1)]}

Lateral Sonde Correction for Bed thickness,
R19c = R19*IF[e>AO,1,IF((CF<1),1,{(0.83-0.41*e/AO)*EXP((0.59*e/AO+0.16)*R19/Rs}]

Invasion Zone Resistivity, Ri,

As a guide to Di/dh, Pirson p144 lists values of Di/dh and porosity, these values were regressed to the averaged formation factor as: $0.27F^{0.7}$

A)R64 & R16,
Invasion effects, relate to Ri/Rm, from Figure 8-12 and 8-13 Pirson[15, 5] .
IF((R16c/Rm)>(10),
(EXP((0.24*LN(AM/Dh)-0.032)*(LN(R16c/Rm))^2+(-1.41*LN(AM/Dh)+1.32)*LN(R16c/Rm)+(2.38*LN(AM/Dh)-1.05))),
IF((Ri-low)>(3*R16c/Rm),R16c/Rm,3.1-5.95*R64c/Rm+4.26*R16/Rm+0.51*(R64c/Rm)^2-0.1*(R16c/Rm)^2))

B)R18-8, R16 Combination
=IF((H25)>(10),(EXP((0.24*LN(16/H12)-0.032)*(LN(H25))^2+(-1.41*LN(16/H12)+1.32)*LN(H25)+(2.38*LN(16/H12)-1.05))),
IF((3.1-5.95*H26+4.26*H24+0.51*H26^2-0.1*H25^2)<(1.3),
(1.76*H25-0.72*H26+0.02*(H26-1)^2-0.07*(H25-1)^2),3.1-5.95*H26+4.26*H24+0.51*H26^2-0.1*H25^2))

For older ES tools, Pirson proposed calculation of apparent F, Fa, from either Ri or Rx and then determining a true F from SP and α, he followed by determining water bound in the shale, H. Pirson's method is a ratio method, which does not adjust the saturation exponent, but includes the term Ft/Fa under the saturation radical.

Ft/Fa = exp[0.0307(α - 1)SSP], and H = [(1-α)+m(SSP)], m=$(0.36\alpha^3 - \alpha^2 + 0.64\alpha)/34$

Pirson's calculation of Hydrated Water determines free water as Archie Water less Hydrated Water, ie at BVW =0.1, 0,3 por, Sw 0.542, -63.5mv, α=0.29 Ft/Fa = 4, H=0.496 free water is 0.542-(0.496)=0.046 or 4.6% free water.

SSP

Effect of bed thickness on SP from 6-6. Pirson[15] . Such corrections are in calculator section. SSP values may also be determined from thick clean section at approximate depth of concerned section. Another alternative is from water catalogue using K(T) and Rmf/Rw.

Rt

Hilchie advocated correcting R64 to Rt as R64*(R64/R16). Looking at invasion charts, it can be seen that this is only valid if Ri/Rm >10. In cases where Ri/Rm<10, the long normal R64, reads very nearly Rt.

In case of Lateral, the program corrects only for thickness and shoulder effects using a regressed form of Guyod's charts.

RELATIVE PERMEABILITY

Pirson's methods were used for kro and krw:

krhc=IF(oil,[(1-((Sw-Swi)/(1-Swi-ROS)))^2],((1-Swm)*(1-(Swm*FRw/Rt)^0.25)*0.5))

Swi = BVW/por + H H is Pirsons hydrated water for shale systems

Swm = IF((Sw-Swi)<0,0.01,(Sw-Swi)/(1-Sw))

krw=((FRw/Rt)^1.5)*SQRT(Swm)

PERMEABILITY

For sands, use the Wylie-Rose[13] equation and carbonates, use the Armstrong Equation[14], as follows:

=IF(sand,(70*por-s^2.25/Swi)^2, otherwise

IF((k-carb)>200,(por-c^1.5*(1/Swi-1)^1.9),(k-carb=10*por-c^1.5*(1/Swi-1)^1.9)))

PRODUCTIVITY

Pirson's' methods were used to calculate productivity and production water ratios as:

cfd/dpsi = K*krhc*he/(Bg*ug) Bg in SCF/cf

bpd STO/dpsi =K*krhc*he/(Bo*uo) Bo in STB/BBL

WGR=Bg (krw/krg)(ug/uw) bbl/cf Bg in STB/cf

WOR= Bo (krw/kro)(uo/uw) bbl/bbl-STO

Arps equation for GOR and Bo, (R=0.1D & Bo =1.05+5D10-5, and Pirson's Equation for live oil viscosity, uo= Bo*uod/(1+4(B-1)uod) p40, with uod corrected to Tf by HP Petro Fluid Pac[8] equations.

Physical Properties Calculations for HC Productivity

In calculation of Rw, the system of Bateman Konen, Asquith[6, 16] Pg.29 is used.

Physical properties (gas-compressibility, uw, uod, u,gas, & Bgas) were calculated using the Equations presented in the HP[8] Hydrocarbon Physical Properties package and Reservoir Engineering Manual[16]. with initial Zg value from R-K method. The calculation used Arps[1] equation for GOR and Bo, (R=0.1Depth, feet & Bo =1.05+5D10-5, and Pirson's Equation for live oil viscosity, uo= Bo*uod/(1+4(Bo-1)uod) p40.

Contained in the spread sheet are several calculations for productivity by this method, with comparison to field test results..