

Appendix E

Drainage Capillary Pressure Curves in Arbuckle

The Pc curves were derived based on a theoretical method (M.F.Alavi) that relates endpoints of capillary pressure curves to Reservoir Quality Index (RQI). Based on this investigation, there are good correlations between endpoints of capillary pressure curves (entry pressure and irreducible water saturation) and RQI.

The key well (well 1-32) was used to calculate Pc curves for the Arbuckle. Generated Pc curves from the NMR log of well 1-32 were used to find correlations between endpoints and RQI for determination of Pc curves. Pc curves from NMR were in mercury-air system and then converted to a CO₂-brine system (Fig. 1).

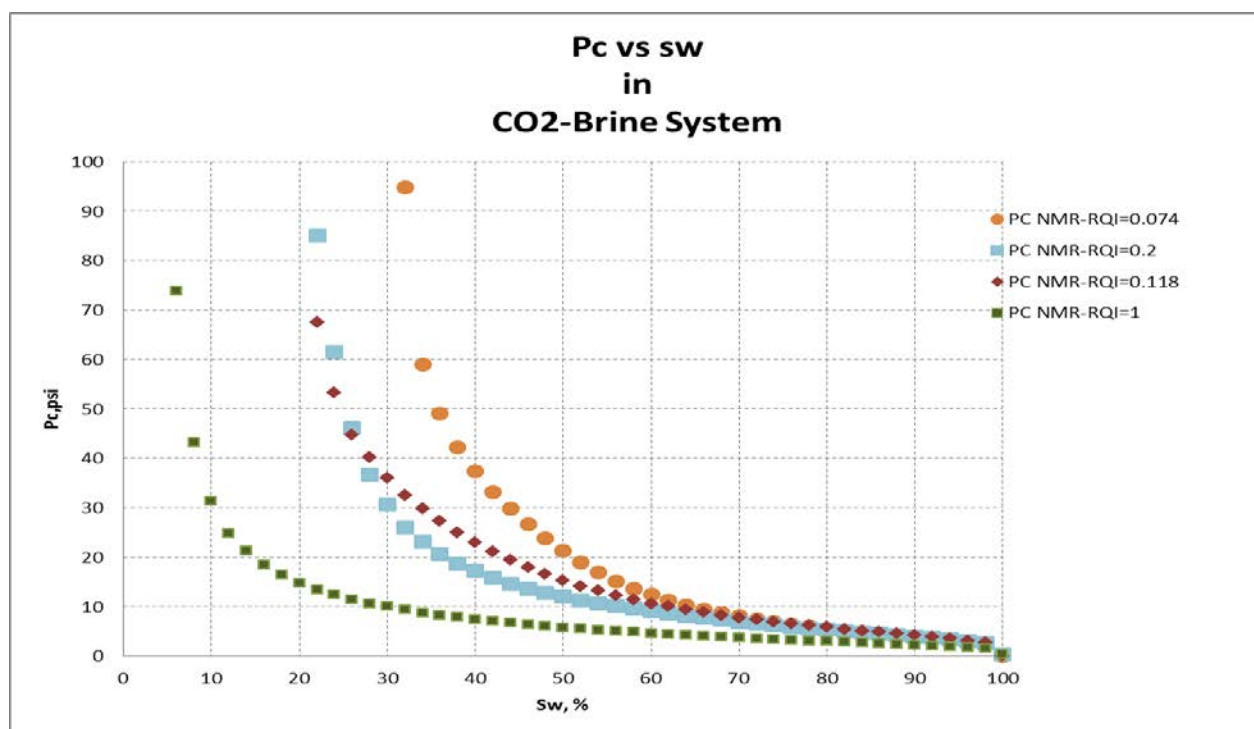


Figure 1: Pc curves generated from NMR

a. Entry Pressure

Based on SCAL data of other fields, a good correlation can be found between capillary entry pressure and RQI. Pore throat at entry pressure in well 1-32 was determined from Winland R35, and entry pressure was calculated from pore throat radius. Winland R35 was calculated using Equation 1:

$$\log R35 = 0.732 + 0.588 \log K - 0.864 \log \phi \quad \text{Eq. 1}$$

Previously, the permeability of the Arbuckle in Well 1-32 was determined. Based on porosity and the calculated permeability of Well 1-32, RQI in this well was obtained. R35 was plotted against RQI in fig. 1 to find an equation in terms of RQI:

$$R35=12.885RQI^{-1.178} \quad \text{Eq. 2}$$

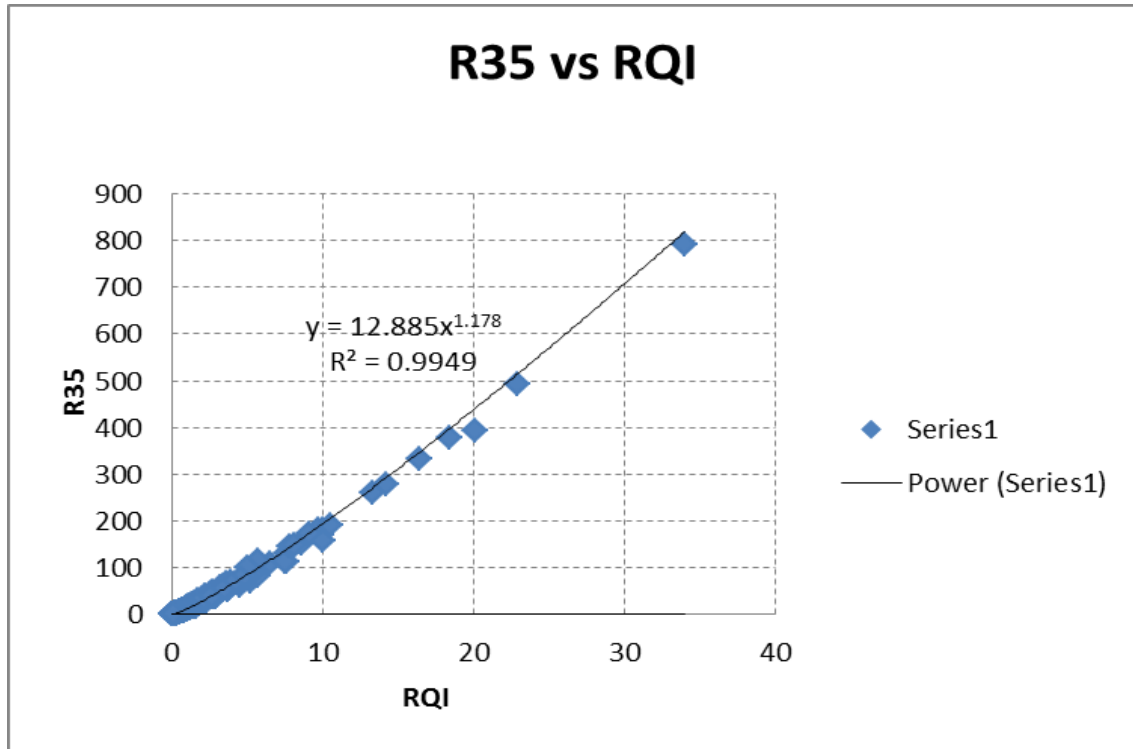


Figure 2: R35 versus RQI

Equation 2 was multiplied by a factor (1.35) to calculate the entry pore throat radius (Equation 3). The factor, 1.35, was determined based on studies of other carbonate reservoirs.

$$R_{\text{entry}} = 1.39 * (a * RQI^b) \tag{Eq. 3}$$

Entry pressure was calculated using Equation 3 and interfacial tension between CO₂ and brine, Equation 4:

$$P_e = \frac{2 * \sigma \cos\theta * 0.147}{1.39 * (a * RQI^b)} \tag{Eq. 4}$$

A function between entry pressure and RQI was found by calculating Equation 4 for P_{entry} in terms of RQI. Interfacial tension of 30 dyne/cm was calculated using an equation from an article, “*Interfacial Tension Data and Correlations of Brine/CO₂ Systems under Reservoir Conditions, (Chalbaud et al. 2006).*” A contact angle of zero was used for the CO₂-brine system. After simplifying, Equation 4 becomes:

$$P_e = 0.49 * RQI^{-1.178} \tag{Eq.5}$$

b. Irreducible Water Saturation

Irreducible water saturation is needed to calculate normalized non-wetting phase saturation (S_{nWn}). Based on irreducible water saturation of SCAL data, mainly carbonate reservoirs, irreducible water saturation at certain capillary pressure can be correlated very well to the RQI of the rock. There is a good correlation between irreducible water saturation of reservoir rocks and RQI. NMR data of Well 1-32 were used to determine irreducible water saturation at a P_c of 20 bars (290 psi). Also interfacial tension between CO₂

and water was given to the Tech-Log Module to find Swir versus depth for this well. Irreducible water saturation in Well 1-32 in the Arbuckle is plotted against RQI in fig. 3.

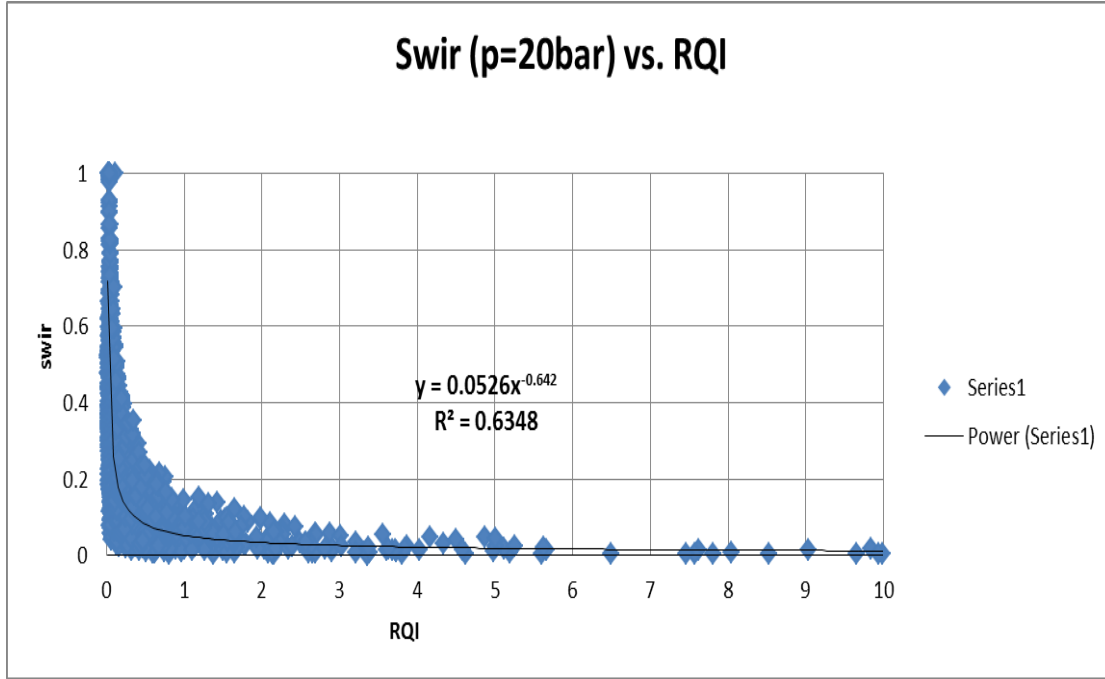


Figure 3: Irreducible water saturation vs. RQI

The relation between swir and RQI was obtained from Figure 3, Eq. 6.:

$$\text{Swir} = 0.0526 * \text{RQI}^{-0.642} \quad \text{Eq. 6}$$

c. Shape of Normalized Pc curve

The Pc curves that were obtained from NMR (fig. 1) were normalized by plotting SnWn (Normalized Non-Wetting Phase Saturation, Equation 9) versus EQR (Equivalent Radius, Equation 7). The shape of normalized Pc curves appears in fig 4. To find EQR at any Pc, entry pressure of the Pc curve was used. A function in the form of Equation 7 was fit through the normalized data points in fig. 4 and constants a and b of this equation were found.

$$S_{nwn} = (1 - aEQR)(1 - EQR^b) \quad \text{Eq. 7}$$

$$a = 1 * 10^{-6}$$

$$b = 0.898$$

Equivalent radius is a function of entry pressure and capillary pressure (Equation 8), where entry pressure is a function of RQI, which is given by Equation 5.

$$EQR = \frac{P_e}{P_c} \quad \text{Eq. 8}$$

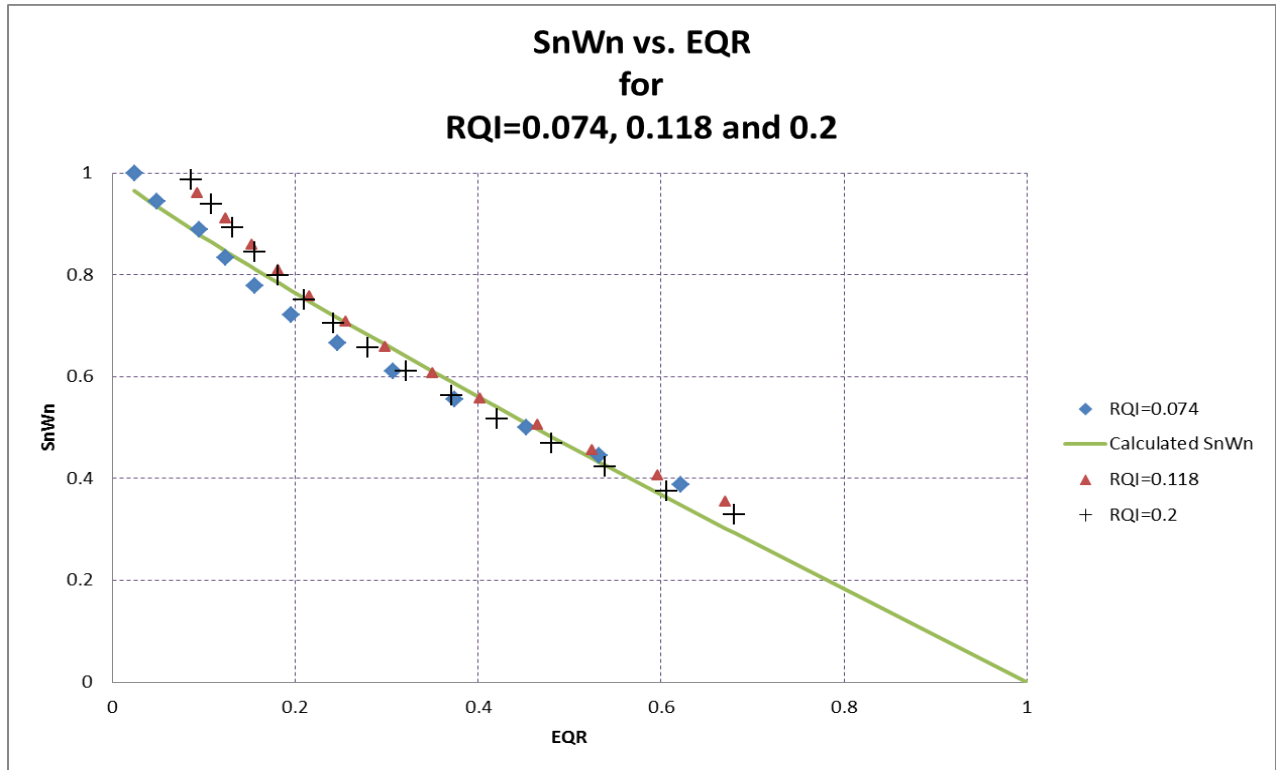


Figure 4: SnWn vs. EQR for RQI 1, 5.19 and 20

Equation 9 defines SnWn (normalized non-wetting phase saturation). Irreducible water saturation was calculated using equation 6 and initial water saturation is known at every Pc.

$$S_{nwn} = \frac{1-S_{wi}}{1-S_{wir}} \quad \text{Eq. 9}$$

Values of constants a and b of Equation 7, which were derived by regression before, were replaced in Equation 7 to get Equation 10. This equation will be used to calculate drainage capillary pressure curves.

$$S_{nwn} = (1 - 1 * 10^{-6} \frac{P_e}{P_c}) (1 - \frac{P_e^{0.898}}{P_c}) \quad \text{Eq. 10}$$

d. Calculation of Drainage Capillary Pressure Curves

Equation 11 is obtained from Equation 9 and will be used for calculating drainage water saturation:

$$S_{wi} = 1 - S_{nwn}(1 - S_{wir}) \quad \text{Eq. 11}$$

According to Equation 11, initial water saturation (Swi) is a function of Snwn . It was shown that Snwn is a function of Pe and Pc (Equation 10), where Pe is a function of RQI. Snwn in Equation 11 can be replaced by respective functions and an equation can be obtained that expresses Swi in terms of RQI and Pc:

$$S_{wi} = 1 - \left(1 - a \frac{0.507RQI^{-1.178}}{P_c}\right) \left(1 - \left(\frac{0.507RQI^{-1.178}}{P_c}\right)^b\right) (1 - 0.0526RQI^{-0.642}) \quad \text{Eq.12}$$

Constants (a and b) were previously found (Equation 7). They were incorporated into Equation 12, which gives water saturation for every Pc and RQI. Nine Pc curves were calculated for nine rock types. RQI in the Arbuckle changes from 0.017 to 34. This range was divided into nine subdivisions (table 1):

Table 1: Subdivisions of RQI range

RT	RQI from	RQI To	Ave RQI
1	40	10	25
2	10	2.5	6.25
3	2.5	1	1.75
4	1	0.5	0.75
5	0.5	0.4	0.45
6	0.4	0.3	0.35
7	0.3	0.2	0.25
8	0.2	0.1	0.15
9	0.1	0.01	0.055

The mid-range of each subdivision was used to calculate 9 Pc curves using Equation 12, Table 2. The generated Pc curves are shown in fig. 5. These curves are in agreement with NMR Pc curves, when the right permeability and RQI are considered and compared (fig. 6). [Figure 7](#) shows water saturation by Equation 12 compared to water saturation from NMR capillary pressure module. The two water saturations are in good agreements which indicate the accuracy of the generated water saturation by equation 12.

Nomenclature

- a = constant
- b = constant
- EQR = Equivalent Radius
- NMR = Nuclear magnetic resonance
- P_e = Entry Pressure
- PC =capillary pressure
- RQI = Reservoir Quality Index (μm)
- $R35$ = Winland R35
- R_{entry} = pore throat radius at entry pressure
- $Snwn$ = Normalized non-wetting phase saturation
- Swi =Initial water saturation
- S_{wir} = Irreducible water saturation (fractional pore volume)

Table 2: Nine Pc curves for nine RQI

a		b		Drainage PcTable in Arbuckle						
0.000001		0.89773								
RQI	25	6.25	1.75	0.75	0.45	0.35	0.25	0.15	0.055	
Pe	0.011107	0.056862	0.254725	0.691113	1.261498	1.696129	2.521144	4.601882	15.00457548	
swir	0.006661	0.016219	0.036724	0.06327	0.087826	0.103203	0.128088	0.177801	0.338589041	
Pc	swi									
0	1	1	1	1	1	1	1	1	1	
0.1	0.145	0.609	1	1	1	1	1	1	1	
0.2	0.081	0.334	1	1	1	1	1	1	1	
0.3	0.058	0.237	0.868	1	1	1	1	1	1	
0.4	0.046	0.187	0.679	1	1	1	1	1	1	
0.5	0.039	0.156	0.563	1	1	1	1	1	1	
0.6	0.034	0.135	0.483	1.000	1	1	1	1	1	
0.7	0.031	0.120	0.425	0.989	1	1	1	1	1	
0.8	0.028	0.108	0.382	0.885	1	1	1	1	1	
0.9	0.026	0.099	0.347	0.802	1	1	1	1	1	
1	0.024	0.091	0.319	0.736	1	1	1	1	1	
2	0.016	0.056	0.188	0.424	0.691	0.877	1	1	1	
3	0.013	0.044	0.142	0.314	0.507	0.641	0.874	1	1	
4	0.012	0.038	0.118	0.257	0.412	0.518	0.704	1.000	1	
5	0.011	0.034	0.103	0.222	0.353	0.443	0.600	0.941	1	
6	0.010	0.031	0.093	0.198	0.313	0.392	0.528	0.826	1	
7	0.010	0.029	0.086	0.180	0.284	0.354	0.477	0.742	1	
8	0.009	0.028	0.080	0.167	0.262	0.326	0.437	0.678	1	
9	0.009	0.027	0.076	0.157	0.244	0.304	0.406	0.628	1	
10	0.009	0.026	0.072	0.148	0.230	0.286	0.381	0.587	1	
12	0.009	0.024	0.067	0.136	0.209	0.258	0.343	0.526	1	
14	0.008	0.023	0.063	0.126	0.193	0.238	0.315	0.481	1.00	
20	0.008	0.021	0.056	0.109	0.164	0.201	0.264	0.398	0.850	
30	0.007	0.020	0.050	0.095	0.141	0.171	0.222	0.331	0.694	
40	0.007	0.019	0.047	0.088	0.129	0.156	0.201	0.296	0.613	
50	0.007	0.018	0.045	0.083	0.121	0.146	0.188	0.274	0.563	
60	0.007	0.018	0.044	0.080	0.116	0.140	0.179	0.260	0.529	
70	0.007	0.018	0.043	0.078	0.113	0.135	0.172	0.249	0.505	
80	0.007	0.018	0.042	0.076	0.110	0.131	0.167	0.241	0.486	
90	0.007	0.018	0.042	0.075	0.108	0.129	0.163	0.235	0.471	
100	0.007	0.017	0.041	0.074	0.106	0.126	0.160	0.230	0.459	
150	0.007	0.017	0.040	0.071	0.100	0.119	0.150	0.214	0.422	
200	0.007	0.017	0.039	0.069	0.097	0.116	0.145	0.206	0.403	
300	0.007	0.017	0.038	0.067	0.095	0.112	0.140	0.197	0.384	

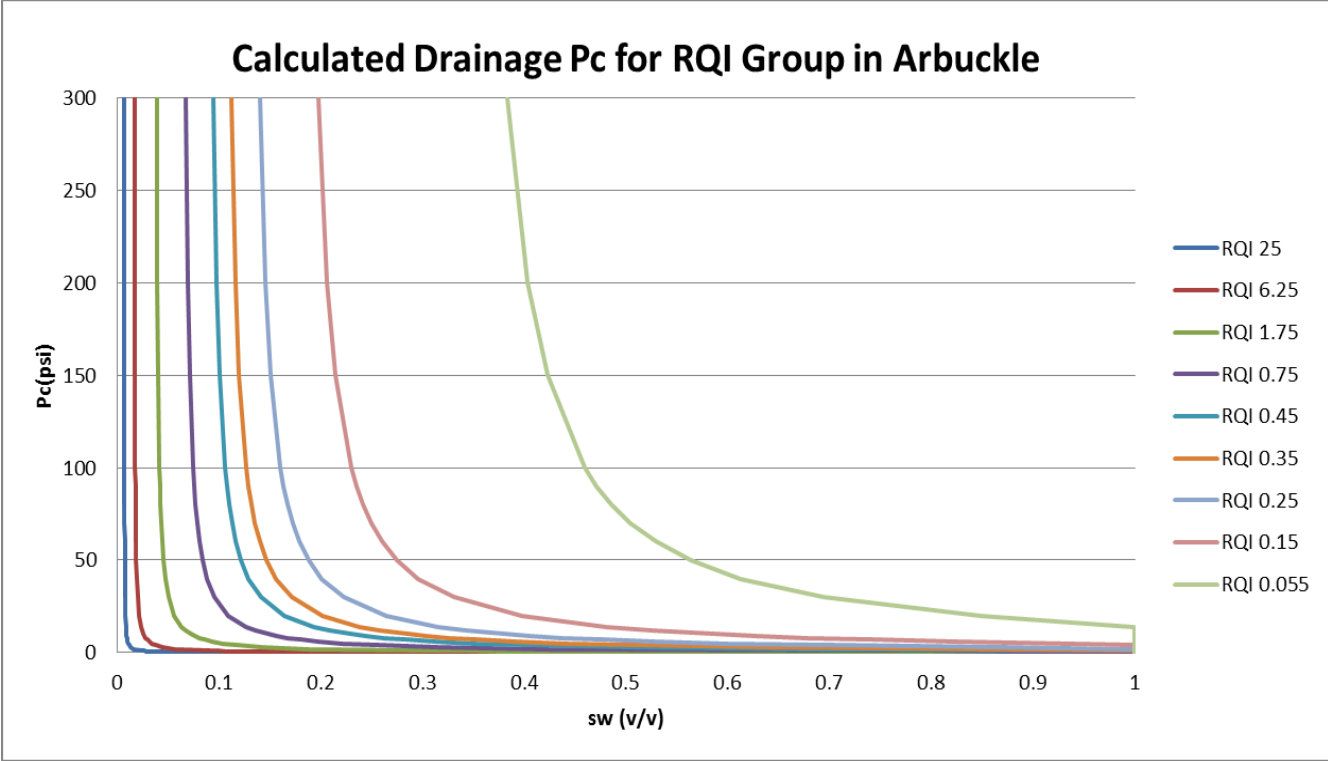


Figure 5: Nine Pc curves for nine rock types for the specified RQI

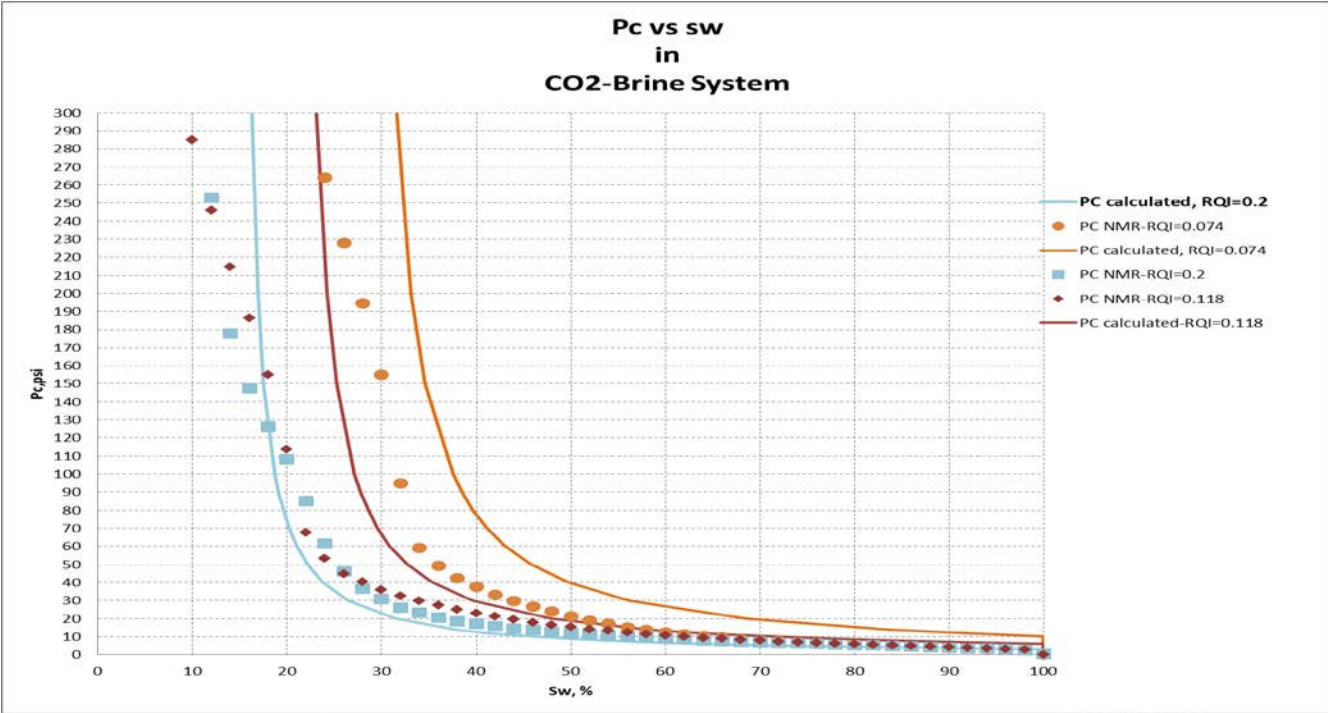


Figure 6: Calculated Pc compared with generated Pc from NMR

SW vs. Depth in Arbuckle

