Appendix A

Relative Permeability Curves in the Arbuckle

Introduction

Relative permeability curves play major roles in simulation for the following reasons: 1) Distribution and residual trapping of CO_2 are dependent on drainage relative permeability curves and, in addition, imbibition curves and hysteresis play important roles in calculating the residual CO_2 that can be permanently immobilized in the subsurface (Krevor et al., 2012). 2) Accurate characterization of relative permeability is important to determine the correct injectivity and, therefore, to minimize the number of injectors for more efficient injection rates and injection volume (Krevor et al., 2012).

There have been some studies, including laboratory experiments, of relative permeability in CO_2-brine systems for different samples in carbonate and sandstone reservoirs (e.g., Bennion and Bachu, 2008; Krevor et al., 2012). However, most and very likely all of the experimental studies do not represent the actual maximum CO_2 relative permeability ($KrCO_{2max}$) and the maximum CO_2 saturation (SCO_{2max}) correctly. In Bennion and Bachu (2005, 2008) studies, maximum measured relative permeability ($KrCO_{2max}$) is 0.54 and more often samples with higher absolute permeability have lower $KrCO_{2max}$ than samples with lower absolute permeability. Often there is no consistency in $KrCO_{2max}$ measurements achieved in the laboratory experiments and inconsistency in maximum CO_2 saturation (SCO_{2max}) and Corey exponents can be seen. Krevor et al. (2012) and Benson et al. (2015) showed that maximum experimental CO_2 saturations (SCO_{2max}) and $KrCO_{2max}$ are limited by the capillary pressure (CO_2 pressures) that can be achieved in the experiment and therefore their values are always lower than the actual. Because of the unattainable high capillary pressure during the experiments when 100% CO_2 is injected, irreducible water saturation cannot be achieved and, therefore, measured $KrCO_{2max}$, CO_2 Corey exponents are inferior.

Another issue is that CO_2-brine relative permeability lab measurements are expensive to run and limited to few samples. Moreover, relative permeability curves vary with different samples and so one set of relative permeability curves cannot represent relative permeability for all rock types in a reservoir. Different sets of relative permeability curves are needed for different samples. In this work, different relative permeabilities were calculated for different Reservoir Quality Index (RQI) ranges, which are more representative and realistic and specific to the Arbuckle reservoir. Drainage and imbibition relative permeability curves were calculated for a CO_2-brine system based on a water-wet system in the Arbuckle. Nine drainage and nine imbibition curves were calculated for nine rock types based on RQI.

I. Drainage Relative Permeability Curves

Nine drainage relative permeability curves were calculated using the equations below (previously patented formula: SMH reference No: 1002061-0002):

$$KrCO2 = krCO2_{max}(1 - Sw_N)^p \qquad \text{(Equation 1)}$$

$$Krw = krw_{max} * (Sw_N)^q \qquad \text{(Equation 2)}$$

$$Sw_N = \frac{(Sw - Swir)}{(1 - Swir)} \qquad \text{(Equation 3)}$$

$$Krw_{max} = 1 \qquad \text{(Equation 4)}$$

$$KrCO2_{max} = 0.67\ RQI^{0.0194} \qquad \text{(Equation 5)}$$

Where,

$KrCO_2$ is relative permeability to CO_2

Krw is relative permeability to water

$KrCO_{2max}$ is maximum CO_2 relative permeability

Krw_{max} is maximum water relative permeability

SW_N is normalized water saturation

P is CO_2 Corey exponent

q is water Corey exponent

Swir is irreducible water saturation

Irreducible Water Saturation (Swir)

Swir was read at Pc equal 300 psi from the previously calculated drainage Pc curves (fig. 1). Pc curves were derived from NMR log based on CO_2-brine interfacial tension (IFT). Interfacial tension of 32 dyne/cm was calculated in CO_2-brine system based on correlations between IFT with salinity, temperature, and pressure (Bennion and Bachu, 2008). There are nine Pc curves, one for each of the nine RQI ranges; therefore, nine Swir values were obtained (fig. 1).

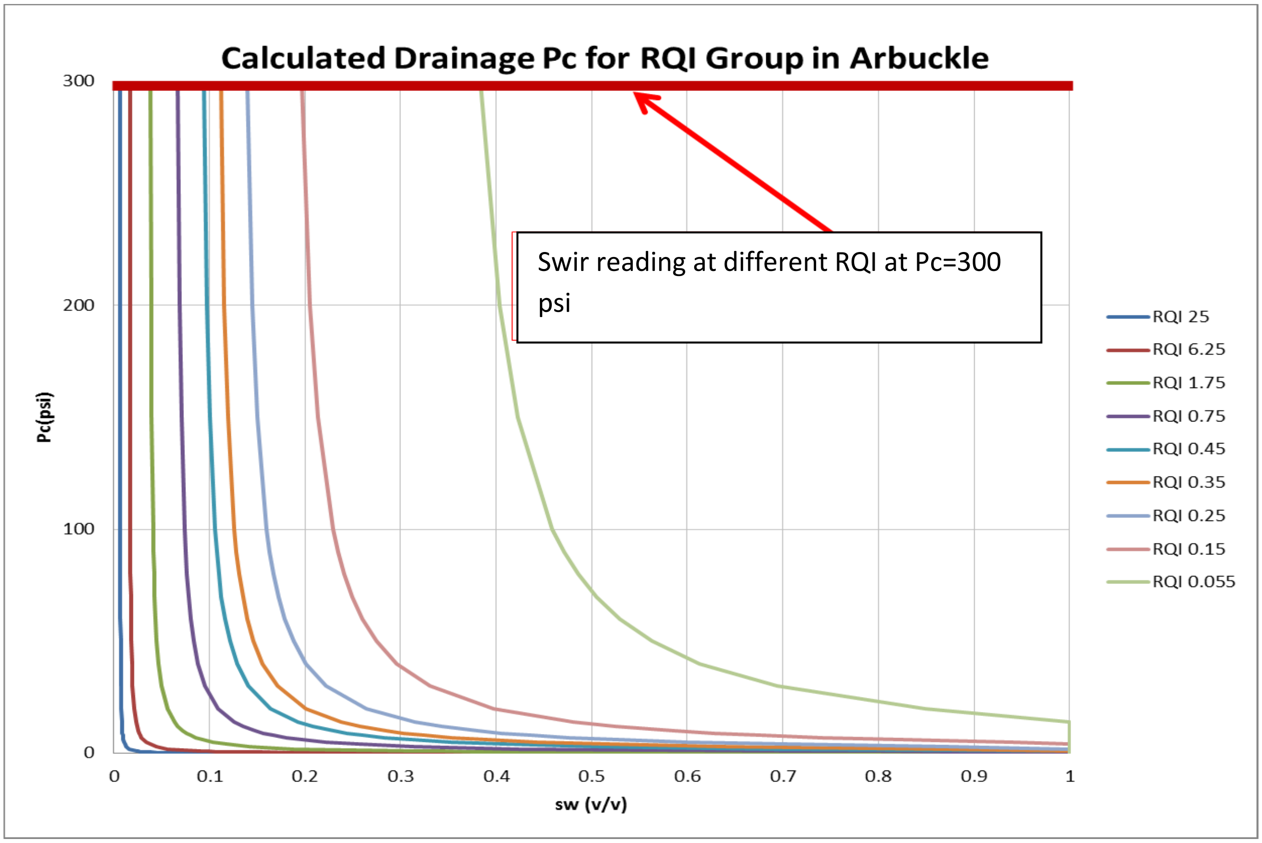


Figure 1: Drainage capillary pressure curves for CO_2-brine system in the Arbuckle.

Corey Exponent for CO_2 (p)

Literature experimental studies, including Bennion and Bachu (2005), were reviewed as discussed in the introduction of this report and, often, results indicated no consistency in Corey exponents for different permeabilities. Higher permeabilities should have higher Corey exponents than lower permeabilities, but often that was not the case. Some results also showed lower permeabilities with higher Corey exponents than the higher permeabilities. For the purpose of this work, highest and lowest Corey exponent values from Bennion and Bachu (2010) were selected for highest and lowest RQI. They were assigned to the nine RQI in descending order as indicated in table 1.

Corey Exponent for Brine (p)

Corey exponents for brine for different permeability do not have great variability and they range from 1.2 to 2.9. Therefore, the average Corey exponent of 1.91 was considered representative for all 9 RQI, Table 1.

Table 1: Values for Drainage Relative Permeability Curves

RQI	25	6.25	1.75	0.75	0.45	0.35	0.25	0.15	0.055
Swir	0.007	0.017	0.038	0.067	0.095	0.112	0.140	0.197	0.384
CO2 Corey ex	4.5	4.35	4.2	4.05	3.9	3.75	3.6	3.45	3.3
Water Corey ex	1.91	1.91	1.91	1.91	1.91	1.91	1.91	1.91	1.91

Maximum Relative Permeability of CO2 and Water ($KrCO_{2max}$ and Krw_{max})

The maximum water relative permeability (Krw_{max}) in the drainage case is always unity. Therefore, a value of 1 was used for Krw_{max} in equation 2.

Benson et al. (2015) pointed out that laboratory relative permeability measurements have limitations due to laboratory capillary pressures that can be achieved in the core measurements during experiments. Measured $KrCO_{2max}$ values in labs are always lower than actual values. Moreover, the same paper noted that measured $KrCO_{2max}$ should be scaled up in the dynamic model. Maximum achieved $KrCO_{2max}$ in most and possibly all laboratory studies is 0.54, which is lower than actual values in reservoirs. A formula was designed that can give more reasonable $KrCO_{2max}$ for each RQI in the reservoir, equation 5. Calculated $KrCO_{2max}$ using equation 4 for maximum RQI (20) is 0.71, which is more realistic than the literature results.

Drainage Relative Permeability for CO_2-Brine

Equations 1 and 2 were used to calculate CO_2 and brine relative permeability curves, respectively. All parameters are listed in table 1. Nine drainage relative permeability curves were calculated for nine rock types based on RQI (figs. 2–10).

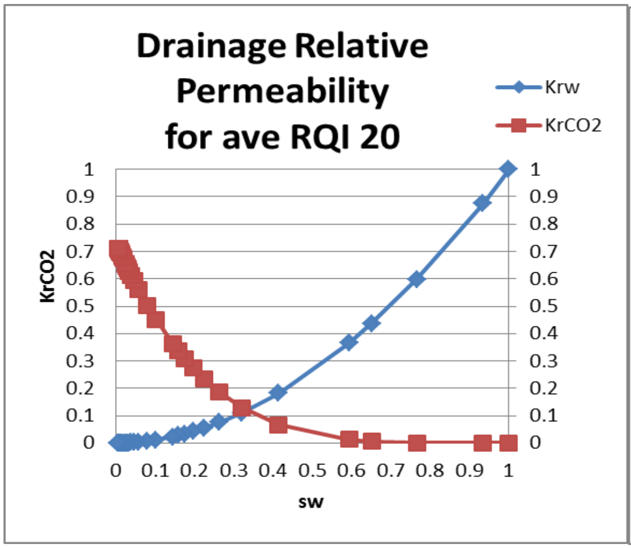


Figure 2: Drainage relative permeability for RQI 20.

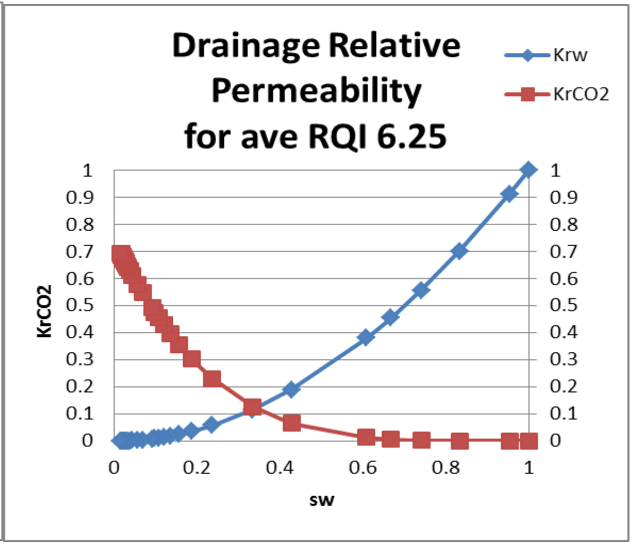
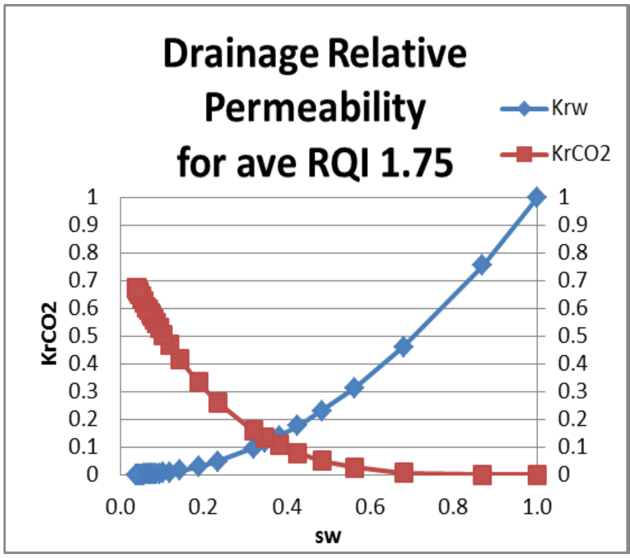


Figure 3: Drainage relative permeability for RQI 6.25.



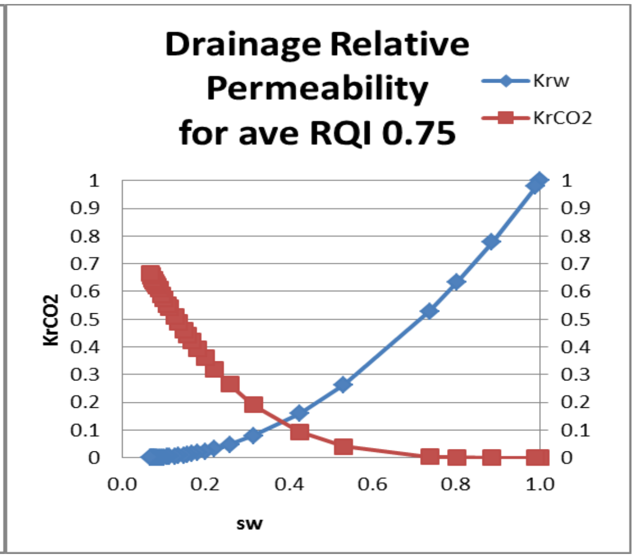
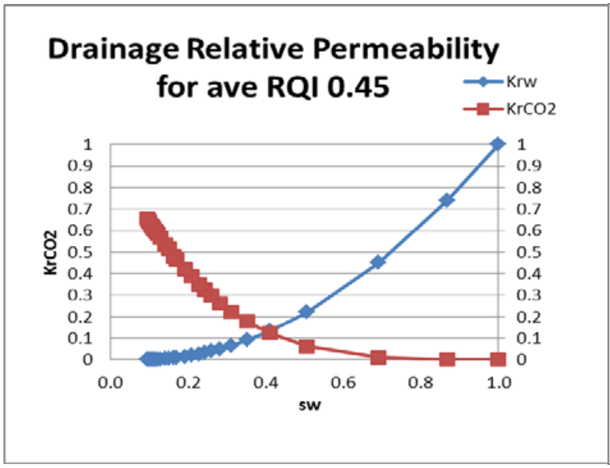


Figure 4: Drainage relative permeability for RQI 1.75. Figure 5: Drainage relative permeability for RQI 0.75.



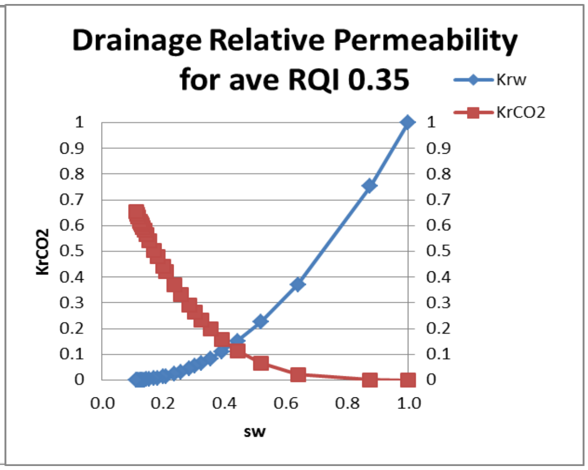
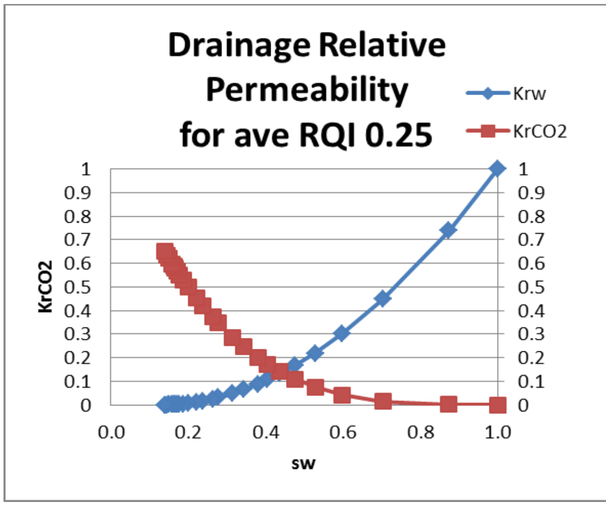


Figure 6: Drainage relative permeability for RQI 0.45. Figure 7: Drainage relative permeability for RQI 0.35.



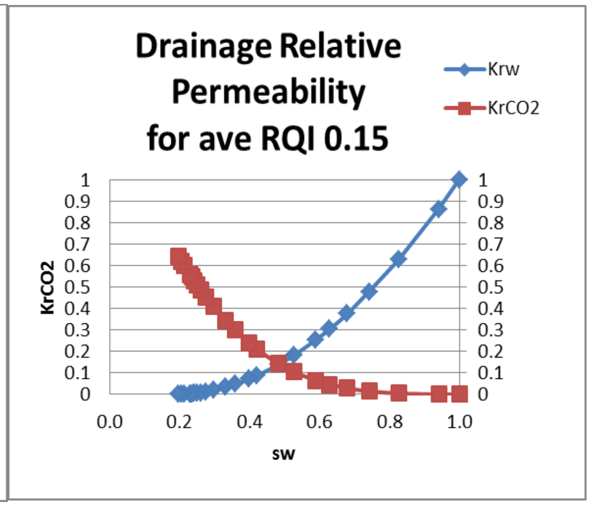


Figure 8: Drainage relative permeability for RQI 0.25. **Figure 9: Drainage relative permeability for RQI 0.15.**

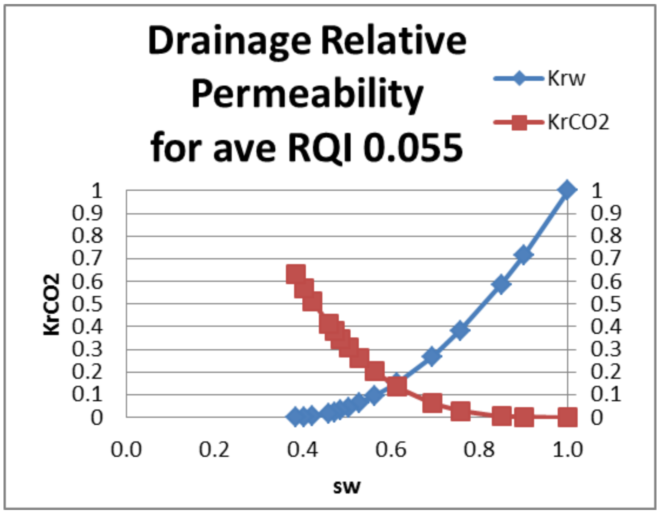


Figure 10: Drainage relative permeability for RQI 0.55.

II. Imbibition Relative Permeability Curves

After the drainage phase, CO_2 migrates to the top of formation and part of CO_2 is replaced by water in the pore space. In this phase, imbibition relative permeability curves determine fluid flow and the amount of CO_2 that is trapped in the pore space as residual CO_2 saturation. Nine imbibition relative permeability curves were calculated using the equations below (previously patented formula):

$$KrCO2 = krCO2_{max}(1 - Sw_N)^p \qquad \text{(Equation 6)}$$

$$Krw = krw_{max} * (Sw_N)^q \qquad \text{(Equation 7)}$$

$$Sw_N = \frac{(Sw-Swir)}{(1-SCO2r-Swir)} \qquad \text{(Equation 8)}$$

$$Krw_{max} = 0.23RQI^{-0.348} \quad \text{(Equation 9)}$$

$$KrCO2_{max} = 0.67\ RQI^{0.0194} \quad \text{(Equation 10)}$$

Where,

$KrCO_2$ is relative permeability to CO_2

Krw is relative permeability to water

$KrCO_{2max}$ is maximum CO_2 relative permeability

Krw_{max} is maximum water relative permeability

SW_N is normalized water saturation

P is CO_2 Corey exponent

q is water Corey exponent

Swir is irreducible water saturation

SCOr is residual CO_2 saturation

Irreducible Water Saturation (Swir)

Irreducible water saturation was read from the plot of previously calculated imbibition Pc curves at Pc equal 300 psi. There are nine Pc curves, one for each of the nine RQI ranges; therefore, nine Swir values were used. The values are listed in table 2.

Residual CO_2 Saturation (SCO_{2r})

Residual CO_2 saturation (SCO_{2r}) was calculated based on a correlation (Burnside and Naylor, 2014) between residual CO_2 saturation (SCO_{2r}) and initial CO_2 saturation (SCO_{2i}) (fig. 11). This correlation is based on samples from carbonate Nisku formation. CO_{2i} is one minus Swir (table 2).

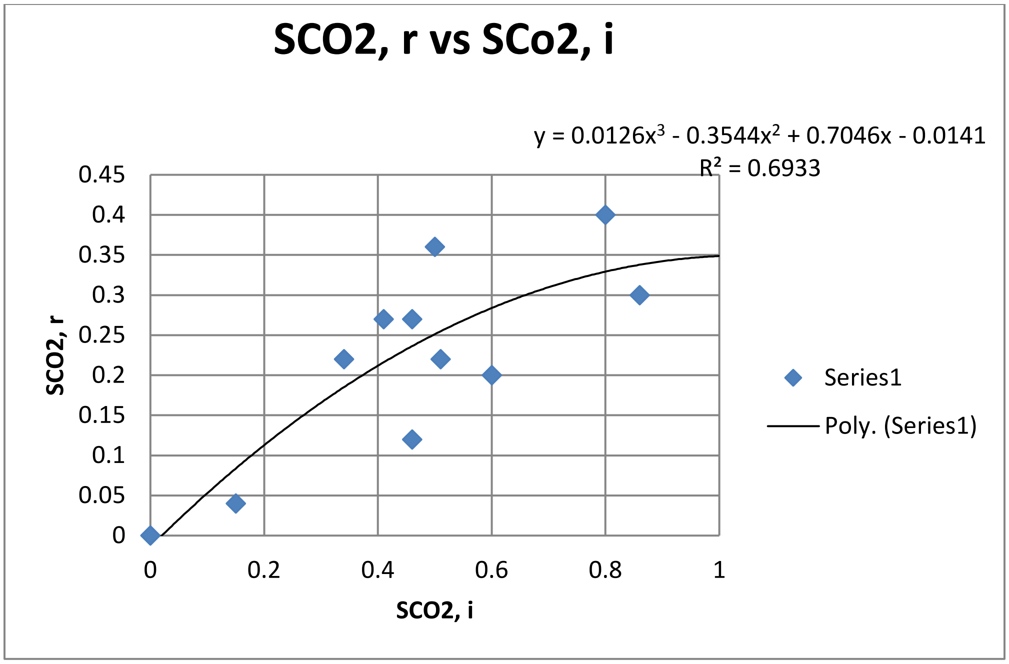


Figure 11: Residual CO_2 saturation versus initial CO_2 saturation.

Corey Exponent for CO_2 (p) and Corey Exponent for Brine (p)

Corey exponent values for CO_2 from literature (e.g., Bennion and Bachu, 2008, 2010) imbibition curves range from 2.9 to 2.1. Corey exponents were assigned in descending order, with the highest Corey exponent (2.9) assigned to the highest RQI value (20) and the lowest Corey exponent (2.1) assigned to the lowest RQI value (0.055).

Corey exponents for brine for different permeabilities don't have great variations, ranging from 1.2 to 4.5. Therefore, an average Corey exponent of 3 was considered for all nine RQI ranges.

Table 2: Values for Imbibition Relative Permeability

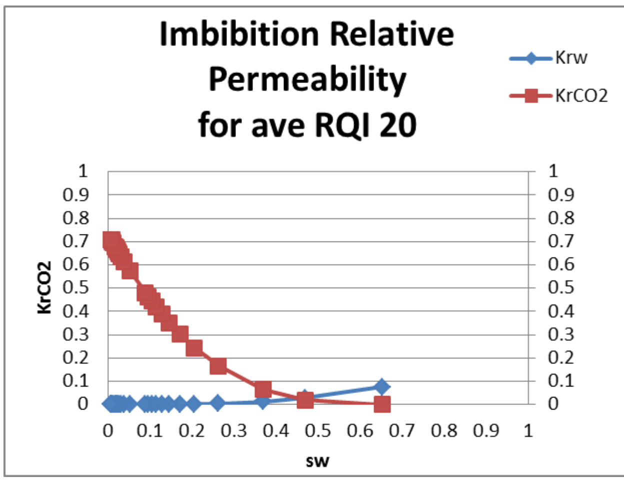
RQI	25	6.25	1.75	0.75	0.45	0.35	0.25	0.15	0.055
Swir @ Pc=300 psi	0.007	0.017	0.038	0.066	0.092	0.109	0.136	0.190	0.371
$S_{co2,i}$	0.993	0.983	0.962	0.934	0.908	0.891	0.864	0.810	0.629
$S_{co2,r}$	0.348	0.348	0.347	0.345	0.343	0.341	0.338	0.331	0.292
CO2 Corey ex	2.9	2.8	2.7	2.6	2.5	2.4	2.3	2.2	2.1
Water Corey ex	3	3	3	3	3	3	3	3	3

Maximum Relative Permeability of CO_2 and Water ($KrCO_{2max}$ and Krw_{max})

Maximum water relative permeability (Krw_{max}) in the imbibition case was calculated using equation 9. The previous section mentioned that laboratory relative permeability measurements have limitations due to the low laboratory capillary pressures that can be achieved in the core measurements during experiments. Therefore, measured $KrCO_{2max}$ values in labs are always lower than actual values in reservoirs. Maximum achieved $KrCO_2$ in most and possibly all laboratory studies is 0.54, which is lower than the actual maximum value in reservoirs. Equation 10, which is the same formula used in the drainage case, was used to calculate $KrCO_{2max}$. Calculated $KrCO_{2max}$ for maximum RQI (20) is 0.71, which is the same as the drainage case.

Imbibition Relative Permeability for CO_2-Brine

Equations 6 and 7 were used to calculate CO_2 and brine relative permeability curves, respectively. All parameters are listed in table 2. Nine sets of imbibition relative permeability curves were calculated for nine rock types based on RQI (figs. 12–20).



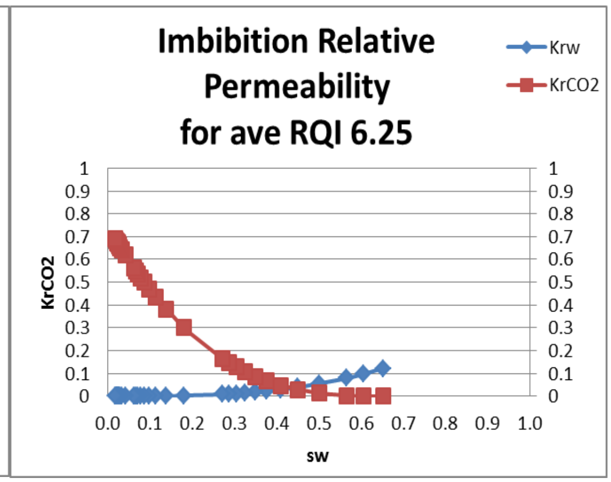
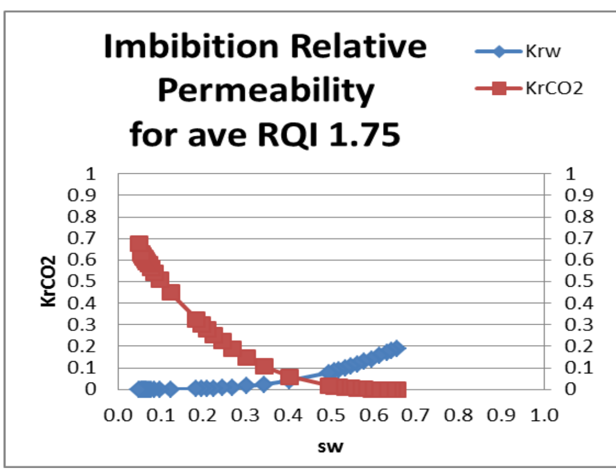


Figure 12: Imbibition relative permeability for RQI 20. Figure 13: Imbibition relative permeability for RQI 6.25.



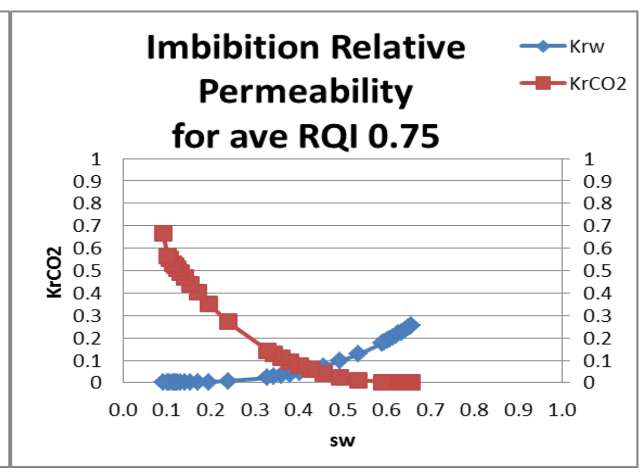


Figure 14: Imbibition relative permeability for RQI 1.75. Figure 15: Imbibition relative permeability for RQI 0.75.

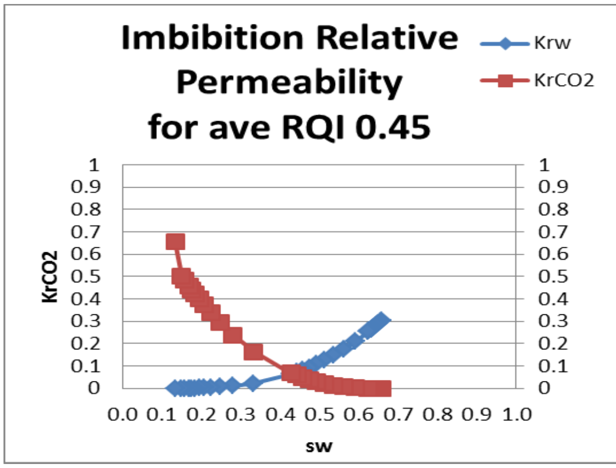


Figure 16: Imbibition relative permeability for RQI 0.45.

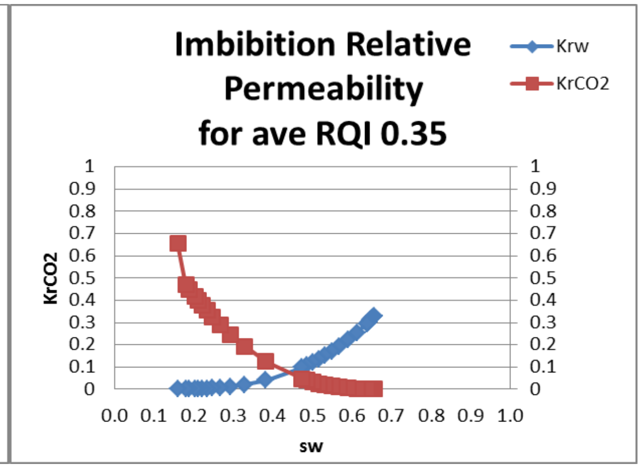


Figure 17: Imbibition relative permeability for RQI 0.35.

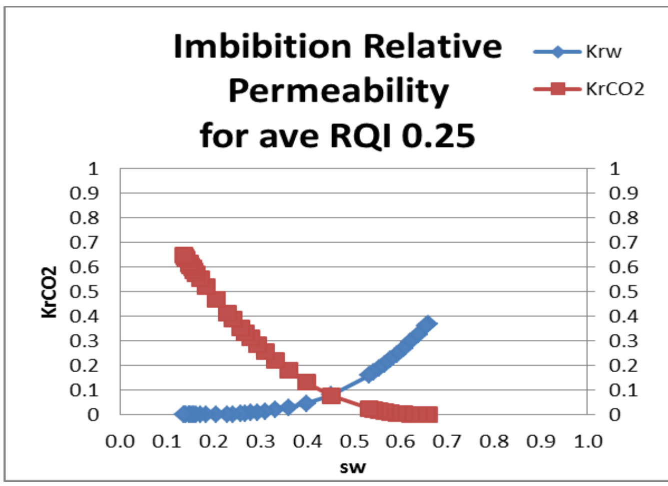


Figure 18: Imbibition relative permeability for RQI 0.25.

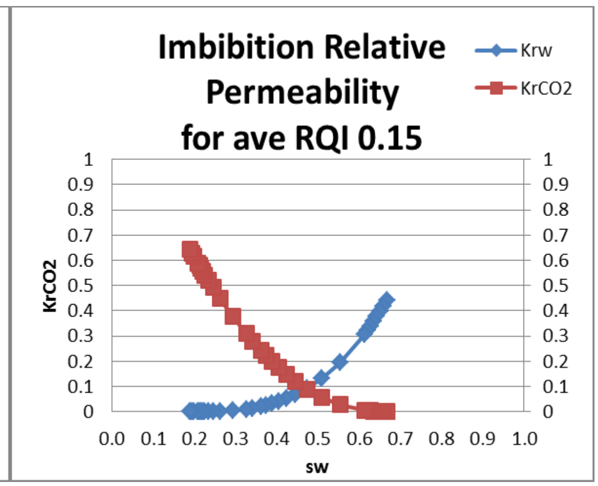


Figure 19: Imbibition relative permeability for RQI 0.15.

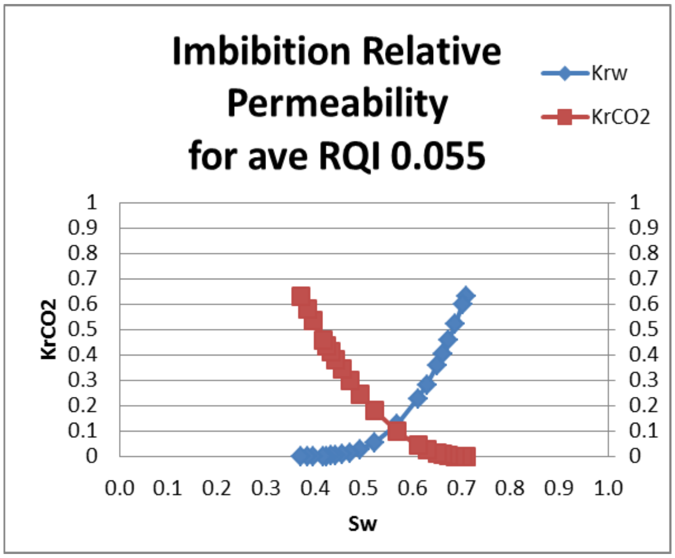


Figure 20: Imbibition relative permeability for RQI 0.055.

Conclusion

This work resulted in more realistic relative permeability curves for drainage and imbibition cases in CO_2-brine systems than the laboratory results from literature. As pointed out, relative permeability results reported in literature do not represent the endpoints of relative permeability curves and need to be scaled up. In this study, Kr max for CO_2 and max CO_2 saturations were increased to reasonable values. These curves will determine CO_2 injection capacity of injection wells more accurately and more realistically than the published curves. In addition, they result in more accurate residual CO_2 that can be trapped as an immobilized phase in the formation. Also, in this work, Corey exponents have consistency with increasing RQIs. Higher RQI values have higher Corey exponents and lower RQIs have lower Corey exponents.

References

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