# MODELING POROUS PLATE CAPILLARY PRESSURE PRODUCTION DATA: SHORTENING TEST DURATION AND QUALITY CONTROLLING DATA

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This paper was prepared for presentation at the SPWLA 48th Annual Logging Symposium held in Austin, Texas, United States, June 3-6, 2007.

## ABSTRACT

Modeling capillary pressure porous plate/membrane production data provides an opportunity to collect data just long enough at each pressure step to predict equilibrium saturation. Modeling production history also provides a means to quality control the production data.

In 1997 Marc Fluery, IFP, presented a two-parameter desaturation model for membrane capillary pressure measurements and subsequently modified the model for centrifuge capillary pressure measurements. The IFP model assumes that the rate of production from desaturation/saturation on a membrane is controlled by the relative permeability of the core plug not the membrane. This is not always the case for high pressure membranes and ceramic/glass porous plates. We have modified the IFP model to account for this.

As long as the porous plate/membrane is controlling production rate, as evidenced by linear production with time, no prediction of the equilibrium production can be made. In such cases, no shortening of the production step duration is possible by modeling. To shorten desaturation duration requires either a bi-layer porous plate or membrane system where the thickness of the layer that determines the entry pressure is very thin minimizing the impact of the low permeability/transmissibility.

We have processed both ceramic and membrane composition porous plate data and have demonstrated the ability of the new model to accurately predict equilibrium desaturation, thus offering a means to shorten capillary pressure experiments and to QC & correct existing porous plate data. However, the accuracy of the prediction depends on having a reasonably constant temperature and pore pressure throughout each pressure step. Experimental protocols for using high entry pressure plates/membranes and optimizing desaturation duration will be provided.

## INTRODUCTION

It is not unusual to encounter reservoirs where the core recovered is at the top of the reservoir structure whose thickness is in excess of 500 feet thick. For such reservoirs, the laboratory equivalent capillary pressures are likely to exceed those obtained by centrifuging with reservoir net confining stress. To simulate reservoir capillary pressure for such reservoir rock requires porous plate desaturation at reservoir net confining stress. Ceramic porous plates typically have an upper range of about 200 psi air-brine capillary pressure. Membranes and Vycor glass plates have an upper range in excess of 500 psi air-brine capillary pressure. The time required to achieve equilibrium desaturation at each pressure can be quite long due to the very low transmissibility of these high entry pressure barriers and relative permeability of the core plug.

With more rock and fluid measurements being obtained down-hole or at well-site and more advance well log interpretation being provided within hours or days after logging, will formation evaluation & reservoir engineering asset teams wait many months for the arrival of accurate capillary pressure data? Modeling porous plate production data can provide the opportunity to shorten and to QC capillary pressure data.

Capillary pressure by porous plate or membrane desaturation (drainage) or saturation (imbibition) requires one to define when capillary pressure equilibrium has been achieved. Ideally one could say when there is no additional production, that is there is zero production, 0.00ml, over a period of 48 hours. In practical terms, a best practices equilibrium definition is defined as "several days without a measured saturation change (less than 0.1 saturation units (0.1% of PV))". Another common equilibrium criteria has been stated as when the production rate has dropped below 0.5% of the pore volume in 24 hours. This final equilibrium definition is subject to error associated with temperature and pore pressure variations which can result in artificially low production rates for a single day resulting in under estimating capillary equilibrium saturation. This is especially true when investigating low porosity materials where incremental volumetric change can be very slow. Experiment duration may be a cost factor for some core analysis services companies.

The following sets of data from two samples illustrate porous plate capillary pressure data obtained using an equilibrium definition of approximately 0.1% (or less) of PV production change over 24 hours. (Please note that these data sets represent equilibrium timing that would be characterized as optimal. Capillary pressure analysis typically requires 3 to 5 months.) Figure 1A is an example of an air-brine 15Bar porous plate desaturation with 8 pressure steps from 4 psi to 150 psi whereas in Figure 1B is the same data showing each pressure step approach to equilibrium.

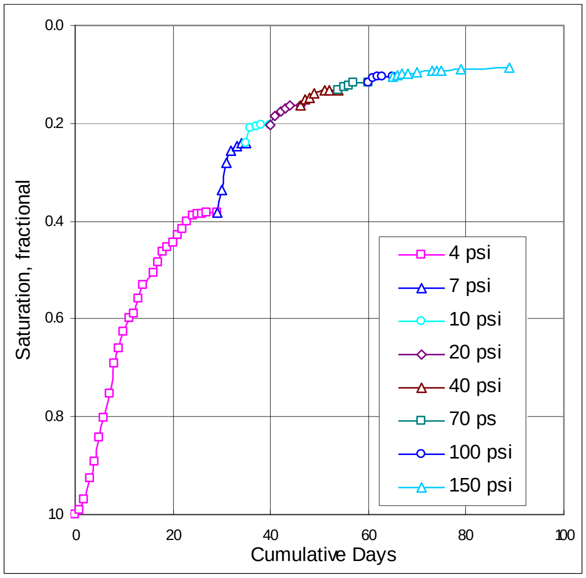

**Figure 1A** Standard air / brine porous plate capillary pressure example showing cumulative production.

It should be noted that with both plate and membrane systems it is often the first few low Pc pressure points that require extended periods of time to establish equilibrium. More will be said about this later.

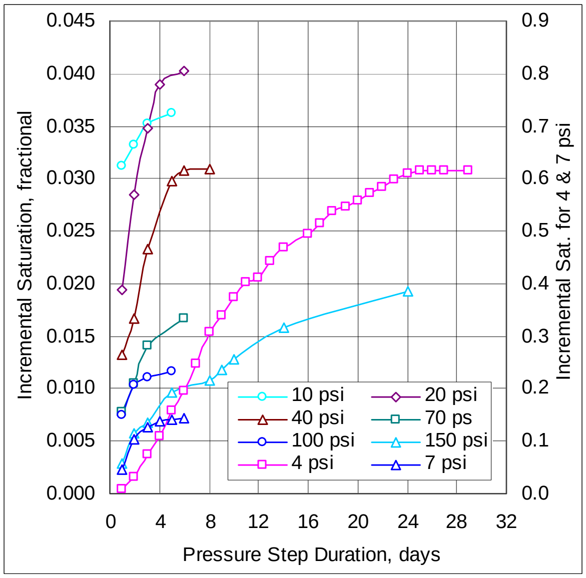

**Figure 1B** Standard air / brine porous plate capillary pressure example showing individual pressure point equilibrium data.

Figures 2A and 2B provide comparable data obtained using a membrane with a final desaturation pressure of 1000psi. (Lasswell 2005) The 1000psi membrane system is mounted in capillary contact with the lower production face of each sample (at net confining stress) and consists of a 0.1mm thick water-wet membrane supported by a high-flux porous plate.

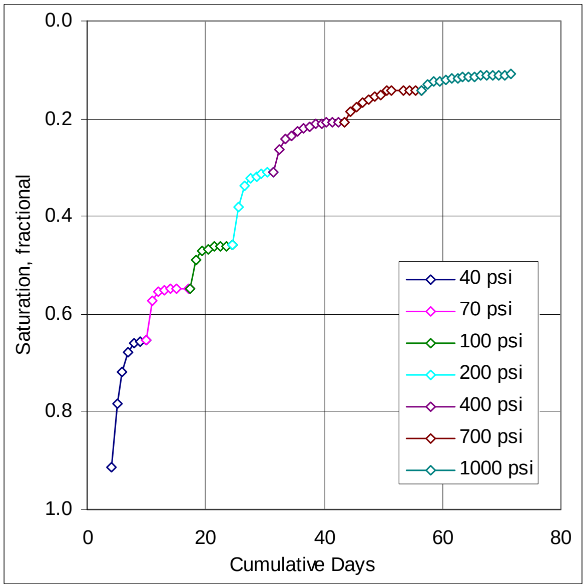

**Figure 2A** 1000 psi air / brine porous plate capillary pressure example showing cumulative production.

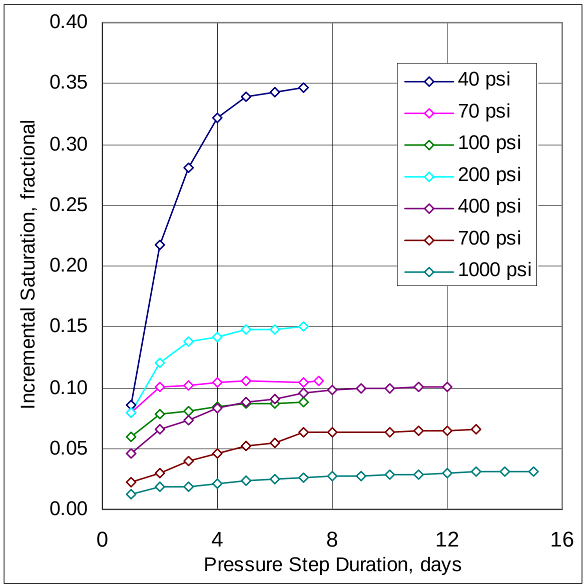

**Figure 2B** 1000 psi air / brine porous plate capillary pressure example showing individual pressure step equilibrium data.

## RESULTS AND DISCUSSION

To illustrate the approach to equilibrium for a single air-brine 9.5 psi desaturation pressure, data are presented in Figure 3A where the change in saturation was about 0.1% (0.1 SU) over the last three days. If we could model desaturation then we could predict equilibrium saturation without waiting to achieve it.

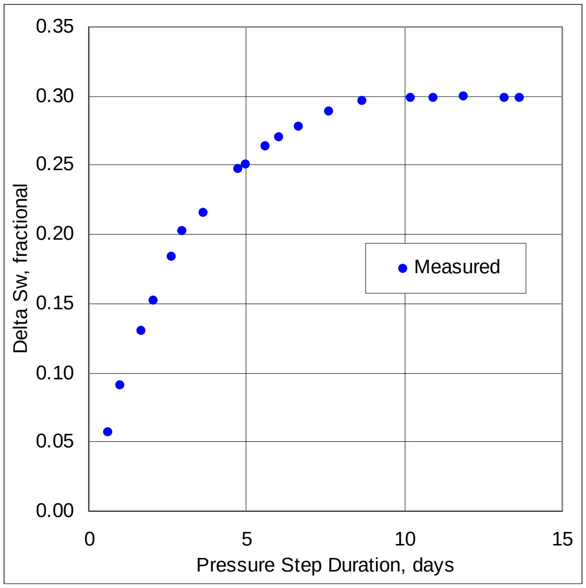

**Figure 3A** 9.5 psi air / brine porous plate capillary pressure example showing individual pressure point equilibrium data (measured).

Marc Fleury et. al with IFP had previously shown (Fleury et. al, 1997) for synthetic membrane desaturation that the production versus time could be modeled with a two-parameter desaturation model. Fleury et. al presented a modification of this model for centrifuge capillary pressure measurements in their SCA paper 2000-31. Wilson and Skjaeveland applied a version of the IFP model to ceramic porous plate desaturation in their SCA paper 2002-16.

IFP's two parameter desaturation model is:

production at any time = Pequ(1-exp(-time/Tc)). Equ (1)

Pequ = equilibrium production; Tc = characteristic time

Equation one is solved for "Pequ" and "Tc" using non-linear least squares to minimize the sum of the squares difference between actual production and predicted production. We used "solver" in Microsoft Excel to perform this operation.

For the data presented in Figure 3B, the value of equilibrium production (Pequ) was 0.306 and the value of characteristic time (Tc) was 2.9 days compared to the measured change in saturation of 0.299 after about 14 days.

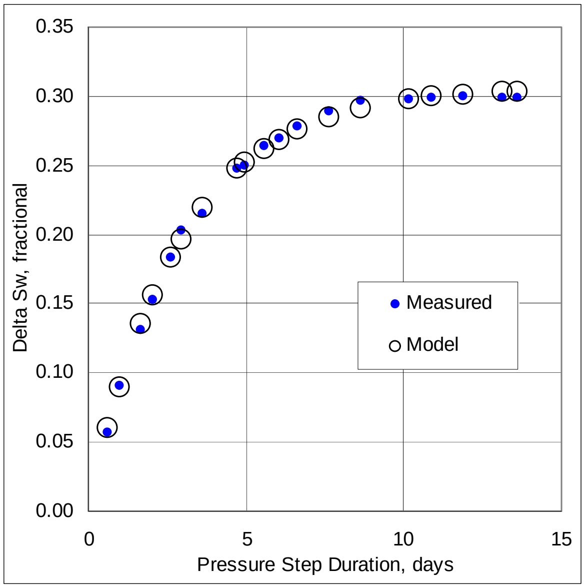

**Figure 3B** 9.5 psi air / brine porous plate capillary pressure example showing individual pressure point equilibrium data, both measured and modeled.

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Fluery proposed in their 1997 and 2000 SCA papers, that to determined when to stop collecting production data without waiting for capillary equilibrium, model the data predicting Pequ until the value no longer appreciably changes. We have done this with the 14 days of data, starting with day 2 up until day 14. After about 6 days, the values of Pequ appears to have stabilized within +/- 0.5 SU, Figure 3C.

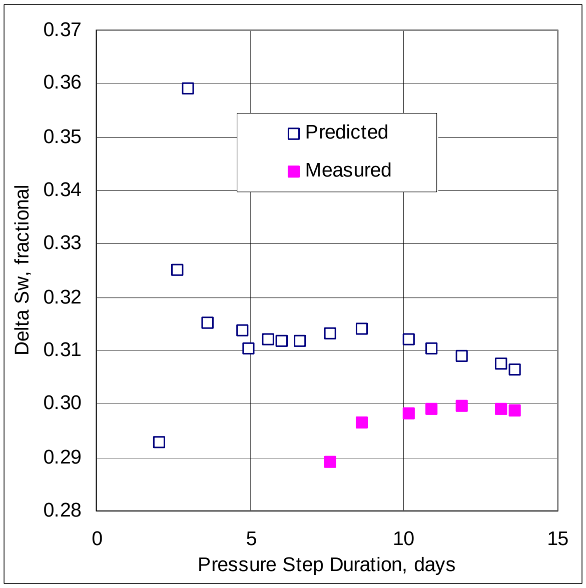

**Figure 3C** 9.5 psi air / brine porous plate capillary pressure example showing prediction of individual pressure point equilibrium data.

The previous example (Figure 3B) illustrated using the Pc model to shorten the duration of the pressure step without waiting to achieve capillary equilibrium. The following is an example of applying the IFP production model to historical data to check if equilibrium desaturation was achieved. In this example the capillary pressure data was obtained with a criteria of increasing the pore pressure to the next pressure step when the production rate was less than 1 saturation unit, SU, (1% of the PV) per day.

A least squares fit to the 19 days of production data for a single 4psi pressure step indicates that the characteristic time is 18.3 days and the equilibrium production is 0.54 delta Sw (PV Fraction) compared to 0.35 delta Sw when the pressure step was stopped predicting an error of about 19 SU for this pressure step. The residual sum of this two parameter least squares fit for the 18 data points was 0.1 SU. A comparison of the data versus the model is presented in Figure 4A.

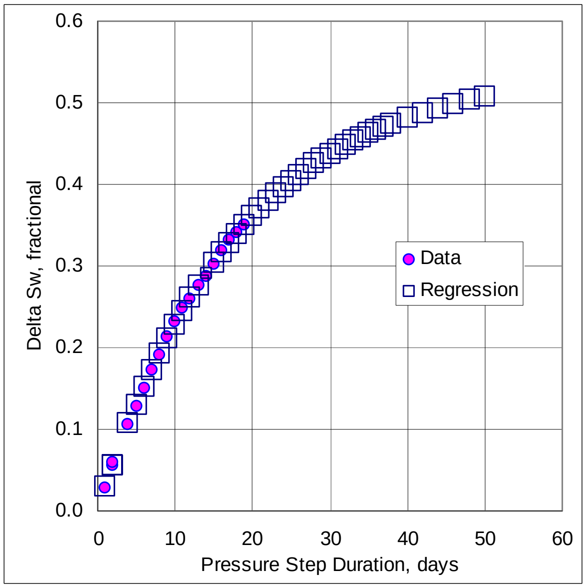

**Figure 4A** Comparison of historical single point porous plate capillary pressure production data with the model calculated equilibrium data.

Figure 4B, a plot of the predicted Pequ and Tc with time indicates that by the last three days of the historical data, the predicted equilibrium had stabilized.

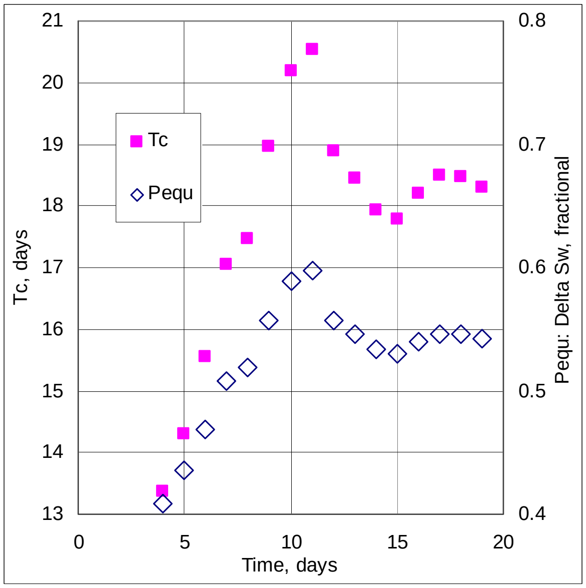

**Figure 4B** Predicted Pequ and Tc data from historical single point porous plate capillary pressure production data.

Using the values of Tc and Pequ, the IFP production model predicts the desaturation rate (Figure 4C) and indicates that the criteria of continuing the pressure step until daily production is less than 0.5% pore volume/day would not have occurred until about day 33. If equilibrium is defined +/- 1SU then last three days of data should be sufficient to accurately predict the equilibrium production.

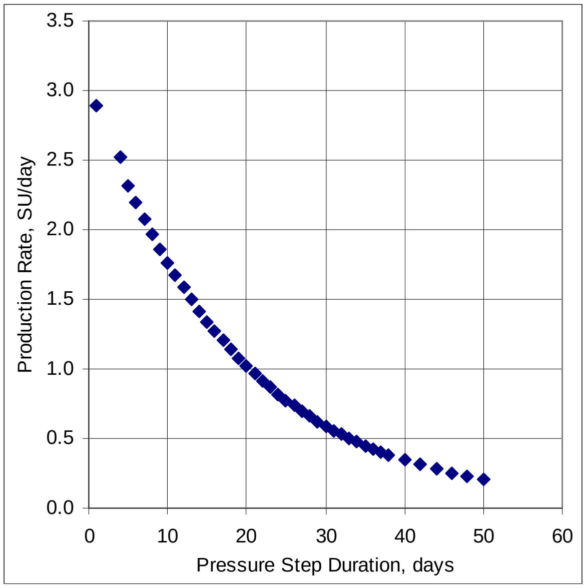

**Figure 4C** Predicted rate data.

## NEW MODEL

We have found in our processing of porous plate/membrane data that the two-parameter model only provides a good estimate of the final equilibrium saturation when the porous plate/membrane does not control the production rate. The IFP model (Fleury et. al, 1997) assumes that the rate of production from desaturation or saturation (imibibition) on a membrane or porous plate is controlled by the rate of saturation equilibrium or (relative permeability of the core plug) not the permeability of the barrier. This is not always the case especially for the low pressure desaturation steps where the saturation of the core plug is likely high and thus its specific perm is high compared to the porous plate/membrane. (Lenormand et. at, 1996)

To model permeability of the composite of the core plug and porous plate or a membrane during desaturation we have assumed the properties for the core plug, porous plate, and the membrane as listed in Table 1.

Table 1

| Material | Thickness (mm) | Permeability (mD) |
|---|---|---|
| Core plug | 50 | 10*(Sw)^-6 (assumed) |
| 15Bar Ceramic plate | 5 | E-03 |
| 1000psi membrane | 0.1 | E-06 |
| Vycor | 5 | E-06 |

The modeled permeability data are plotted in Figure 5. They indicate that the initial core plug desaturation rate whether on a porous plate or a membrane is solely being controlled by the permeability of the barrier until the desaturated core plug's effective permeability drops below the specific permeability of the barrier. Prior to the later, the combined permeability of the composite (core and barrier) is relatively constant and thus the production rate is constant. While the production rate is constant it is impossible to determine what the final desaturation value will be. There is some transition in production rate in going from barrier dominated transmissibility and desaturated core plug dominated transmissibility. Non-uniform saturation profile during initial desaturation of the core plug will change the permeability calculation of the composite.

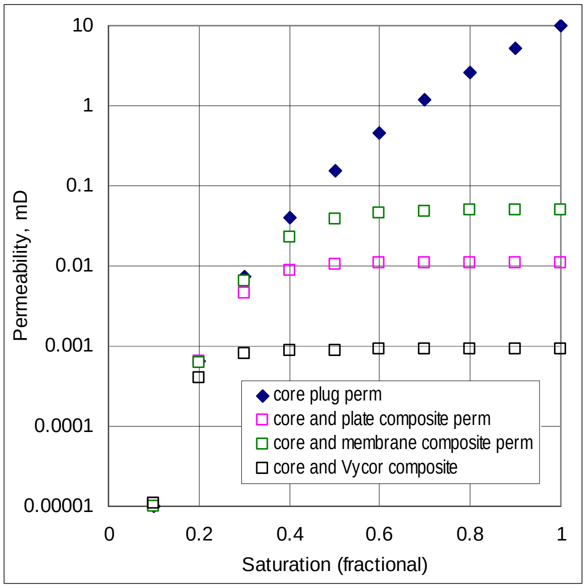

**Figure 5** Modeled plug and barrier permeability data.

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When the initial portion of the desaturation production versus time is linear, then the two-parameter model will over-predict the equilibrium saturation. We have modified the model to account for this situation.

## FOUR PARAMETER MODEL

production at any time = linear production rate * duration + non-linear equilibrium production(1-exp(-non-linear production rate duration/characteristic time)). Equ. (2)

Two new parameters, linear production rate and duration, have been added to the two parameter equation. Using "solver" in Excel one minimizes the sum of the squares of the difference between actual production and predicted production while optimizing the four variables.

The advantage of the additional two parameters is illustrated in Figure 6A, where both the two and four parameter models are plotted against the experimental data. The production rate is linear for about the first 13 days. The two-parameter model predicts an equilibrium saturation of 0.68 (delta Sw on a fractional PV basis) while the four-parameter model predicts 0.55 and the experimental value after 32 days was 0.55. Figure 6B presents the predicted equilibrium production versus production duration in days. The predicted equilibrium value after about 25 days has begun to stabilize. The four-parameter model predicts final delta Sw to within about 2 SU after 25 days.

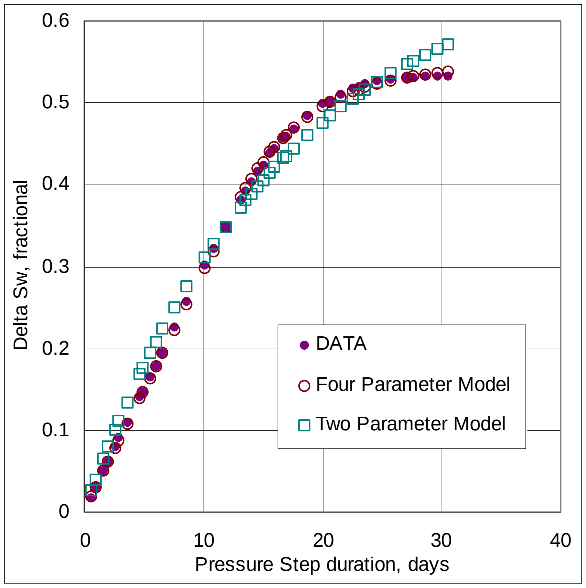

**Figure 6A** Four parameter model comparison to two parameter model.

Figure 6B indicates that sufficient deviation from the initial linear production rate, in excess of 25%, is required in order to obtain an accurate prediction of the equilibrium production. As long as production is linear with time, the porous plate/membrane is controlling the production rate and thus no prediction of the equilibrium production can be made. In such cases, no shortening of the production step duration is possible by modeling. To shorten desaturation duration requires a bi-layer porous plate or membrane porous plate support composite where the thickness of the layer that determines the entry pressure is very thin minimizing the impact of the low permeability and transmissibility.

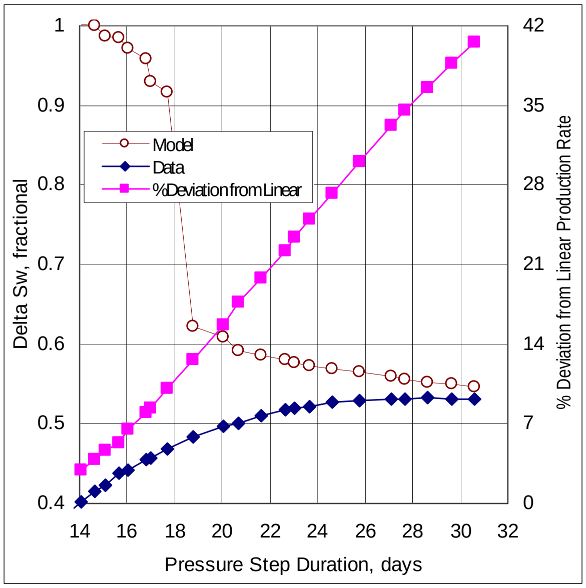

**Figure 6B** Air / brine porous plate capillary pressure example showing prediction of individual pressure point equilibrium data using the new four parameter model.

Also, if the core plug desaturation pressure step results in a core specific permeability greater than the barrier, then the drainage rate would be linear almost to the moment when production ceases. (Figure 7).

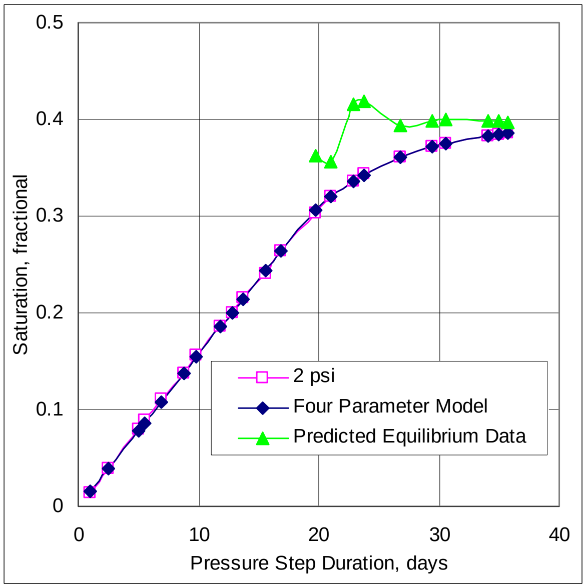

**Figure 7** Air / brine porous plate capillary pressure example showing significant production rate control by the porous plate and the associated predicted equilibrium data.

All of the data discussed within this paper have been examples of drainage capillary pressure. Imbibition capillary pressure data, while not presented, have been subjected to the same modeling process. Our proposed methodology was shown to be equally valid.

## SUMMARY AND CONCLUSIONS

We have revised a modeling technique as first proposed by IFP (Marc Fluery et. al) to speed up the collection of porous plate/membrane capillary pressure by not waiting for capillary equilibrium at each pressure step. This may offer the potential to speed up delivery of capillary pressure data. Secondly, we have shown potentially an even more advantageous use for the model in QC'ing porous plate/membrane derived capillary pressure data either as data is being generated or in reprocessing historical data. We have provided in the Appendix an experimental protocol for porous plate/membrane capillary pressure measurements that provides guidance on data collection for modeling equilibrium saturations. (Lasswell 2006)

*Specific conclusions from this study are:*

1. The accuracy of the prediction of equilibrium saturation depends on having a reasonably constant temperature and pore pressure throughout each pressure step.
2. If one is to have a hope of reassessing historical data, then it is critical that all of the experimental raw data are still available.
3. This new four parameter model can provide superior saturation estimations as compared to the two parameter model, especially in situations where a significant portion of the production profile is characterized by plate/membrane controlled production rates.
4. For samples that have not achieved capillary equilibrium, as with all non-linear regression optimization, one needs to examine the reasonableness of the solution. One also needs to verify that the final solution is not just a local minimum by changing the starting input values.
5. The magnitude of an evaporation correction may compromise one's ability to accurately model production data if an "open system" volumetric collection system is employed. (See the experimental protocol appendix.)
6. Equilibrium prediction is best suited to relatively simple pore structure regimens and is not necessarily adaptable to atypical or complex core materials such as vugular carbonates.
7. Porous plate/membrane capillary pressure is conducted in conjunction with electrical properties determinations in the majority of testing programs. It is the authors' opinions that whether Pc equilibrium is actually achieved or not, does not significantly impact or question the validity of the associated Rt data. However, electrical property data is adversely affected by too high of a production rate as evidenced by a non-linear relationship between resistivity and saturation data, especially data collected soon after a Pc pressure change.

## ACKNOWLEDGEMENTS

The authors wish to thank and acknowledge ConocoPhillips for use of their historical core analysis data. We also thank OMNI and Reservoir Management Group for their support and approval to publish this paper.

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## ABOUT THE AUTHORS

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**Patrick M. Lasswell** is the Electrical Properties and Capillary Pressure Manager for OMNI Laboratories, Inc. in Houston, Texas, USA. He has over 25 years experience in electrical properties and capillary pressure analysis and has authored 3 technical papers on electrical properties/capillary pressure and co-authored 3 technical papers on tight gas sand investigations. His professional interests include 4 electrode advancements, development of high pressure plate systems, investigations of tight gas sands, special core analysis involving full diameter samples and stress mercury injection. Mr. Lasswell graduated with a Bachelor of Science degree from the University of California at San Diego in 1974.

## APPENDIX: EXPERIMENTAL PROTOCOLS

The following is a generic experimental protocol for air-brine porous plate drainage capillary pressure experiment for samples at reservoir net confining stress. Where appropriate, comments have been added concerning obtaining sufficient data for modeling purposes.

1. 1" or 1 ½" diameter plug samples are drilled at selected depths. The samples are trimmed to 1 ½" and 2" in length respectively. (1 ½" diameter samples preferred). Whole core samples might be considered with vugular or conglomeritic materials.)
2. Cool solvent extract samples using solvent cycles until all solvent effluents remain clear. Typical solvents include chloroform/methanol azeotrope, toluene and methanol. Routine analysis Dean-Stark extracted plugs are not recommended.
3. Dry samples to stable weight and determine physical properties at the appropriate net confining stress. The drying method employed (humidity, convection oven, critical point or vacuum at specific set temperatures) should be selected such that the rock fabric is preserved. The drying process may be conducted at the conclusion of testing when particularly fragile rock fabrics are encountered so that the analysis is not conducted on non-representative damaged material. In such cases the final methanol flush in step #2 is followed by propane flush and flash for a pseudo critical point drying.
4. Vacuum saturate samples with a synthetic formation brine. If formation brine total dissolved solids (TDS) is approximately known but the actually composition is unknown then consider using 80% NaCl, 10% $CaCl_2$ and 5% each KCl and $MgCl_2$. If nothing is known of the formation brine then consider using a brine of 2% by weight of KCl + 1% by weight of $CaCl_2$.
5. Vacuum saturate porous plate. There is some question as to whether the re-use of plates is advisable since a reduction in plate permeability would slow the initial rate of desaturation. Typically, we have not seen an overt degradation of standard 5 and 15 bar plates with re-use as long as the plates are kept brine saturated between use cycles. If oil-brine use is employed then the plates need to be flow through cleaned and not allowed to dry with brine in place between use cycles. Membranes are not re-used.
6. Mount samples at net confining stress with a plate or membrane in capillary contact with the lower sample face. Match the plate design/type to each specific sample's properties.
7. Back pressure flush the samples to insure complete saturation (20-40 pore volumes).
8. Install a volumetric collection apparatus for each sample. The collection system design should maximize incremental and cumulative volumetric accuracy. Two collection systems are common: a closed system (volumetric measurement) in direct linkage to the sample downstream end-stem or a separate weighed collection flask with an open air-brine surface. Each method has its' inherent strengths and weaknesses.

First the closed volumetric system. Within this system, an appropriately sized pipet is attached to the sample effluent endstem and displacement volumes are read directly from the pipet. The upper brine surface is layered with a heavy grade laboratory oil to counteract evaporation. To remain accurate the effluent system must remain completely filled with only the produced fluid. However, with high pressure air-brine desaturation, there are two mechanisms for gas to be transported across the porous plate or membrane barrier. First, gas will saturate the brine phase within the sample during the course of testing and upon production through the plate (or membrane) this dissolved gas will evolve from the brine on the low gas pressure side and must be accounted for in processing the effluent production volume. Second, the other mechanism is for gas to diffuse thru the brine trapped within the membrane or porous plate from the high gas pressure side to the low gas pressure side. It is particularly critical to account for gas diffusion effects when tight-gas-sand (TGS) samples are being tested.

The separate weighed flask system. A flask is attached to the sample effluent endstem and a two hole-stopper is used to seal the flask, one hole for tubing coming from mentioned porous plate core holder and the other hole is used as a vent to ensure pressure equalization. Production is collected and the flask weighed. Endstem volume holdup must be accounted for with respect to the starting volumetric zero point especially with respect to gas diffusion mentioned above. In the weighed flask method with the open air-brine surface (cumulative weight), evaporation is a major concern and potential source of error. This method may well add an unreasonable level of uncertainty. For example the magnitude of evaporation correction data collected for the open air-brine weight collection flask was about 0.8 ml of evaporation over 100 days. For low porosity and low permeability tight-gas-sands with low production volumes and long duration capillary pressure tests this magnitude of evaporation correction certainly represents a very significant contribution to the saturation calculations. It is strongly suggested that only the closed volumetric system be used with low porosity materials, such as TGS samples.

9. Remove excess brine from each injection end-stem and apply a low initial pressure to the top of each sample to produce the remaining free brine volume. The initial pressure must be matched to each sample's properties (permeability and porosity) so that gas entry does not occur into the sample pore structures.

10. Desaturate samples in a series of 6 to 8 pressure steps using pressures matched to each sample's properties, without exceeding the threshold pressure of each installed plate/membrane. Gas used in the desaturation process should be humidified at test temperature to preserve sample Sw saturations. Desaturation pressure accuracy and control is extremely important and is best obtained by using digital readouts and precision regulators. Typical air-brine desaturation pressure sequences are as follows:
2, 4, 7, 10, 20, 40, 100, 200 psi for typical high quality samples (e.g. Gulf Coast sandstones)
20, 40, 100, 200, 400, 600, 1000 psi for typical low quality samples (e.g. TGS materials)
Specific desaturation pressure regimes should be matched to individual sample properties.

11. Volumetric equilibrium (at each pressure step) should be defined at the outset of each test program. A best practices default equilibrium is defined as several days without a measured saturation change (less than 0.1 saturation units (0.1% of PV)) following an obvious decreasing volumetric progression at any given pressure. Equilibrium can be mis-interpreted considering an isolated 24 hour period alone. A review of production vs time in Figure 1A illustrates the decreasing production with time (following an initial linear response) that needs to be observed prior to assuming that equilibrium has been reached. Low porosity materials (e.g. TGS) equilibrate more slowly during the desaturation process and therefore additional caution must be employed in the assessment of volumetric equilibrium.

12. Depending on the experimental set-up employed one may need to correct for evaporation of the receiving flask. Please see comments in Step #8.

13. Production should be controlled so that a sample does not desaturate faster than approximately 5 PU in a 24 hour period. This is especially true if electrical property data is being collected concurrently with the Pc analysis. During the initial production phase after a Pc pressure change, the volumetric response should be recorded several times a day. Readings should be spaced so that saturation changes are no greater that about 2 saturation units and a minimum of one reading per day. Record exact time that readings are taken. Track predicted equilibrium production by entering daily production into excel worksheet set-up to calculate “”Pequ”.

14. Upon volumetric stability at the final desaturation pressure, isolate the effluent end of each sample so that imbibition does not occur and carefully release the final pore pressure. The gas volume can be measured by Boyle's law as a quality control of the volumetric measure of the produced fluids.

15. Dismount samples and weigh at Swi. Dean-Stark extract to confirm material balance Swi saturations. Dry samples using the original drying protocol and calculate the final Sw percentages.