POROUS PLATES INFLUENCE ON EFFECTIVE DRAINAGE RATES IN CAPILLARY PRESSURE EXPERIMENTS

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ABSTRACT

Capillary displacement using the porous plate technique has been used for decades to determine capillary behaviour in a reservoir. The disadvantage is that the technique is quite time consuming.

During the last few years, different techniques, such as the membrane technique, have been developed to speed up the experiments. However, membranes have problems of enduring mechanical stress and resisting wettability change during an experiment. Other fast techniques, like the continuous injection technique, have been introduced in order to reduce the time required to obtain data.

In this paper we present a technique with the use of a recently developed, hydrophilic and hydrophobic, layered ceramic porous plate. We document the properties of this high-flux porous plate both theoretically and experimentally, and compare the results against standard types of porous plates.

Parallel experiments using standard industry porous plates have been done on both reference and reservoir rocks from the North Sea. The results of the study prove how the flux properties of porous plates affect the effective rates and stabilisation time during drainage. A much faster stabilisation at each capillary pressure step is achieved by minimising the flux restriction in the porous plate. Experimental turnaround time has been reduced by a factor of more than 5.

Use of layered porous plates may lead to a new standard for the porous plate technique and could reinforce the interest of using the technique in core analysis.

INTRODUCTION

The determination of representative capillary pressures is of vital importance for the mapping of the reservoir fluid distribution. However, variations between the data obtained by various standard techniques (mercury injection, porous plate technique and centrifugation) or for different fluid systems have often been observed and reported in the literature.

During the last few years, substantial work has been done to improve the laboratory procedures for measurement of relative permeability behaviour. Less effort has been made to improve the techniques for determination of capillary properties.
The traditional porous plate technique is a very reliable, but quite time consuming.

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During recent decades, different techniques like the membrane technique and the continuous injection technique have been developed to reduce the amount of time required. The membrane technique[1] is a fruitful improvement to reduce the experimental turnaround in a capillary pressure experiment. The technique, which is analogous to the standard porous plate technique, has been reported[1] to be 30 times faster than the standard porous plate technique. However, this technique seems to have problems in enduring mechanical stress and resisting wettability change during the experiment.

In this paper we present a new ceramic porous plate technique with the use of a recently developed, hydrophilic and hydrophobic, layered ceramic porous plate. The idea behind this new technique is to minimise the flow restriction through the plate, similar to the idea behind the membrane technique. This is achieved by optimising the pore architecture on the different ceramic layers.

We present the outcome of four experimental studies. The first study is performed on Bentheimer rocks. The motivation was to verify consistent capillary behaviour at different pressure steps using both standard homogenous porous plates and layered porous plates. In addition, three studies on reservoir rocks are presented that illustrate the new technique to different reservoir rocks with different petrophysical properties.

Capillarity on a microscopic pore level is a complex matter to investigate due to the irregular and complex pore architecture of a natural reservoir rock. In order to illustrate how porous plates influence time to achieve capillary equilibrium, we use a simple porous model without drawing a parallel to pore architecture in porous rock matrix.

DESCRIPTION OF THE POROUS PLATES

Three different water-wet ceramic porous plates have been compared in the analytical experiments.

The Soil Moisture type is well known as a homogeneous porous plate with different threshold pressures. We have used the 15 bar (gas/water) version with a diameter of 38.1 mm (1.5”) in our experiments. The thickness of this type is 9.5mm. Water flux for a 100% water saturated Soil Moisture 1.5” diameter plate given by the manufacturer to be 0.13 ml/h at 1 bar differential pressure.

The other two new types called KeraFlux are layered porous plates. The structure of this porous plate is shown in Figure 1. The layered porous plates has a highly permeable and homogeneous substrate structure with large pore size. This substrate is approximately 4.8 mm thick. On top of the substrate is a top layer with smaller pore size. This layer is constructed as a graded layer with respect to pore size, porosity and composition.
Due to the low thickness (0.2 mm) and the graded nature of this layer, the flux is much higher (about 15-150 times) than the Soil Moisture plate.

Two types of the layered porous plate with a diameter of 38.1 mm (1.5”) have been used:

Type-1 is an 18 bar (gas/water) version with a water flux of approx. 2ml/h at 1 bar.
The Type-1 plate is used in the Bentheimer core plugs experiments.

Type-2 is a 12 bar (gas/water) version with a water flux of approx. 10 ml/h at 1 bar. The Type-2 plate is used in the reservoir core plugs experiments.

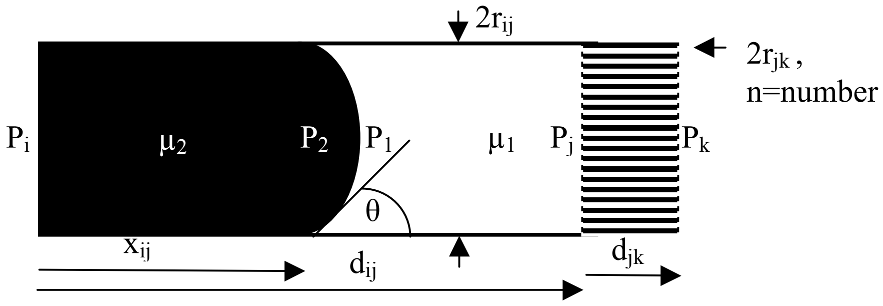
The layered plates are available in both hydrophilic and hydrophobic versions.
Measured properties for the porous plates are listed in Table 1.

THEORETICAL CONSIDERATIONS

Two synthetic porous media, each represented by a two-dimensional square lattice of cylindrical tubes, are connected together like a composite core experiment. The first network has a different radius distribution than the other, which has a radius distribution analogous to a ceramic plate.

Initially, the system is filled with a defending fluid of viscosity μ1. We restrict the discussion to drainage displacement and let the invading fluid be non-wetting and the defending fluid be wetting. The fluids are immiscible and there is a well-defined interface between the two phases. The curvature of this interface gives rise to capillary pressure given by the interfacial tension. Moreover, we assume that the fluids are incompressible.

We restrict the discussion further to an area in the composite lattice where a single tube meets the restriction.



The volume flux q_{ij} from node i to node j in the tube is found from the Washburn equation[2] for capillary flow with two fluids present:

$$q_{ij} = \frac{\pi r_{ij}^2 k_{ij}}{\mu_{eff}} \frac{1}{d_{ij}} \left(\Delta P_{ij} - P_c\right)^+$$

where:

$k_{ij} = \frac{r_{ij}^2}{8}$ is the permeability of a cylindrical tube

$\mu_{eff} = \mu_2 x_{ij} + \mu_1(1 - x_{ij})$ is the weighted effective viscosity

$\Delta P_{ij} = P_i - P_j$ is the pressure difference between node i and node j

$P_c = P_2 - P_1$ is the capillary pressure in the tube

x_{ij} is the position of the pore-interface in the tube

r_{ij} is the radius of the tube

$^+$ indicates that $(P_i - P_j) > P_c$ otherwise $q_{ij} = 0$

The capillary pressure is derived under the assumption that the fluids are in static equilibrium, i.e. there is no flow in the tube and $\Delta P_{ij} = P_c$. The dynamics of the moving interface is still unsolved theoretically, but at low velocities without turbulence it can be assumed that capillary pressure is given by the Young-Laplace equation

$$P_c = \frac{2\sigma \cos(\theta)}{r_{ij}}$$

For tubes completely filled with either the invading or the defending fluid, $P_c = 0$ and the Washburn equation reduces to Hagen-Poiseuille flow in a cylinder. Hence, the volume flux q_{jk} from node j to node k in the tubes, illustrating the ceramic plate, is for one of the tubes:

$$q_{jk} = \frac{\pi r_{jk}^2 k_{jk}}{\mu_{eff}} \frac{1}{d_{jk}} (\Delta P_{jk})$$

where: $\mu_{eff} = \mu_1$

The assumption of incompressible fluids leads to volume flux conservation at each node. Hence, The Kirchoff equations become:

$$q_{ij} = q_{jk}$$

The total pressure across the composite system is given by $\Delta P_{ik} = P_i - P_k$, which is the pressure difference between inlet and outlet. This pressure difference is kept constant in a porous plate experiment. The pressure difference can be written:

$$\Delta P_{ik} = (\Delta P_{ij} - P_c)^+ + \Delta P_{jk} \qquad (P_i - P_k) = \left[(P_i - P_j) - P_c\right]^+ + (P_j - P_k)$$

Initially, the composite is filled with the defending fluid and $P_i = P_j = P_k$. Gradually the pressure of the inlet side is increased until $(P_i - P_j) = P_c$ and $P_j = P_k$. When P_i is further increased such that $(P_i - P_j) > P_c$, there will build up a pressure difference $\Delta P_{jk} = P_j - P_k$ which will be determinant with respect to rate in the non-invaded zone of the composite.

The hierarchy in a drainage sequence dictates that nonwetting fluid is going into smaller and smaller tubes when P_i is further increased. ΔP_{jk} will therefore be less and less important as a flow- restriction towards irreducible water saturation. It's therefore reasonable to believe that the influence of ceramic plates is somehow related to effective composite permeability of the non-invaded part of the composite porous media (harmonic average permeability in the non-invaded part).

It follows from the summary given above, ΔP_{jk} will be more important in a highly permeable rock than a less permeable rock. In other words, porous plate type has less rate influence on less permeable rocks than on more permeable rocks.

EXPERIMENTAL RESULTS

Traditionally, capillary pressure curves have been generated by the porous plate method for many decades. It is well known that drainage and imbibition could take over a year to complete. It's not uncommon to use between 20-30 weeks to establish oil-water drainage curves at ambient conditions.

All presented results are performed at ambient temperature using either Isopar (laboratory oil) or Nitrogen (gas) as the invading non-wetting fluid. We present, (a) capillary pressure versus water saturation, (b) water saturation versus time and (c) rate versus time.

It should be noted that drainage data for the reservoir rocks are presented in order to illustrate experience with layered porous plates. Core plugs from the same reservoir were drained in a parallel set-up. In a set-up like this heterogeneous core plugs will reach equilibrium at different times. However, the applied pressure is increased after obtaining equilibrium on all samples.

We have chosen to use $\frac{dS_w}{dt} \approx \frac{\Delta S_w}{\Delta t}$ as a rate indicator in order to exclude the effect of the pore volume itself.

All presented data are derived values at equilibrium. Capillary pressure was increased to the next pressure step when water production ceased and electrical resistivity changes were recorded over a period of 2 days.

A consolidated Bentheimer outcrop sandstone with homogenous properties ($\Phi \approx 0.230$ and $k \approx 1800mD$) has been used to provide baseline data. The rocks were drained by oil to irreducible water saturation using six capillary pressure steps at 25 bar hydrostatic confining pressure. Final equilibrium, using layered porous plates, was reached 41 days after initiating drainage (figures 2a-c). Repeat measurements on two rocks, but using homogenous plates, gave the same results as for the layered plates (figures 3a-c).

The curves for reservoir A, come from a poorly consolidated sandstone reservoir with very homogenous properties ($\Phi \approx 0.160$ and $k \approx 300mD$) are shown in figures 4a-c. The rocks were drained by oil to irreducible water saturation, using seven capillary pressure steps at 125 bar hydrostatic confining pressure. Final equilibrium, using layered porous plates, was reached 27 days after initiating drainage.

The curves presented for reservoir B (figures 5a-c), show results for a poorly consolidated sandstone reservoir in the North Sea with heterogeneous properties ($\Phi \approx 0.270 - 0.330$ and $k \approx 400 - 4000mD$). The rocks were drained by gas to irreducible water saturation, using seven capillary pressure steps at 250 bar hydrostatic confining pressure. Final equilibrium, using layered porous plates, was reached 22 days after initiating drainage.

Reservoir C (figures 6a-c), is a consolidated laminated sandstone reservoir in the North Sea with very heterogeneous properties ($\Phi \approx 0.190 - 0.240$ and $k \approx 0.4 - 300mD$). The rocks were drained by gas to irreducible water saturation using seven- and ten capillary pressure steps at 200 bar hydrostatic confining pressure. Final equilibrium, using both layered and homogenous porous plates, was reached 71 and 207 days respectively after initiating drainage.

All reservoir data is plotted together (figures 7a-b) in order to illustrate the differences among them. There is a tendency towards decreasing time required as a function of increasing permeability.

SIMULATIONS

We have simulated primary drainage for the Bentheimer core both with Soil Moisture and KeraFlux properties for the porous plate. The simulations were done using a 1-D Lab simulator. The Bentheimer core had the properties as described above, and we used capillary pressure data from Table 2. The physical properties of the porous plates including threshold pressure were from Table 1. The porous plate permeability was calculated from the water flux data, and for the layered system plate the permeability was also estimated by geometric averaging and tortuosity data. The simulation showed that equilibrium was achieved for a pressure of 0,1bar in 40 days for a homogeneous membrane, while only three days were required for a model using properties of the more high permeable layered plate. The simulations confirm the trend observed by the experimental results.

CONCLUSIONS

Effective drainage rates are affected by the properties of the porous plate itself. Drainage behaviour (distribution and electrical properties) seems to be unaffected by the flux properties of the porous plate.

There is a clear tendency towards decreasing time requirements as a function of increasing permeability. Drainage from cores with layered porous plates is 3-10 times faster than homogenous porous plates in the permeability interval 2-4000 mD.

It's reasonable to believe that the influence of ceramic plates is related to effective composite permeability of the non-invaded part of the composite porous media

NOMENCLATURE

k:	permeability
P:	pressure
Sw	water saturation
r:	radii
d:	length
Pc	capillary pressure
n	number of pore channels
dS_w	change in water saturation
dt	change in experimental time

$k_{ij}{}^{2} = \frac{r_{ij}}{8}$ is the permeability of a cylindrical tube

$\mu_{eff} = \mu_2 x_{ij} + \mu_1 (1 - x_{ij})$ is the weighted effective viscosity

$\Delta P_{ij} = P_i - P_j$ is the pressure difference between node i and node j

$P_c = P_2 - P_1$ is the capillary pressure in the tube

x_{ij} is the position of the pore-interface in the tube

r_{ij} is the radius of the tube

$^{+}$ indicates that $(P_i - P_j) > P_c$ otherwise $q_{ij} = 0$

Hydrophobic: Water is non spreading on the surface ($\theta \geq 90$)

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Table 1: Porous plate parameters (W= water-wet, O= oil-wet)

Parameter	**Soil Moisture-W**	**KeraFlux-W Type-1**	**KeraFlux-W Type-2**	**KeraFlux-O**
Diameter	1.5” (38.1mm)	1.5” (38.1mm)	1.5” (38.1mm)	1.5” (38.1mm)
Thickness/length	9.5 mm	5 mm	5 mm	5 mm
Average pore size	160nm	50nm/4miron	100nm/4miron	100nm/4miron
Pc-max g/w	15 bar	12 bar	18 bar	-
Pc-max o/w	14 bar	24 bar	36 bar	-
Pc-max w/o	-	-	-	18 bar
Flux using water	0.13ml/h @ 1bar	2ml/h @ 1 bar	10ml/h @ 1 bar	-
Flux using oil	-	-	-	>20ml/h @ 1 bar

Table 2:
Average drainage data on Bentheimer plugs

Layered plate			**Homogenous plate**		
n=1.76			**n=**		
Pc (bar)	**Sw** (frac.)	**Time** (days)	**Pc** (bar)	**Sw** (frac.)	**Time** (days)
0.000	1.000	0	0.000	1.000	0
0.100	0.186	14.8	0.100	0.187	98.8
0.200	0.138	29.9	0.200		
0.400	0.129	34.8	0.400		
0.800	0.121	39.8	0.800		
2.000	0.115	40.9	2.000		
5.000	0.105	42.8	5.000		

Figure-1: Layered porous plate:

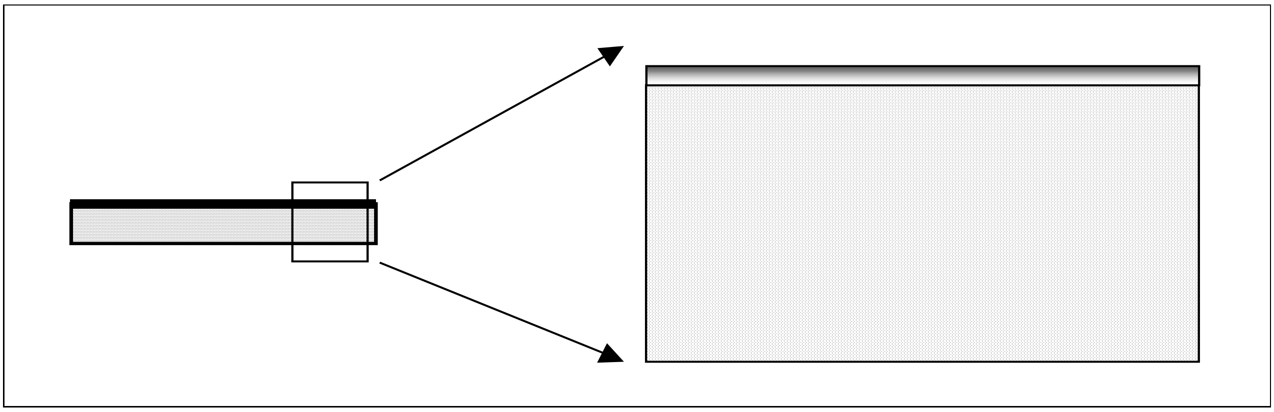


Figure 2a-c:
Bentheimer core plugs using layered porous plate Type-1 (laboratory oil/water)

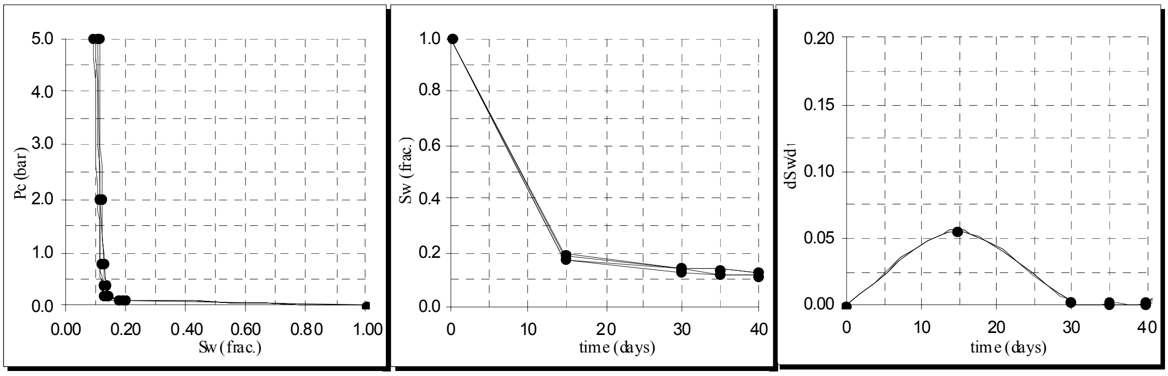


Figure-2a Figure-2b Figure-2c

Figure 3a-c:
Bentheimer core plugs using homogeneous porous plate (Laboratory oil/water)

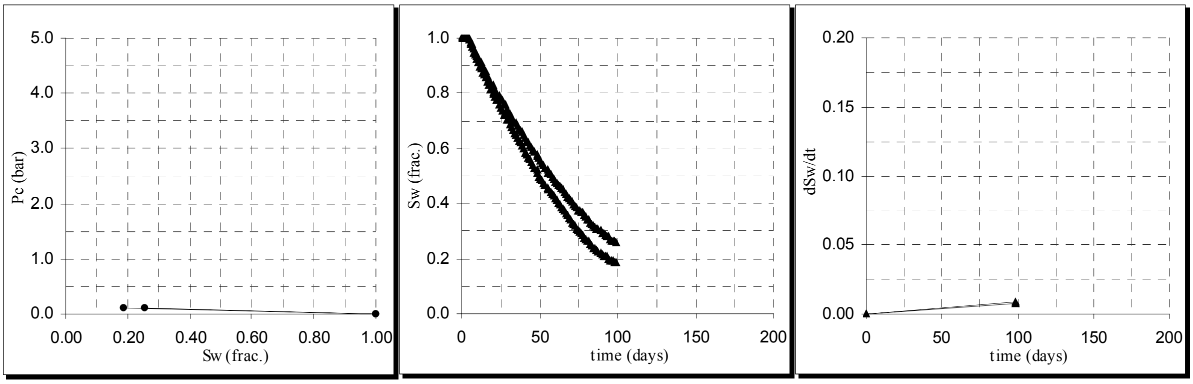


Figure-3a Figure-3b Figure-3c

Figure 4a-c:
Reservoir-A core plugs using layered porous plate Type-2 (laboratory oil/water)

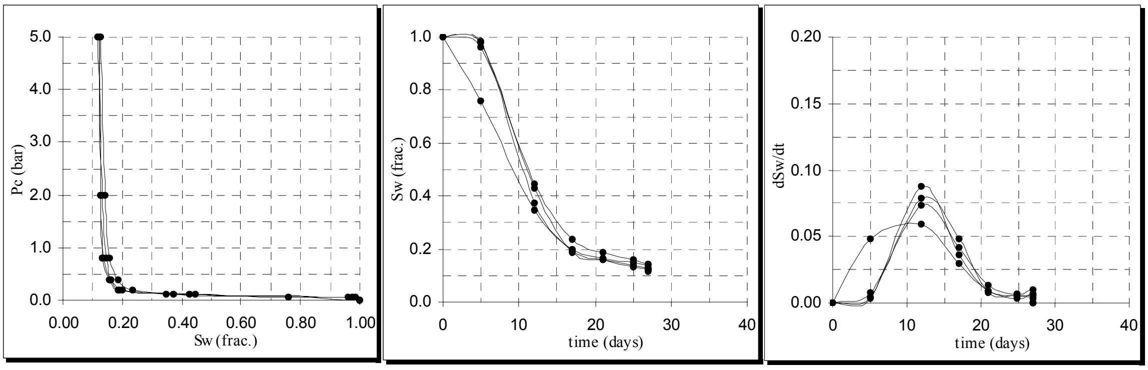


Figure-4a Figure-4b Figure-4c

Figure 5a-c:
Reservoir-B core plugs using layered porous plate Type-2 (gas/water)

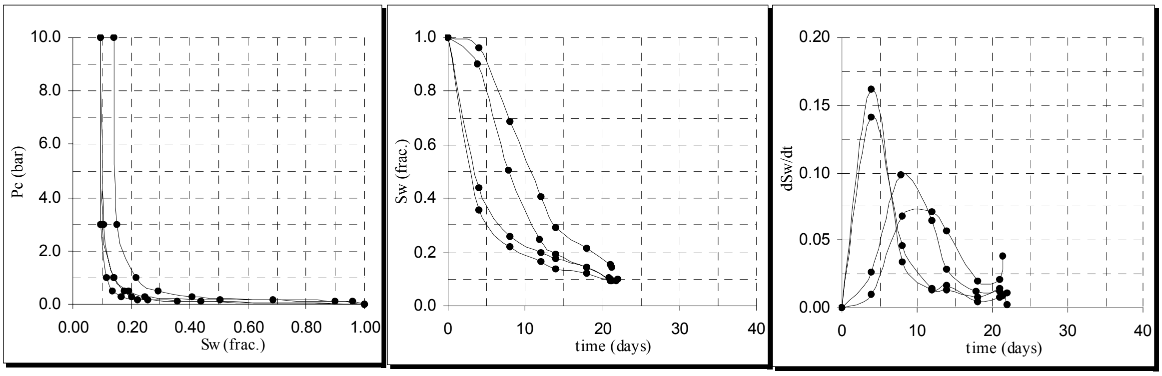


Figure-5a Figure-5b Figure-5c

Figure 6a-c:
Reservoir-C core plugs using layered Type-2 and homogenous porous plates (gas/water)

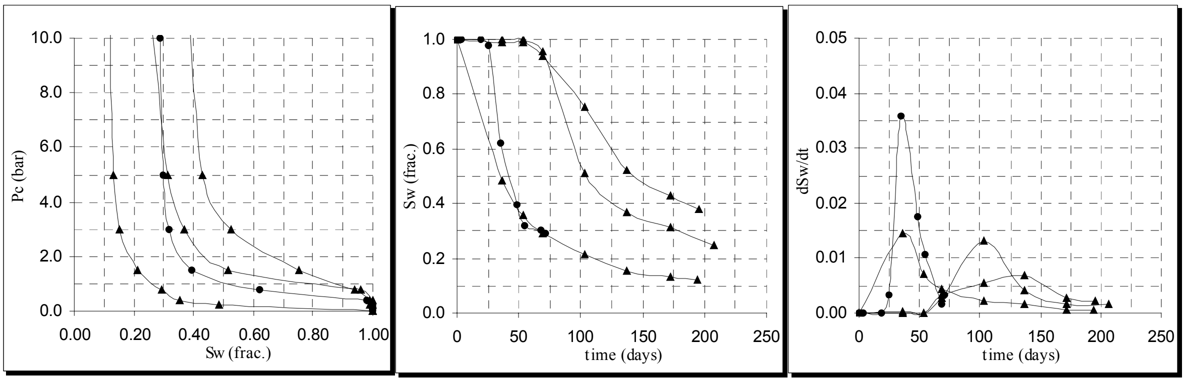
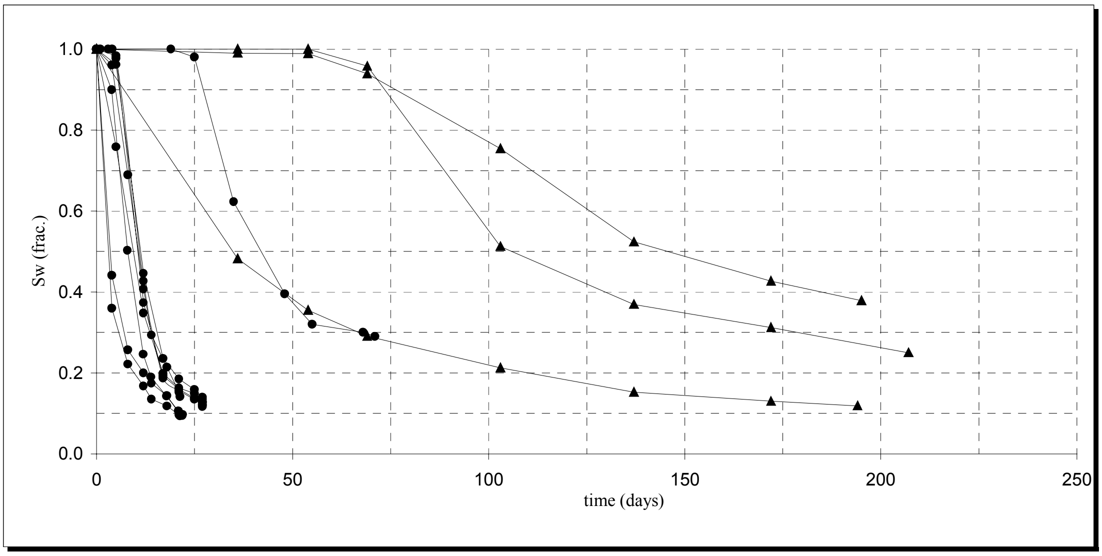


Figure-6a Figure-6b Figure-6c

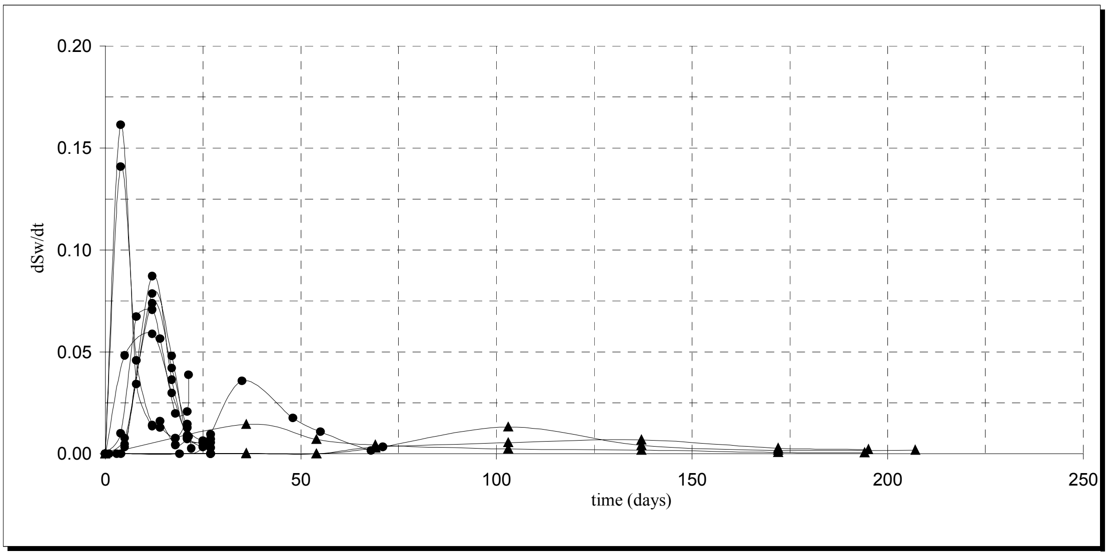
▲: Homogeneous porous plate used, ●: Layered porous plate type-2 used

Figure 7a: Reservoir A+B+C core plugs using layered and homogeneous porous plate



▲: Homogeneous porous plate used ●: Layered porous plate used

Figure 7b: Reservoir A+B+C core plugs using layered and homogeneous porous plate



▲: Homogeneous porous plate used ●: Layered porous plate used

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