

Chapter 7: Wettability

7.1 Introduction and Definition

There exists a surface tension between a fluid and a solid, in the same way that a surface tension exists between an interface between two immiscible fluids (*cf.* the surface tension on water under air that is sufficient to support the weight of a needle.). When two fluids are in contact with a solid surface, the equilibrium configuration of the two fluid phases (say air and water) depends on the relative values of the surface tension between each pair of the three phases (Figure 7.1). Let us denote surface tension as \mathbf{g} and solid, liquid and gas as s, l, and g respectively. Each surface tension acts upon its respective interface, and define the angle \mathbf{q} at which the liquid contacts the surface. This is known as the wetting (or dihedral) angle of the liquid to the solid in the presence of the gas. Equilibrium considerations allow us to calculate the wetting angle from the surface tensions:

$$\mathbf{g}_{lg} \cos \mathbf{q} = \mathbf{g}_{sg} - \mathbf{g}_{sl} \quad (7.1)$$

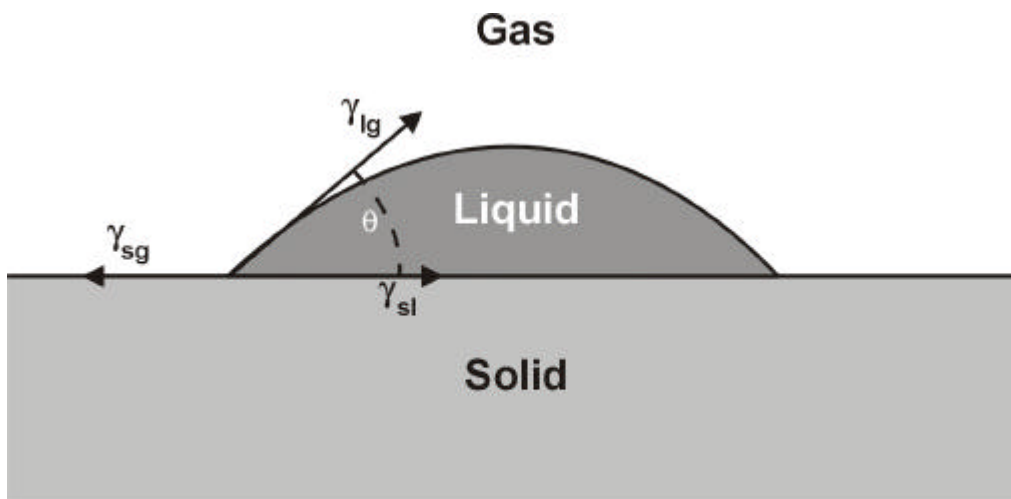


Figure 7.1 Liquid/Solid/Gas Wetting Angle

This is known as Young's equation (1805). Table 7.1 shows some contact angles and surface tensions for common fluids in the hydrocarbon industry.

Table 7.1 Contact angles and interfacial tension for common fluid-fluid interfaces

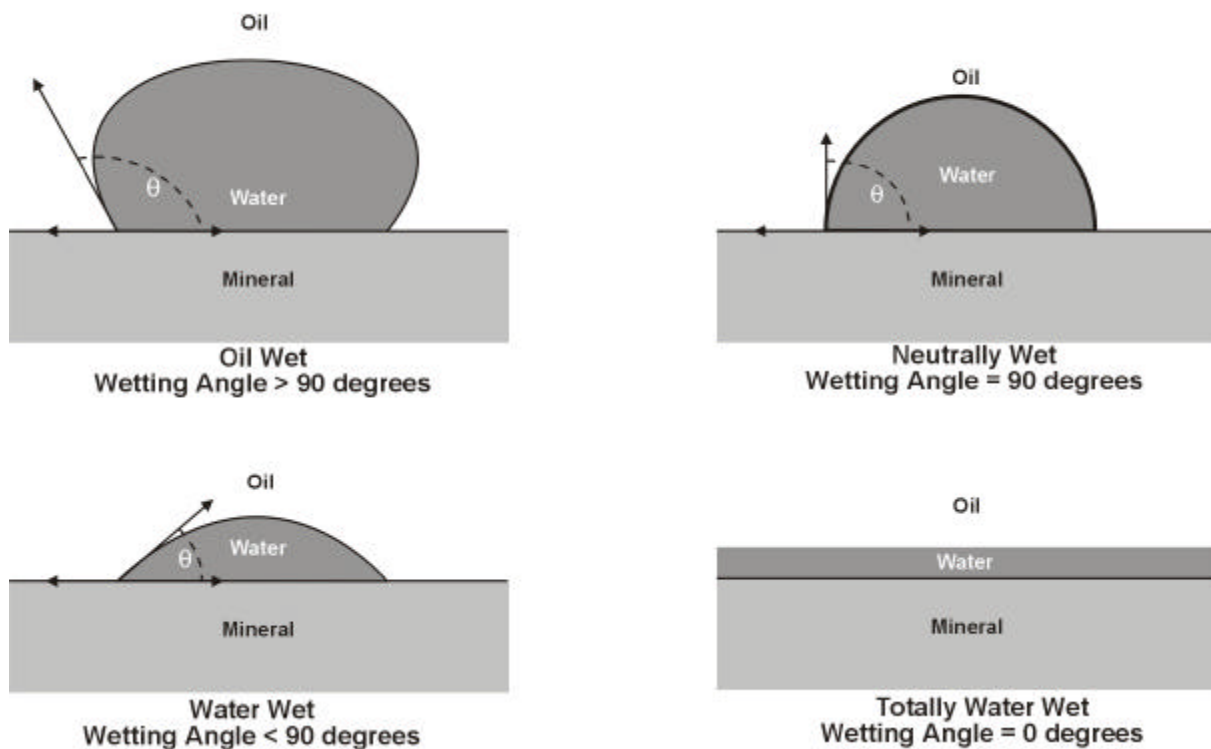
Interface	Contact Angle, \mathbf{q} , degrees	$\cos \mathbf{q}$	Interfacial Tension, dynes/cm
Air-Water	0	1.0	72
Oil-Water	30	0.866	48
Air-Oil	0	1.0	24
Air-Mercury	140	-0.765	480

Note that:

- If $\gamma_{sg} > \gamma_{sl}$, then $\cos q > 0$ and $q < 90^\circ$.
- If $\gamma_{sg} < \gamma_{sl}$, then $\cos q < 0$ and $q > 90^\circ$.

For a stable contact $|\cos q| \leq 1$, or equivalently $|\gamma_{sg} - \gamma_{sl}| \leq \gamma_{gl}$. This inequality is not satisfied when $\gamma_{lg} + \gamma_{sl} < \gamma_{sg}$, when liquid covers the whole solid surface. Alternatively, when $\gamma_{lg} + \gamma_{sg} < \gamma_{sl}$, the gas displaces the liquid away from the surface completely. Figure 7.2 shows a range of different wetting conditions.

Figure 7.2 Wetting Angles for Various Wetting Properties



When one fluid preferentially covers the surface, it is called the wetting fluid, and the other fluid is called the non-wetting fluid. The origin of these surface tensions arises in the different strengths of molecular level interactions taking place between the pairs of fluids. For example a quartz sandstone grain generally develops greater molecular forces between itself and water than between itself and oils. Clean sandstones are therefore commonly water wet. However, should that same grain have been baked at high temperatures in the presence of oil at depth, then (i) its surface chemical structure can be altered, or (ii) the surface itself can become coated, in such a way that results in the grain having greater molecular interaction with oils than water, and hence become oil wet. **IMPORTANT NOTE** Properly measured wettabilities on well preserved core and core plugs should form the initial step in choosing relative permeability test methods.

7.2 Laboratory Determination

There are several methods for determining wettability of a rock to various fluids. The main ones are:

- (i) **Microscopic observation** This involves the direct observation and measurement of wetting angles on small rock samples. Either a petrographic microscope or SEM fitted with an environmental stage is used. The measurements are extremely difficult, and good data relies more on luck than judgement.
- (ii) **Amott wettability measurements** This is a macroscopic mean wettability of a rock to given fluids. It involves the measurement of the amount of fluids spontaneously and forcibly imbibed by a rock sample. It has no validity as an absolute measurement, but is industry standard for comparing the wettability of various core plugs.
- (iii) **USBM (U.S. Bureau of Mines) method.** This is a macroscopic mean wettability of a rock to given fluids. It is similar to the Amott method but considers the work required to do a forced fluid displacement. As with the Amott method, it has no validity as an absolute measurement, but is industry standard for comparing the wettability of various core plugs.
- (iv) **NMR longitudinal relaxation and other wettability methods.** These are briefly summarised in Table 7.2.

Table 7.2 Summary of Wettability Measurement Techniques

Measurement Technique	Physical Observation
Amott and Amott-Harvey	Amounts of oil and water imbibed by a sample spontaneously and by force.
U.S. Bureau of Mines (USBM)	Work required to imbibe oil and water.
Microscopic examination	Microscopic examination of the interaction between the fluids and the rock matrix.
Nuclear Magnetic Resonance	Changes in longitudinal relaxation time.
Flotation method	The distribution of grains at water/oil or air/water interfaces.
Glass slide method	Displacement of the non-wetting fluid from a glass slide.
Relative permeability method	Shape and magnitudes of K_{ro} and K_{rw} curves.
Reservoir logs	Resistivity logs before and after injection of a reverse wetting agent.
Dye adsorption	Adsorption of a dye in an aqueous solvent.

The first two methods are the commonest within the oil industry and are described in greater detail in the next two sections.

7.2.1 Amott Wettability Measurements

Wettability measurements by the Amott method give a guide to the relative oil or brine wetting tendencies of reservoir rocks. This can be crucial in the selection of relative permeability test methods to generate data relevant to the reservoir situation. It is not always possible to reproduce reservoir wettabilities in room condition relative permeability tests. However, an appreciation of the difference between reservoir and laboratory wettabilities can assist in interpretation of laboratory waterfloods.

The Amott method (Figure 7.3) involves four basic measurements. Figure 7.4 shows the data produced with the *water wetting index* given by AB/AC and the *oil wetting index* by CD/CA .

- (i) The amount of water or brine spontaneously imbibed, AB.
- (ii) The amount of water or brine forcibly imbibed, BC.
- (iii) The amount of oil spontaneously imbibed, CD
- (iv) The amount of oil forcibly imbibed, DA

Figure 7.3 Amott Wetting Technique

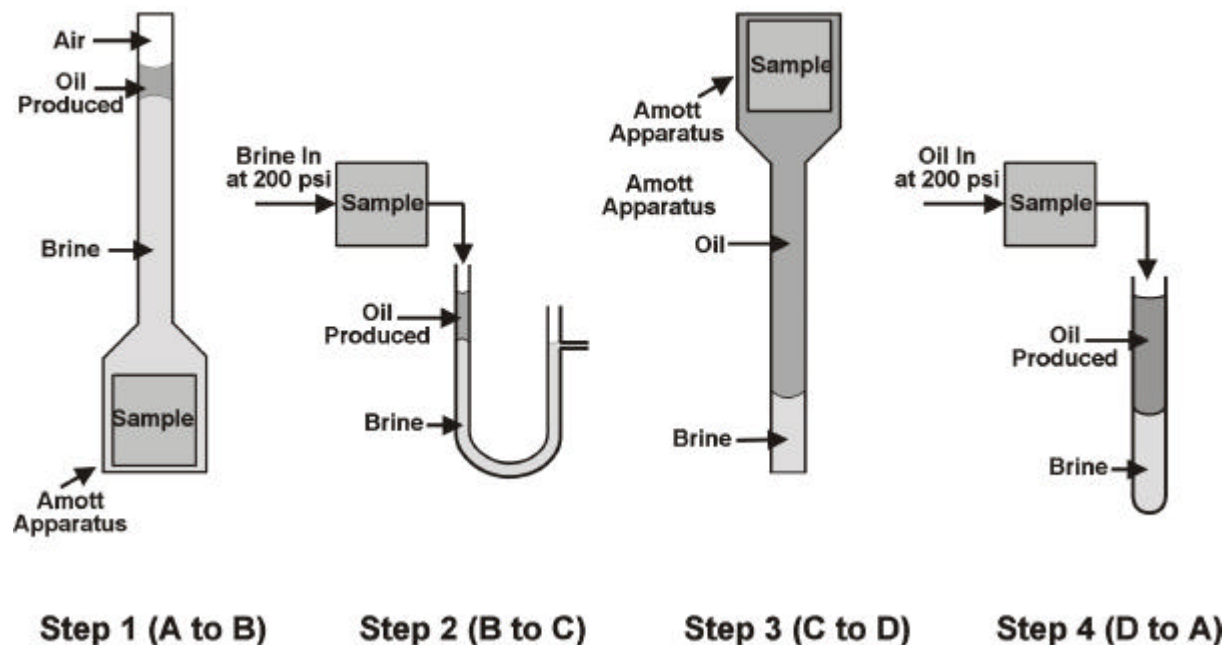
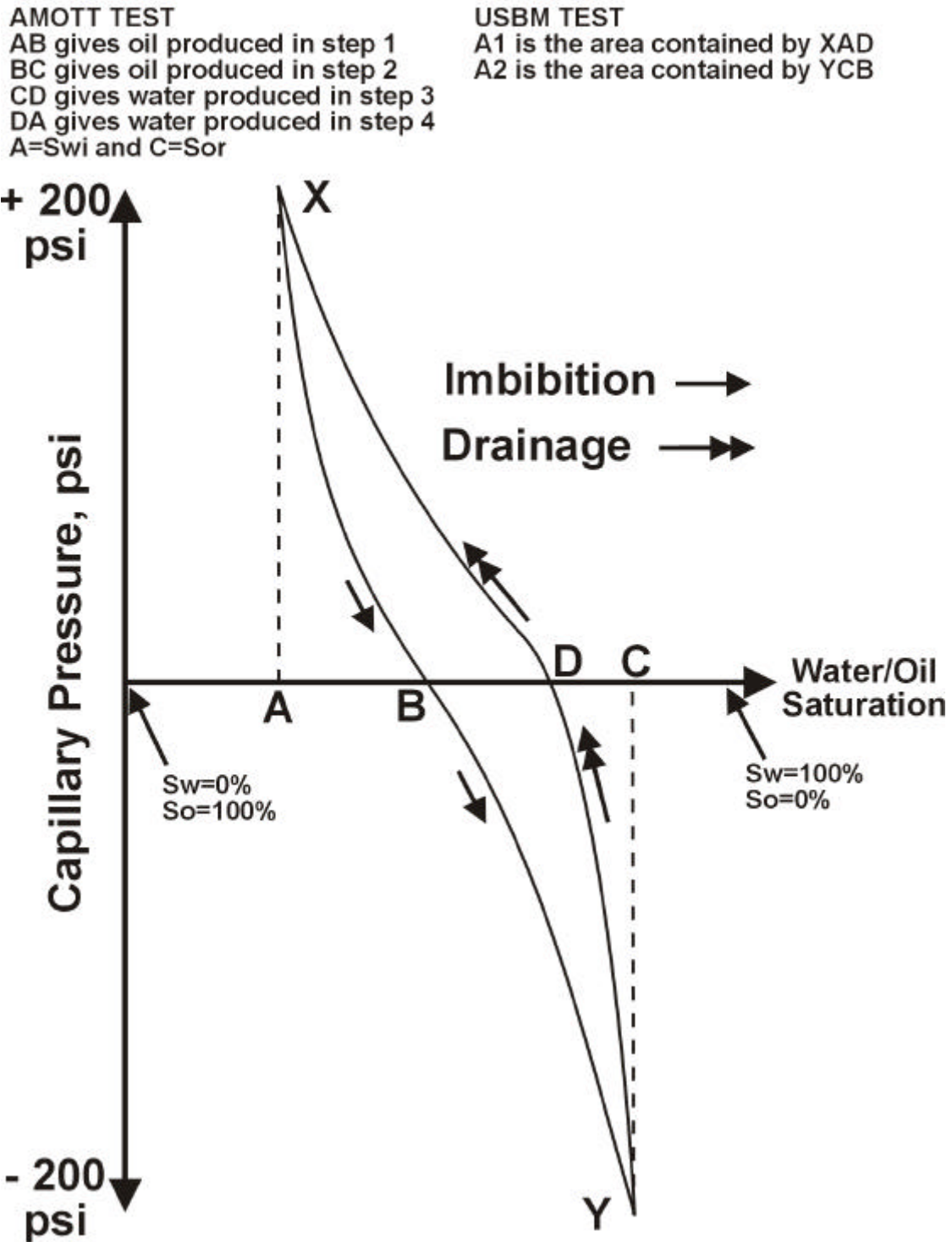


Figure 7.4 shows the initial conditions of the sample (point X) to be oil saturated at S_{wi} . The spontaneous measurements are carried out by placing the sample in a container containing a known volume of the fluid to be imbibed such that it is completely submerged (steps 1 and 3 in Figure 7.3 for water and oil respectively), and measuring the volume of the fluid displaced by the imbibing fluid (e.g. oil in step 1 of Figure 7.3). The forced measurements are carried out by flowing the 'imbibing' fluid through the rock sample and measuring the amount of the displaced fluid (steps 2 and 4 in Figure 7.3), or by the use of a centrifuge. The important measurements are the spontaneous imbibitions of oil and water, and the total (spontaneous and forced) imbibitions of oil and water. Water-wet samples *only* spontaneously imbibe water,

oil-wet samples *only* spontaneously imbibe oil, and those that spontaneously imbibe neither are called neutrally-wet. The wettability ratios for oil (AB/AC) or water (CD/CA) are the ratios of the spontaneous imbibition to the total imbibition of the each fluid.

Figure 7.4 Wettability Test Data



In general use the samples to be measured are centrifuged or flooded with brine, and then flooding or centrifuging in oil to obtain S_{wi} . The standard Amott method is then followed. At the end of the experiment the so called Amott-Harvey wettability index is calculated:

$$\text{Index} = \frac{\text{Spontaneous Water Imbibition}}{\text{Total Water Imbibition}} - \frac{\text{Spontaneous Oil Imbibition}}{\text{Total Oil Imbibition}} \quad (7.2)$$

$$= \frac{AB}{AC} - \frac{CD}{CA}$$

Wettability indices are usually quoted to the nearest 0.1 and are often further reduced to weakly, moderately or strongly wetting. The closer to unity the stronger the tendency.

7.2.2 USBM Wettability Measurements

This method is very similar to the Amott method, but measures the work required to do the imbibitions. It is usually done by centrifuge, and the wettability index W is calculated from the areas under the capillary pressure curves $A1$ and $A2$:

$$W = \log \frac{A1}{A2} \quad (7.3)$$

where, $A1$ and $A2$ are defined in Figure 7.5. Note that in this case the initial conditions of the rock are $S_w=100\%$, and an initial flood down to S_{wi} is required (shown as step 1 in Figure 7.5), although either case may be necessary for either the Amott or USBM methods. Figure 7.6 shows typical USBM test curves for water wet, oil wet and neutrally wet cores.

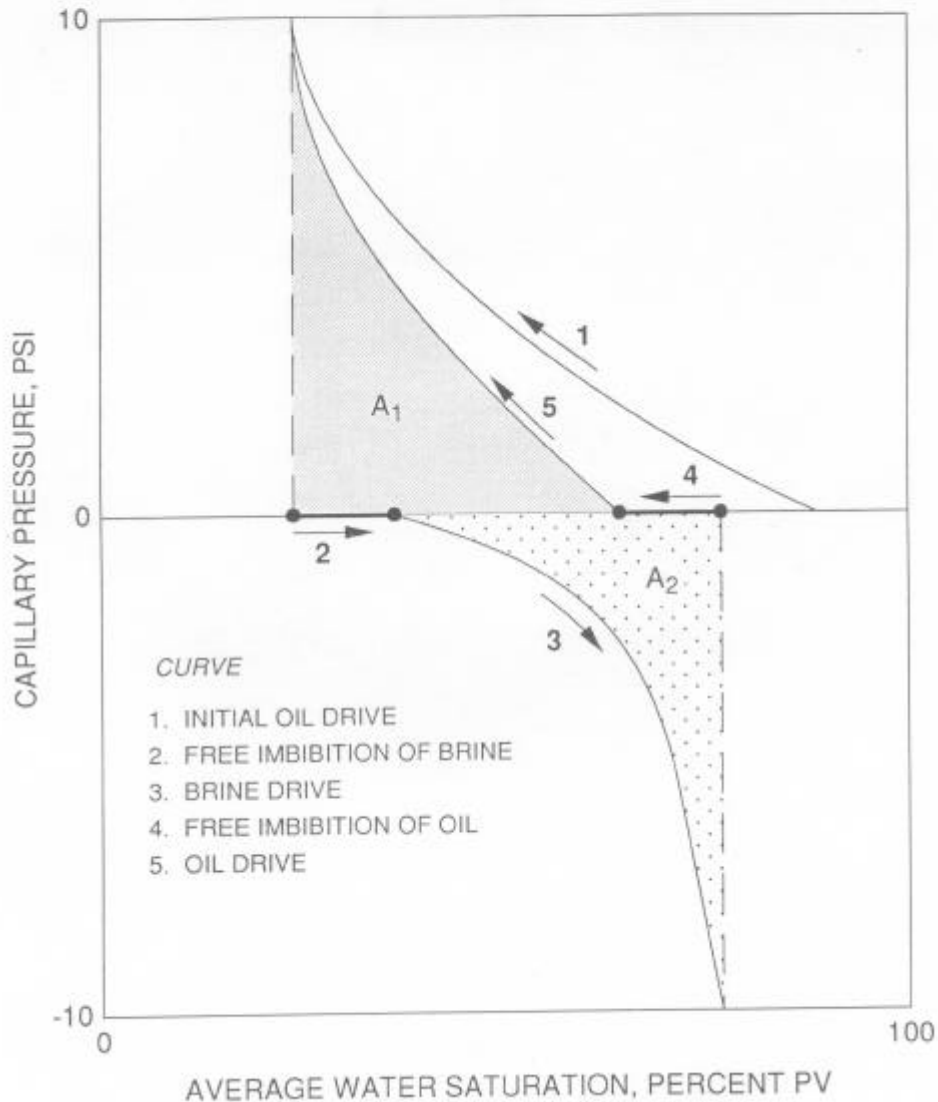
7.2.3 USBM and Amott Technique Comparison

Warning. While both methods are common within the oil industry, they show remarkable differences especially near the neutral wettability region. In general, the Amott method is probably the most reliable and accurate especially in the neutral wettability region. A comparison of the two methods, together with contact angles, is given in Table 7.3.

Table 7.3 Comparison of the Amott and USBM Wettability Methods

	Oil Wet	Neutral Wet	Water Wet
Amott wettability index water ratio	0	0	>0
Amott wettability index oil ratio	>0	0	0
Amott-Harvey wettability index	-1.0 to -0.3	-0.3 to 0.3	0.3 to 1.0
USBM wettability index	about -1	about 0	about 1
Minimum contact angle	105° to 120°	60° to 75°	0°
Maximum contact angle	180°	105° to 120°	60° to 75°

Figure 7.5 USBM Wettability Test Capillary Pressure Curve (Numbers indicate the progress of the test from $S_w=100\%$)



7.3 Sample Preservation and the Effect on Wettability

Sample preservation, preparation, storage and test conditions are important since wettability is sensitive to oxidation of crude oil and to temperature. Preservation of samples at the well-site is generally by wrapping in foil and wax coating. The process should be carried out *as soon as possible* after removal of the core from the barrel. Samples are drilled and trimmed with deaerated, simulated depolarised kerosene prior to testing. Tests carried out to assess reservoir wettability must be made on preserved core at a temperature high enough to ensure that any wax present in the residual core remains in solution. If the wax precipitates, it will tend to increase the oil wetting tendency of the core. Room condition wettabilities may only apply to reservoirs containing wax free crude or cleaned cores from laboratory tests.

Figure 7.6 USBM Wettability Test Capillary Pressure Curves for (a) water wet, (b) oil wet, and (c) neutrally wet samples

