## Effect of trapped gas on waterflood recovery

The presence of initial gas saturation has an effect on waterflood recovery. Early research indicated that the waterflooding of a linear system results in the formation of an oil bank, or zone of increased oil saturation, ahead of the injection water. The moving oil bank will displace a portion of the free gas ahead of it, trapping the rest as a residual gas. An illustration of the water saturation profile is shown in Figure 1. The oil recovery by water is improved as a result of the establishment ***of trapped gas saturation***, $S_{gt}$, in the reservoir.

Oil recovery can be increased if the reservoir pressure is carefully controlled so as to leave optimum trapped gas saturation within the oil bank. The idea is to reduce the residual oil saturation value, $S_{or}$, by an amount equal to the trapped gas saturation. For example, if the residual oil saturation is 35% and if a trapped gas saturation can be maintained at 5%, the residual oil saturation would be 30%.

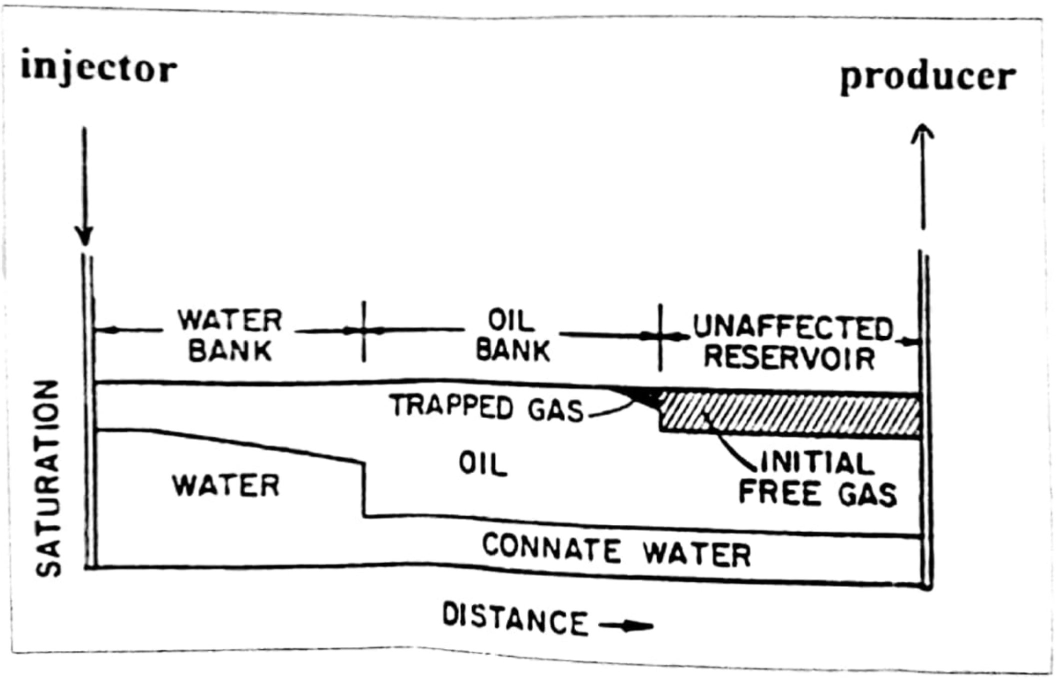


Figure 1: Water saturation profile during a waterflood.

Craig (1971) presented two graphical correlations that are designed to account for the reduction in the residual oil saturation due to the presence of the trapped gas. The first graphical correlation, shown in Figure 2, correlates the trapped gas saturation (Sgt) as a function of the initial gas saturation (Sgi). The second correlation as presented in Figure 3 illustrates the effect of the trapped gas saturation on the reduction in residual oil saturation ( $\Delta S_{or}$ ) for preferentially water-wet rock. The two graphic correlations can be expressed mathematically by the following two expressions:

$$S_{gt} = a_1 + a_2 S_{gi} + a_3 S_{gi}^2 + a_4 S_{gi}^3 + \frac{a_5}{S_{gi}} \qquad (14\text{-}1)$$

and

$$\Delta S_{or} = a_1 + a_2 S_{gt} + a_3 S_{gt}^2 + a_5 S_{gt}^3 + \frac{a_5}{S_{gt}} \qquad (14\text{-}2)$$

where $S_{gi}$ = initial gas saturation
$S_{gt}$ = trapped gas saturation
$\Delta S_{or}$ = reduction in residual oil saturation

Values of coefficients $a_1$ through $a_5$ for both expressions are tabulated below:

| Coefficients | Equation 14-1 | Equation 14-2 |
|---|---|---|
| $a_1$ | 0.030517211 | 0.026936065 |
| $a_2$ | 0.4764700 | 0.41062853 |
| $a_3$ | 0.69469046 | 0.29560322 |
| $a_4$ | −1.8994762 | −1.4478797 |
| $a_5$ | $-4.1603083 \times 10^{-4}$ | $-3.0564771 \times 10^{-4}$ |

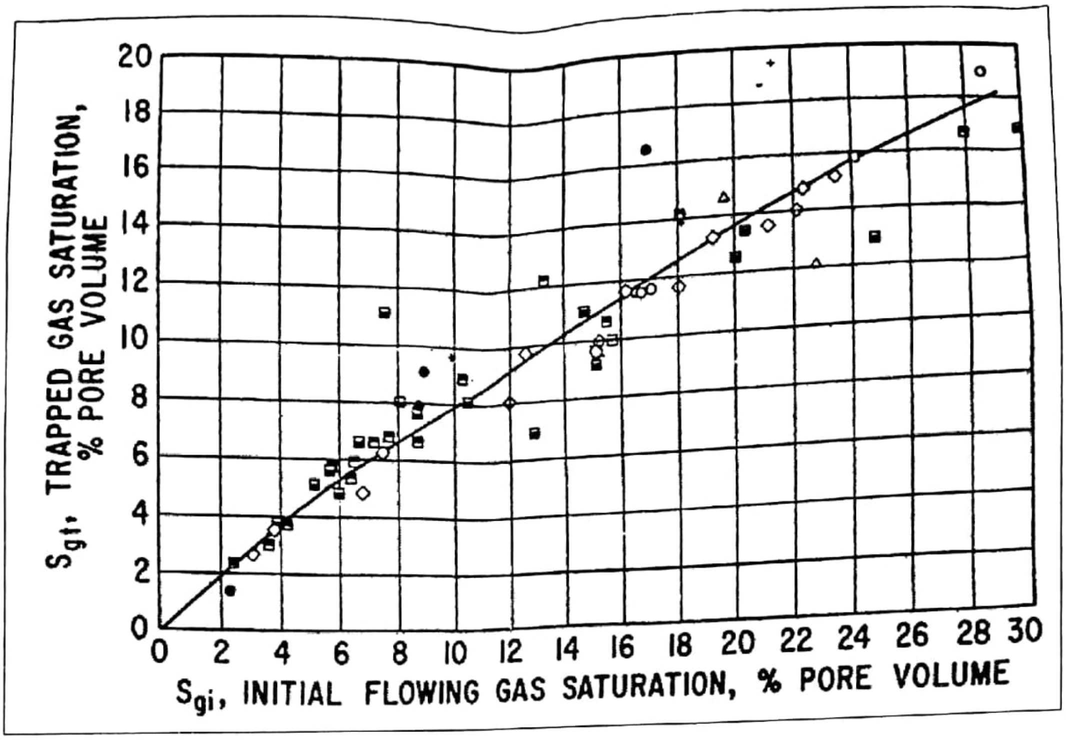


Figure 2: Relation between $S_{gi}$ and $S_{gt}$.

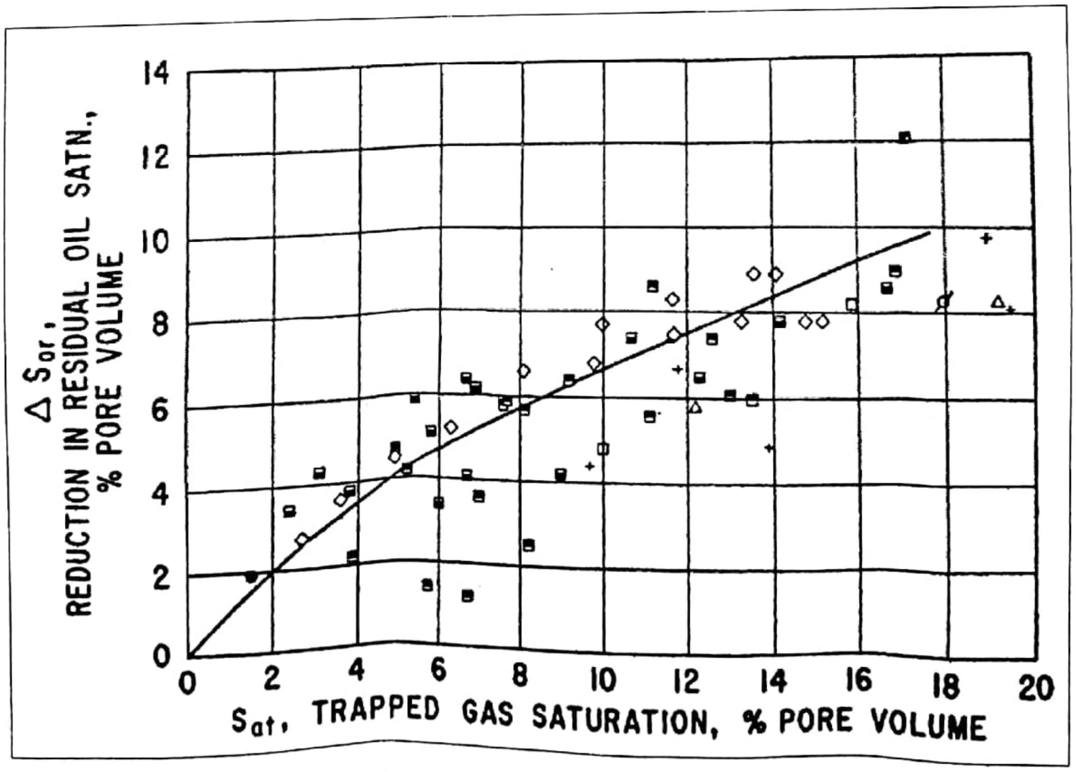


Figure 3: Effect of Sgt on waterflood recovery.

Khelil (1983) suggests that waterflood recovery can possibly be improved if a so-called "optimum gas saturation" is present at the start of the flood. This optimum gas saturation is given by:

$$(S_g)_{opt} = \frac{0.001867\,k^{0.634}\,B_o^{0.902}}{\left(\frac{S_o}{\mu_o}\right)^{0.352}\left(\frac{S_{wi}}{\mu_w}\right)^{0.166}\phi^{1.152}} \tag{14-3}$$

where $(S_g)_{opt}$ = optimum gas saturation, fraction
$S_o$, $S_{wi}$ = oil and initial water saturations, fraction
$\mu_o$, $\mu_w$ = oil and water viscosities, cp
$k$ = absolute permeability, md
$B_o$ = oil formation volume factor, bbl/STB
$\phi$ = porosity, fraction

The above correlation is not explicit and must be used in conjunction with the material balance equation (MBE). The proposed methodology of determing (Sg)opt is based on calculating the gas saturation as a function of reservoir pressure (or time) by using both the MBE and equation 14-3.

**Example 1:**

An oil reservoir is being considered for further development by initiating a waterflooding project. The oil-water relative permeability data indicate that the residual oil saturation is 35%. It is projected that the initial gas saturation at the start of the flood is approximately 10%. Calculate the anticipated reduction in residual oil, $\Delta S_{or}$, due to the presence of the initial gas at the start of the flood.

**Example 2:**

An absolute permeability of 33 md, porosity of 25%, and an initial water saturation of 30% characterize a saturated oil reservoir that exists at its bubble-point pressure of 1925 psi. The water viscosity is treated as a constant a value of 0.6 cp. Results of the material balance calculations are given below:

| Pressure, psi | Bo, bbl/STB | $\mu_o$, cp | $S_o$ | $S_g = 1 - S_o - S_{wi}$ |
|---|---|---|---|---|
| 1925 | 1.333 | 0.600 | 0.700 | 0.000 |
| 1760 | 1.287 | 0.625 | 0.628 | 0.072 |
| 1540 | 1.250 | 0.650 | 0.568 | 0.132 |
| 1342 | 1.221 | 0.700 | 0.527 | 0.173 |

Using the above data, calculate the optimum gas saturation.