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Waterflood History and Design Fundamentals

PDHengineer.com
5870 Highway 6 North, Suite 310
Houston, TX 77084
Toll Free: 877 500-7145
administrator@PDHengineer.com

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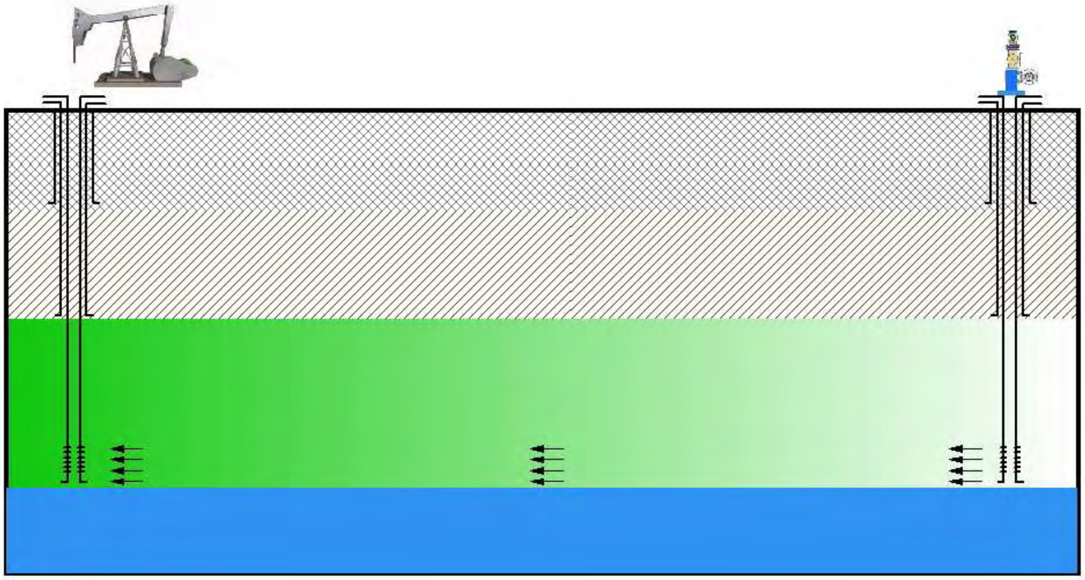


Introduction

The subject of this course is the review of waterfloods as a method of improved oil recovery. The emphasis of the analytical section of the course will be the application of simple techniques to conduct preliminary analyses of existing and potential waterfloods Included in the course are reviews of surface facility requirements as well as subsurface considerations.

What is waterflooding?

The Society of Petroleum Engineers defines waterflooding as the injection of water into an oil reservoir to “push” additional oil out of the reservoir rock and into the wellbores of producing wells.

Waterflooding is a method of secondary recovery in which water is injected into the reservoir formation to displace residual oil. The water from injection wells sweeps the displaced oil to adjacent production wells. The purpose of waterflooding includes the maintenance of reservoir pressure and the displacement of hydrocarbons toward the wellbore.

The secondary recovery stage reaches its limit when the water cut the production wells exceeds 90% or more or production is no longer economical. The combination of primary recovery and secondary

recovery in an oil reservoir can produce 40% or more of the original oil in place.

In 2005 there were over 167,000 water injection wells in the U.S. with 31,000 active wells and an additional 22,000 inactive wells in Texas.

3. Waterflood History

One of the earliest formal recognition of the potential of waterfloods was U.S. patent number 308,522 that was issued in 1884 to William Richards. Richards recognized that the pressure on the water injected would force oil to surrounding producing wells.

One of the first documented waterfloods was in Pennsylvania's Bradford field. The accidental flooding of the field is thought to have begun in 1905, six years after the field began production. Flooding continued for 15 years. During this time, production rates trended upward. In a U.S. Bureau of Mines Bulletin published in 1917 some of the early Bradford Field waterfloods are described. Most operators credited the production increase to the accidental flooding. The Richards patent suggests that intentional waterflooding began as early as 1864. Although water floods were not legalized until 1921, operators in both the U.S. and Canada instituted intentional field waterfloods. While the unintentional flooding of fields is well-documented, data on intentional waterfloods by operators prior to 1921 are rare. Forrest Oil was one of the pioneers in legitimate waterfloods in Bradford Field.

The earliest water floods were called "circle floods" because of the growth pattern of the water invaded zone. When producing wells were watered out, they were converted to injection wells to expand the area under waterflood. When the rate of advance of the waterflood slowed as the areal extent increased one operator converted a series of wells to form a line drive that was the first of the pattern floods and increased oil recovery and production rates significantly.

The first five spot pattern waterflood was attempted in 1924 on a tract in the southern part of the Bradford field. Frank Haskell is credited with the idea, but Arthur Yahn receives credit for the technique's first successful deployment. Haskell's attempt failed to produce a speedy response because of the 500-ft distance between like wells. Yahn's 190-ft distance between wells produced a much quicker response. Initially, only surface water, so called dump floods, were injected into the wells but in late 1929 a facility was built to provide pressure to increase the rate of injection. The five spot pattern was even more successful when the injection wells were worked over to maximize the injection into reservoir zones that had the most cumulative production. The result was a faster response to the waterflood. Five spot well spacing varied areally depending on formation permeability. By 1937 the five spot pattern waterflood had been widely adopted by the operators.

However, operators were slow to extend waterflood activities outside Pennsylvania due to the economic conditions of 1929 and 1930. However, in 1931, the Carter Oil Co. initiated a pilot flood in the shallow Bartlesville sand of Oklahoma. Soon, others followed; and all enjoyed favorable

results. In early 1936, waterflooding operations were extended to the shallow sands of the Fry Pool in Brown County, Texas. However, results were marginal, and it wasn’t until Magnolia Petroleum Co. initiated the West Burkburnett flood in 1944 that outstanding results were achieved. Operations soon followed in other states between 1944 and 1949.

During this expansion period, engineers became aware of the advantages of pressure control by reinjecting produced water in natural waterdrive fields. In 1936, the East Texas field was the site of initial experiments involving reservoir pressure control as a result of the disposal of produced water in natural waterdrive fields. Schilthuis in 1936 and Hurst in 1943 published landmark papers on the effect of water influx on fields with natural water drives. The equations presented in these papers led to the conclusion that as the reservoir pressure declined salt water in the aquifer of the sand expanded and encroached into the oil reservoir. Depending on the rate of production, the water sustained an equilibrium level of reservoir pressure that was dependent on the rate of production. After several years of implementation of water re-injection in the East Texas Field the program was declared a success and was expanded to other fields. The field’s natural waterdrive supplemented by water injection resulted in a recovery factor that is more than 70%.

Early water floods were designed and implemented with empirical methods. The breakthrough in analytical design of waterfloods began in 1942 with the publication of a paper by Buckley and Leverett. The paper, “Mechanism of Fluid Displacement in Sands” derived the linear frontal advance equation describing the rate of advance of the waterflood front. In 1952 Welge published “A Simplified Method for Computing Oil Recovery by Gas or Water Drive”. Welge presented a graphical method of solution of the Buckley-Leverett equation that enabled the wide spread use of the method. These two works established the foundation for analytical design and evaluation of waterflood performance.

Magnolia Petroleum Co.’s West Burkburnett field in Texas is an example of the success of a large waterflood secondary recovery operation. Using a five-spot water-injection program, the company’s flood recovered 9 million bbl of oil between 1944 and 1953, or 1.4 times that recovered by primary methods.

In Illinois, an initial five-spot program in Patoka field, Marion County, resulted in a much more rapid response in the oil production rate than expected. The field produced 2.8 million bbl of oil by primary production and 6.4 million bbl of waterflood oil by August 1960.

The first waterfloods in California were started in 1954 in the Calitroleum Pool and the Monarch Pool. In the Norwegan North Sea, the first chalk reservoir waterfloods were started in the mid 1980s in the Ekofisk area fields.

Analytical Techniques

Rock and Fluid Properties

The basic analysis of waterfloods requires the knowledge of a relatively few rock and fluid properties. The three basic properties are porosity, relative permeability, and viscosity. Values of relative permeability and viscosity for oil and water will be used in the following basic analyses. Modification of water viscosity due to temperature and salinity can be done using Figures 2 and 3. The effects of oil gravity, temperature, gas in solution, and pressure can be accounted for using Figures 4 through 6.

Rock Properties

Porosity(Φ)-Ratio of the void volume to the bulk volume of a given rock. Measured as per cent.

Permeability(k)-Measure of the capacity of a rock volume to transmit fluids. The Darcy is the primary unit.

Relative Permeability(k_{ro}, k_{rw}, and k_{rg})-The ratio of the effective permeability of a specific phase to the absolute permeability(k_o/k, k_w/k, and k_g/k).

Fluid Properties

Viscosity(μ_o, μ_w, and μ_g)-The internal resistance of a fluid to flow.

Darcy's Law for Horizontal Flow

$$q = (1.1271)\frac{kA(P_1 - P_2)}{\mu L}$$

where $q - Flow\ \ Rate(bbls/day)$

$k - Permeability(Darcies)$

$A - Area(ft^2)$

$P_1 - P_2 - \mathrm{Pr}essure\ \ Drop(lbf/in^2)$

$$\mu - Viscosity(cp)$$
$$L - Flow\ Length(ft)$$

Note-The Darcy is the standard unit of permeability as adapted by the petroleum industry. A porous medium has a permeability of one darcy when a single phase fluid of one centipoise viscosity completely fills the voids of the porous medium and flows through it in viscous flow at a rate of one cubic centimeter per second per square centimeter of cross sectional area under a pressure or equivalent hydraulic gradient of one atmosphere per centimeter. Viscous flow is the flow rate which is directly proportional to the potential gradient.

Horizontal Fractional Flow Equation

$$f_w = \frac{1}{1 + \frac{\mu_w}{\mu_o}\frac{k_{ro}}{k_{rw}}}$$

where ***f_w-Fractional flow of water[q_w/(q_w+q_o)] at a point in the reservoir. Also referred to as watercut***

μ_w-Viscosity of water(cp)
μ_o-Viscosity of oil(cp)
k_{ro}-Relative permeability to oil(Fraction)
k_{rw}-Relative permeability to water(Fraction)

Note-The ratio $\frac{\mu_w}{\mu_o}\frac{k_{ro}}{k_{rw}}$ evaluates the relative permeabilities at a specific point(specific saturation) in the reservoir. It is not the inverse of the Mobility Ratio $\frac{k_{rw}}{\mu_w}\frac{\mu_0}{k_{ro}}$ where the water permeability is evaluated in the water contacted reservoir volume and the oil permeability is evaluated in the oil bank volume of the reservoir.

Frontal Advance Equation

$$L = \frac{W_i}{A\phi}\left(\frac{df_w}{dS_w}\right)$$

where ***L*-Total distance that a specified water saturation plane has moved**

***W_i*-Cumulative volume of injected water. Also equal to the volume of oil displaced**

***A*-Cross section area perpendicular to the direction of frontal advance**

***ϕ*-Porosity**

***$\left(\frac{df_w}{dS_w}\right)$*-Slope of the curve of fractional flow, f_w, versus water saturation, S_w**

Time to Breakthrough

$$t_b = AL\phi(S_{wf} - S_{wi})/q_t$$

where ***t_b*-Time to water breakthrough**

A, L, and ϕ have been previously defined

***S_{wf}* –Water saturation at breakthrough**

***S_{wi}* –Initial water saturation**

***q_t* –Injection rate**

Waterflood Performance Prediction

Analysis of waterfloods such as edge or peripheral injection, line drive, and sweeps can be successful using the linear fractional flow equation, the frontal advance equation, and the time to breakthrough equation presented above. The parameters $\frac{k_{ro}}{k_{rw}}$ and $\frac{\mu_w}{\mu_o}$ can be determined from Figures 1 through 6. The fractional flow equation can then be used to develop a plot of S_w versus f_w. The resulting s shaped curve intercepts the S_w axis at the irreducible water saturation, S_{wi}, and intercepts the line for f_w=1 at a water saturation of 1-S_{or} where S_{or} is the irreducible oil saturation. This curve is shown in Figure 7. The average water saturation, S_{wf}, at breakthrough can be determined by drawing a straight line from S_{wi} on the S_w axis tangent to the S_w versus f_w curve. This graphical solution is shown in Figure 8. The intercept of the straight line with the line for f_w=1 is S_{wf}.

The S_w versus f_w curve can also be used with the frontal advance equation to determine the distance that the flood front has moved as a function of time. The term $\frac{df_w}{dS_w}$ can be calculated and used in the frontal advance equation along with an assumed injection rate and injection time to determine the position of the front.

Finally, the time to water breakthrough at the producer can be determined using the breakthrough equation presented above.

Other Factors to Consider

The basic analysis using the Buckley-Leverett approach can be fine tuned by the consideration of other elements such as the waterflood pattern to be used and the resulting sweep efficiency, the effect of reservoir permeability heterogeneity, the oil wet or water wet nature of the reservoir rock, and the effect of fractures if present. Different waterflood patterns are shown in Figure 9.

Reservoir Simulation

The use of reservoir simulators can provide detailed results as follow on studies of waterfloods. Simulators require large volumes of information, time to initialize, and experienced users. Simulation software is provided for two types of fluids. The pseudo component versions require basic oil, gas, and water data. The multi-component simulation models require information on the composition of oil and gas. Other dedicated simulators are available for fractured reservoirs, coal bed methane production, and thermal recovery modeling to name a few. Commercial reservoir simulation software includes ECLIPSE from Schlumberger, GEM from Computer Modelling Group, MERLIN from Gemini Solutions, Landmark Graphics VIP, Epic Consulting's ResAssist, and Roxar's TEMPEST. ResAssist was developed specifically to provide optimized waterflood solutions. The U.S. Department of Energy's BOAST simulator is available at no charge and provides an excellent capability for smaller companies. IFLOW is an upgraded version of BOAST that is relatively inexpensive.

Buckley-Leverett type simulations of a one dimensional waterflood and a two dimensional five spot waterflood are presented in Figures 10 and 11.

Surface Facilities

The components of the waterflood surface facilities, illustrated in Figure 12, are the gathering system, the treating plant and tankage , and the injection system. The gathering system includes the flow lines used to transport produced water from the oil-water separator and /or from a water supply source such as a water supply well or a surface reservoir including the ocean. The treating plant prepares the water for injection and may include storage facilities. The injection system includes manifolds, pumps and motors, controls, surge tanks, distribution flow lines, well head connections, and corrosion control systems.

The surface facilities can be in the form of an open or closed system. The open system usually aerates the injection fluid and adds chemicals to release dissolved gases and remove suspended solids. The closed system minimizes the contact of the injection fluid with oxygen and minimizes the need for chemical additives and filtration. The closed system also reduces air pollution.

Waterflood injection pumps include positive displacement pumps and centrifugal pumps for low pressure and high volume applications and Triplex plunger pumps for high pressure applications.

A critical element in the design of a waterflood is the compatibility of the injection water with the formation. Obviously the water must be available in the required volume and inexpensive. Three major areas of injection water quality are suspended solids, mineral compounds in solution, and algae. Suspended solids can cause plugging of the formation at the wellbore face. Suspended solids are removed through flocculation or sedimentation. Mineral compounds that can make water unsuitable for injection include oxides, carbonates, sulfides, and sulfates of barium, strontium, calcium, and iron. Dissolved oxygen, carbon dioxide, and hydrogen sulfide can damage the surface facilities and wellbores as well as the formation. Sulfate reducing bacteria and iron bacteria can also plug surface facilities, wellbores, and the wellbore face. Compatibility of injected waters with the formation minerals and formation waters is also critical. The presence of swelling clays such as montmorillonite can plug the formation if there is an incompatibility with the injected water. Precipitation of minerals in the formation can occur if the injected water is incompatible with the formation water.

Summary

This course has reviewed the history of oil field waterfloods and provided overviews of the elements of a waterflood project. These elements included reservoir rock and fluid properties, basic analytical techniques, and required surface facilities. The basic analytical techniques can be used in scoping studies and, if the scoping work is positive, can be followed up using the reservoir simulation tools discussed.

Appendix

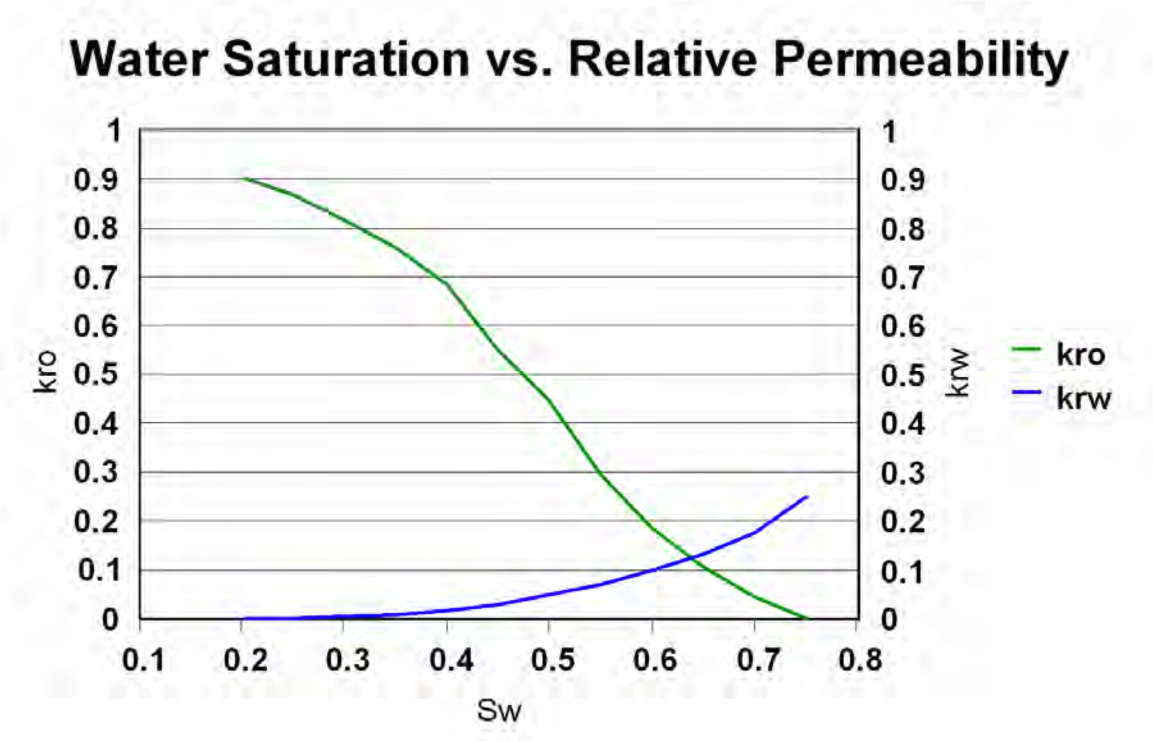

Water Saturation vs. Relative Permeability
kro
krw
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Sw
kro
krw

Figure 1

Water Viscosity

Temperature Effect on Water Viscosity

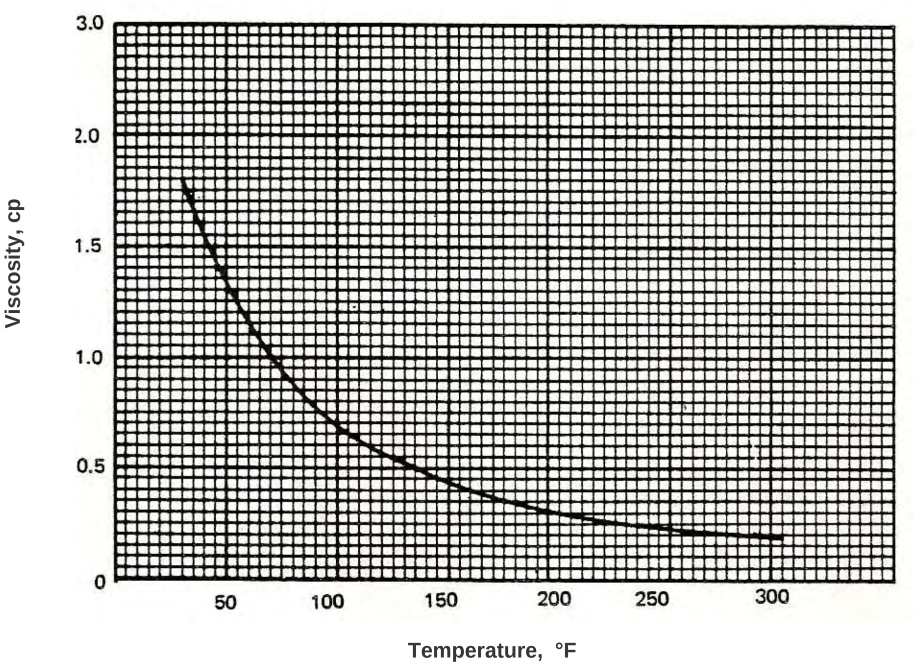


Figure 2

Salinity Effect on Water Viscosity

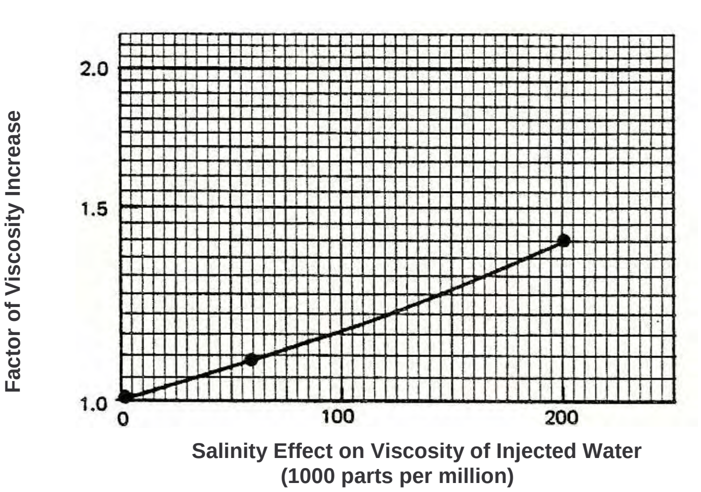
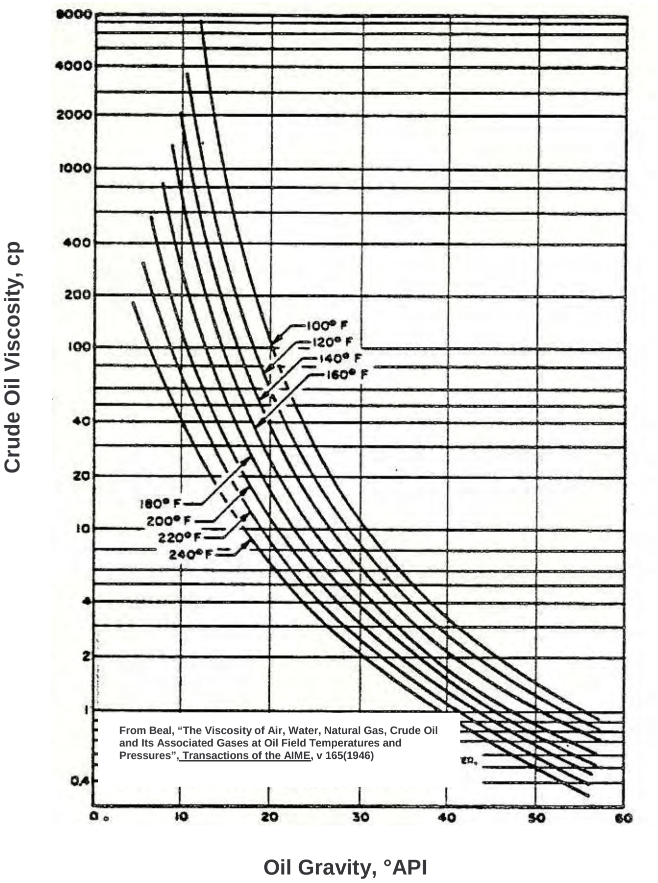


Figure 3

Oil Viscosity

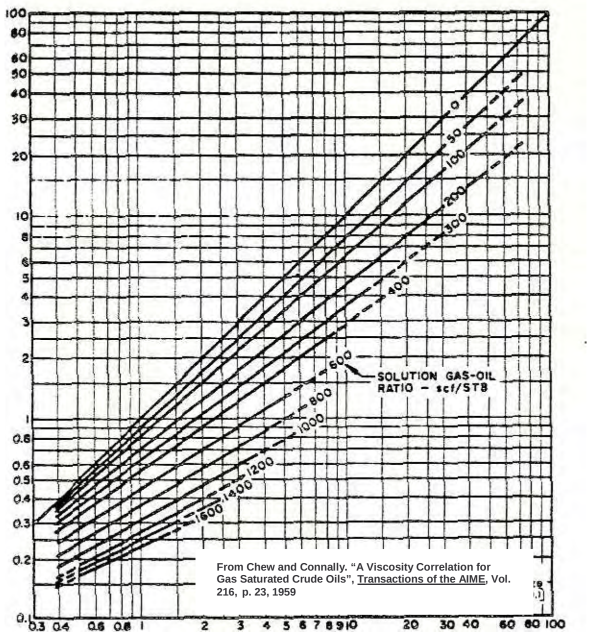
Gas Free Crude Oil Viscosity at Atmospheric Pressure



From Beal, "The Viscosity of Air, Water, Natural Gas, Crude Oil and Its Associated Gases at Oil Field Temperatures and Pressures", Transactions of the AIME, v 165(1946)

Figure 4

Gas Saturated Crude Oil Viscosity at Reservoir Pressure and Temperature

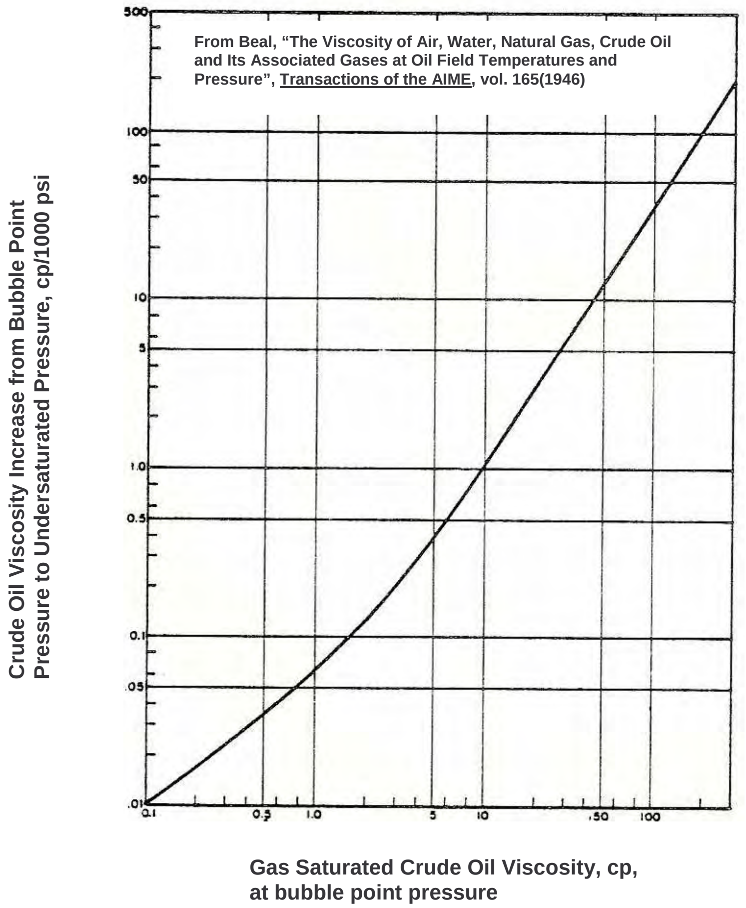


From Chew and Connally. "A Viscosity Correlation for Gas Saturated Crude Oils", Transactions of the AIME, Vol. 216, p. 23, 1959

Gas Saturated Crude Oil Viscosity at Reservoir Saturation Pressure and

Dead Oil Viscosity, cp, at Reservoir Pressure and Temperature

Figure 5



From Beal, "The Viscosity of Air, Water, Natural Gas, Crude Oil and Its Associated Gases at Oil Field Temperatures and Pressure", Transactions of the AIME, vol. 165(1946)

Figure 6

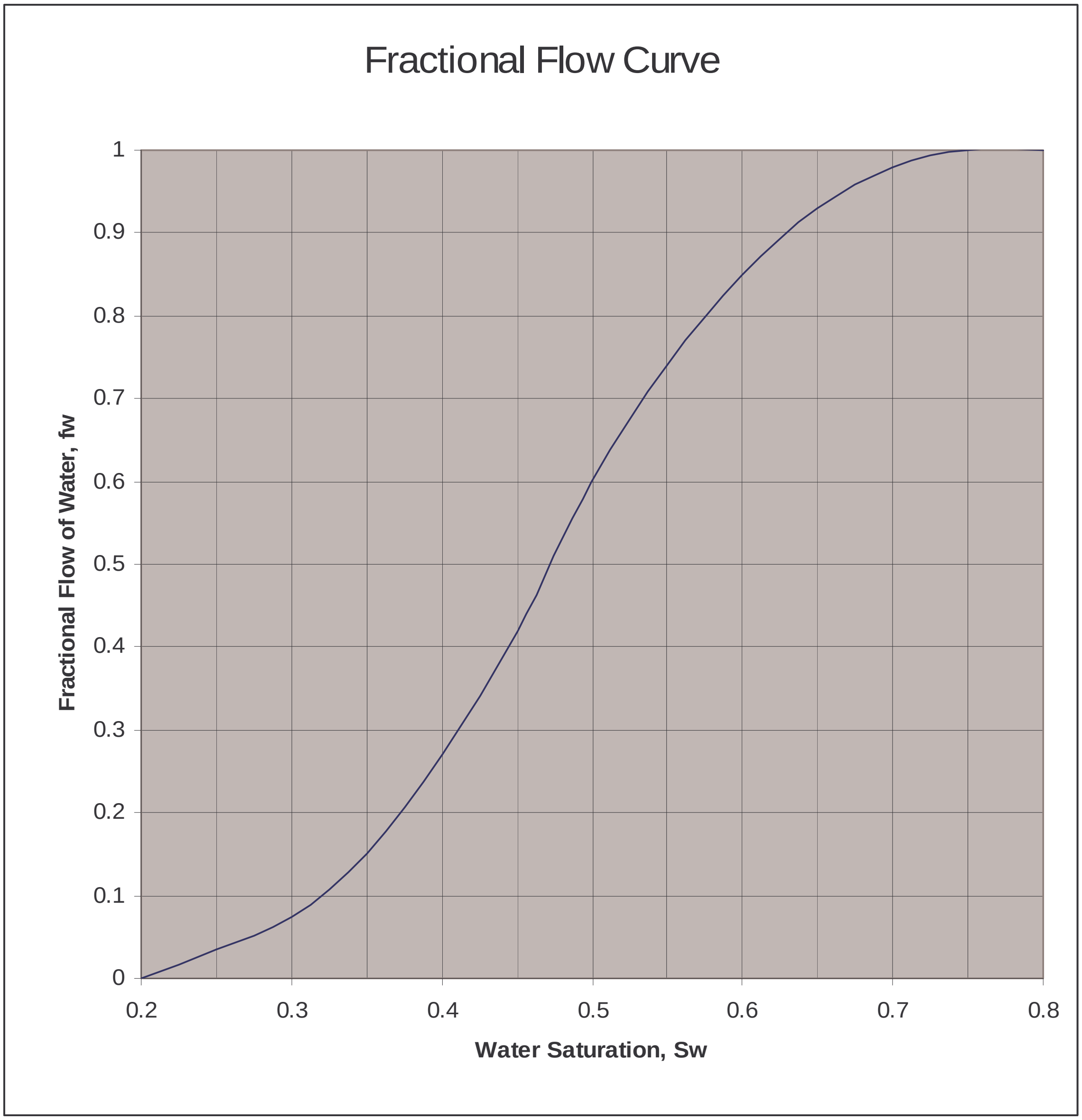

Fractional Flow Curve
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Fractional Flow of Water, fw
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Water Saturation, Sw

Figure 7

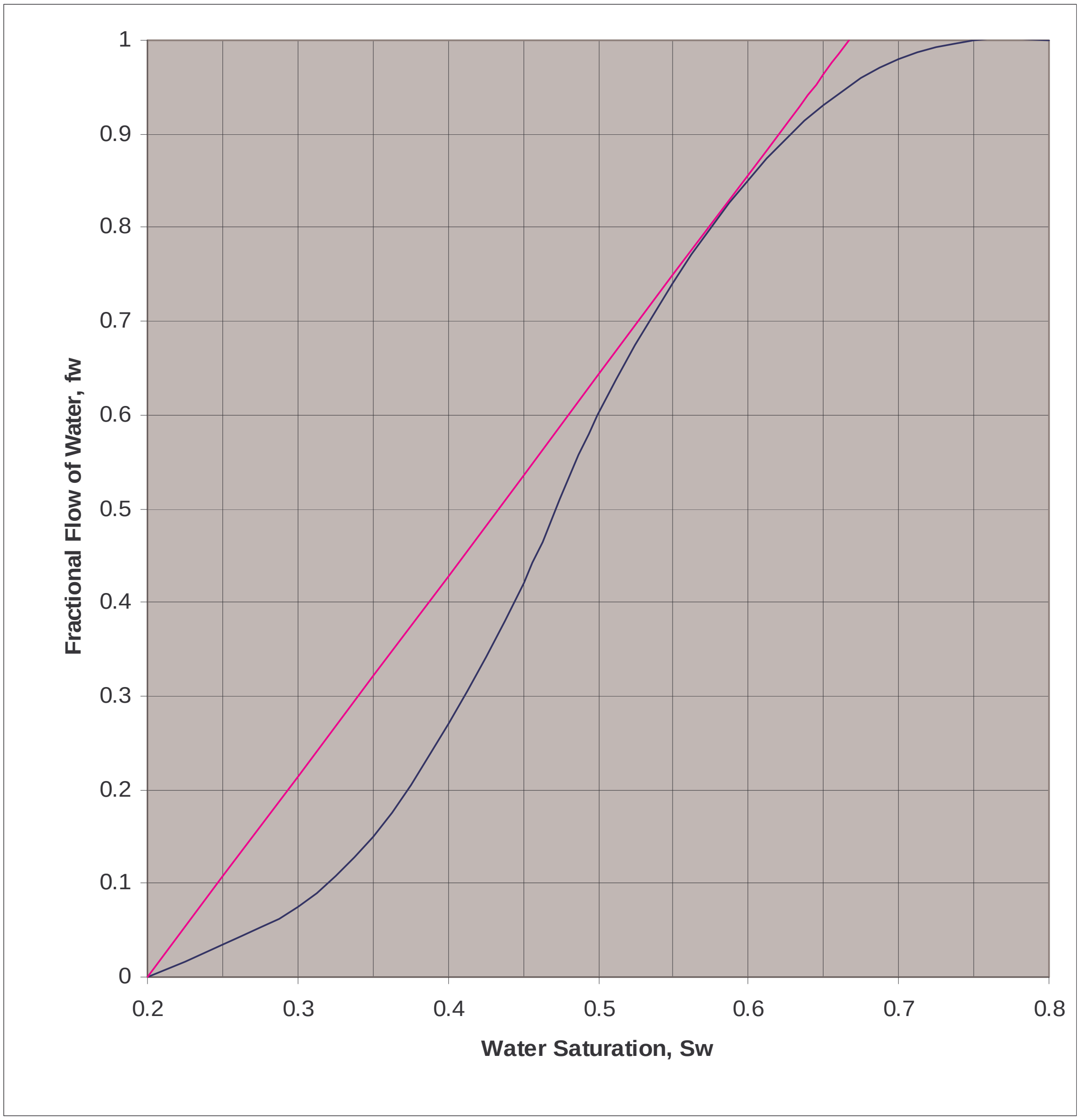
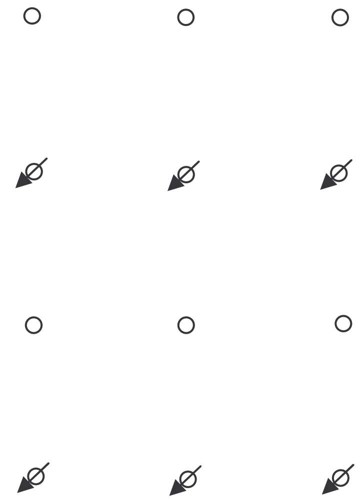
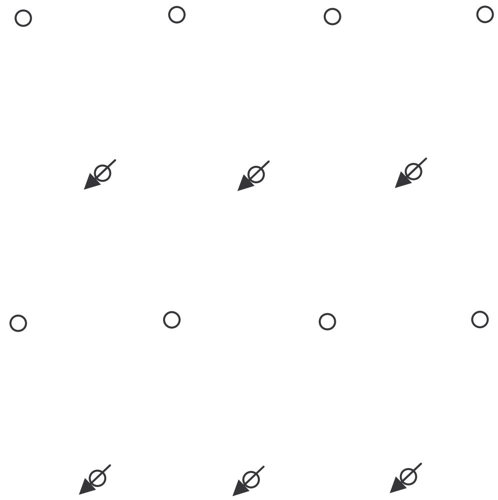

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Fractional Flow of Water, fw
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Water Saturation, Sw

Figure 8

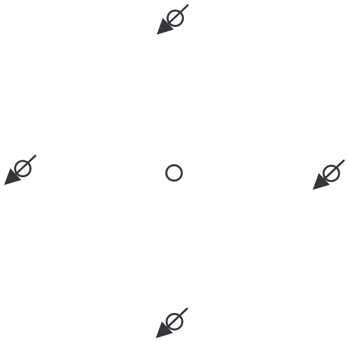
Line Drive



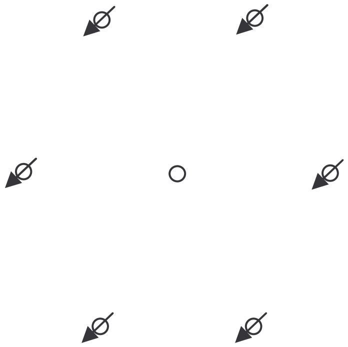
Staggered Line Drive



Five Spot



Seven Spot



Nine Spot

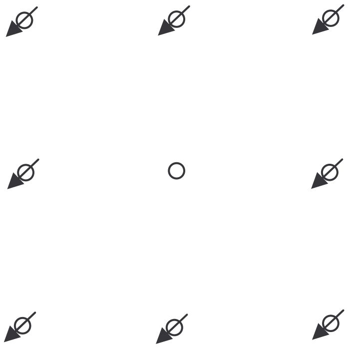


Figure 9

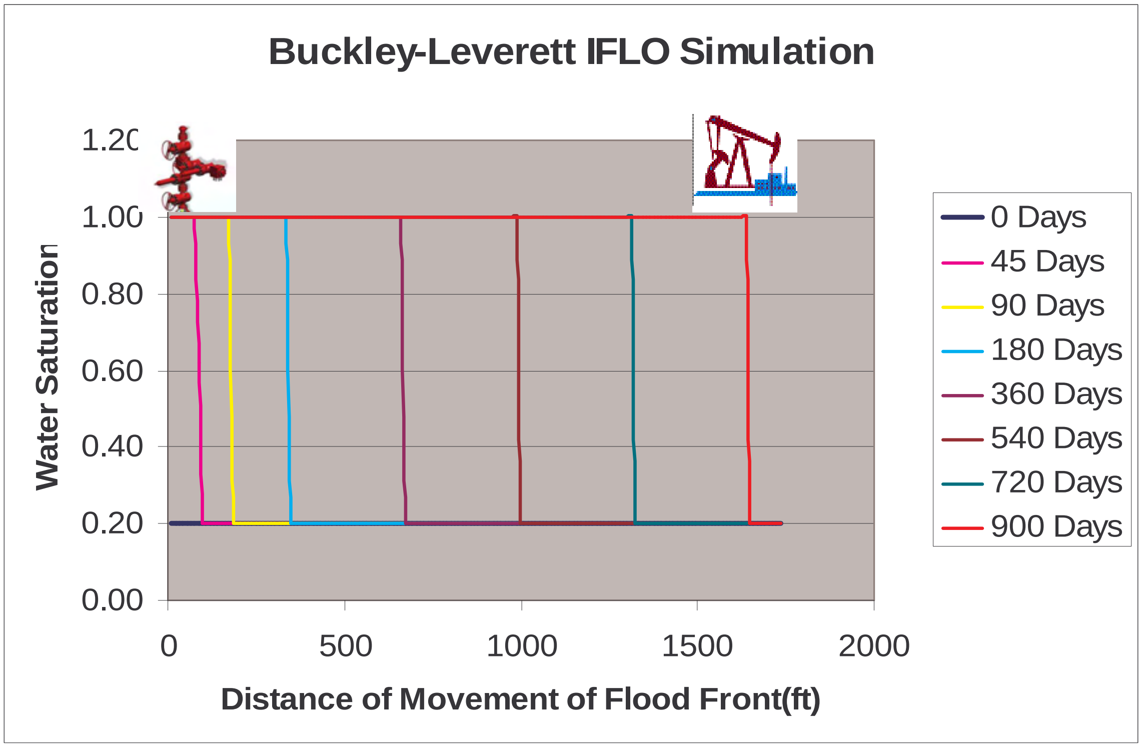

Buckley-Leverett IFLO Simulation
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Water Saturation
0
500
1000
1500
2000
Distance of Movement of Flood Front(ft)
0 Days
45 Days
90 Days
180 Days
360 Days
540 Days
720 Days
900 Days

Figure 10

5 Spot Waterflood Buckley-Leverett Simulation

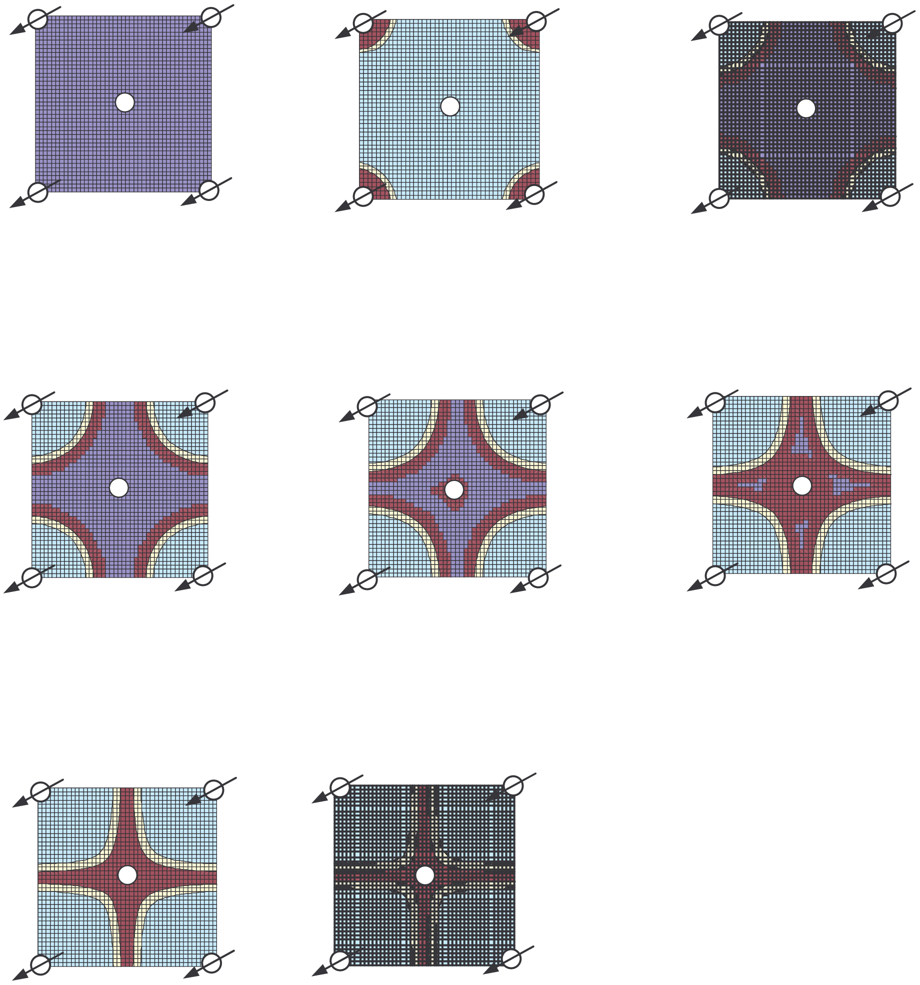


Figure 11

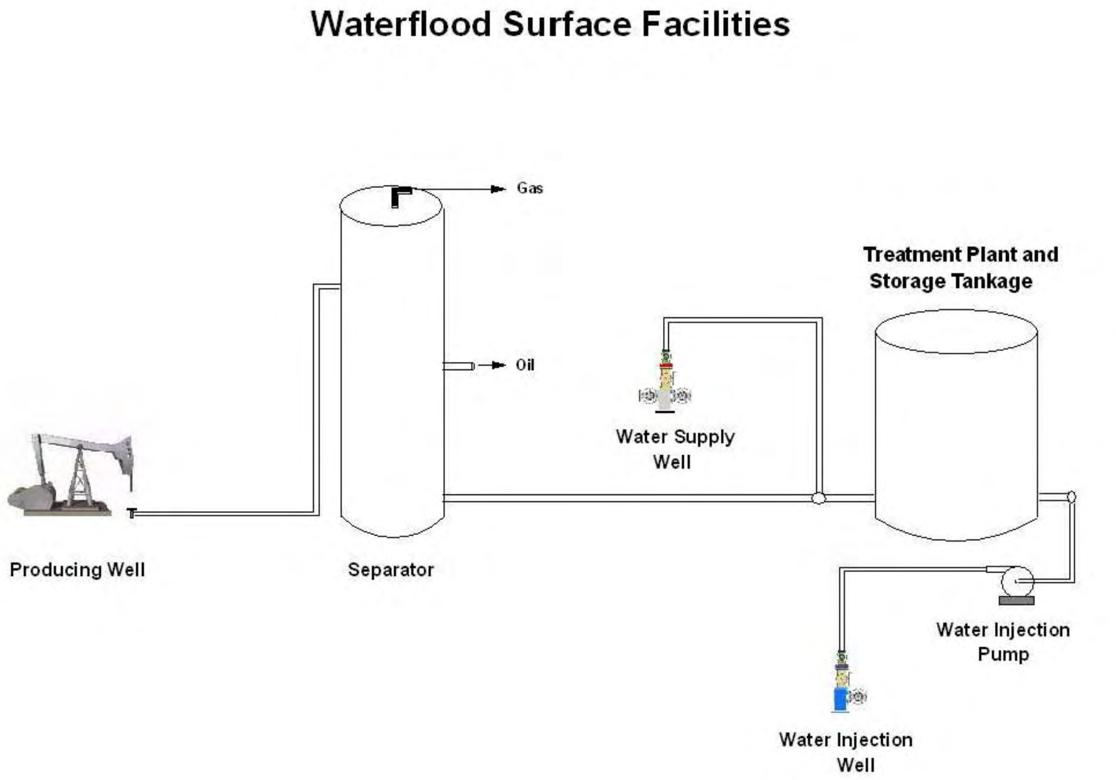

Waterflood Surface Facilities
Gas
Treatment Plant and Storage Tankage
Oil
Water Supply Well
Producing Well
Separator
Water Injection Pump
Water Injection Well

Figure 12