Step 6. Calculate the trapped gas saturation from Figure 14-5 or Equation 14-1, to give:

$$S_{gt} = a_1 + a_2 S_{gi} + a_3 S_{gi}^2 + a_4 S_{gi}^3 + \frac{a_5}{S_{gi}}$$

$$S_{gt} = 12.6\%$$

Step 7. Calculate the gas solubility when all the trapped gas is dissolved in the oil by applying Equation 14-4:

$$R_S^{new} = R_S + \left(\frac{S_{gt}}{S_o}\right)\left(\frac{B_o}{B_g}\right)$$

$$R_S^{new} = 657 + \left(\frac{0.126}{0.619}\right)\left(\frac{1.501}{0.00194}\right) = 814 \text{ scf/STB}$$

Step 8. Enter the tabulated PVT data with the new gas solubility of 814 scf/STB and find the corresponding pressure of approximately 2088 psi. This pressure is identified as the pressure that is required to dissolve the trapped gas.

WATER FLOODING PATTERNS

One of the first steps in designing a waterflooding project is flood pattern selection. The objective is to select the proper pattern that will provide the injection fluid with the maximum possible contact with the crude oil system. This selection can be achieved by (1) converting existing production wells into injectors or (2) drilling infill injection wells. When making the selection, the following factors must be considered:

- Reservoir heterogeneity and directional permeability
- Direction of formation fractures
- Availability of the injection fluid (gas or water)
- Desired and anticipated flood life
- Maximum oil recovery
- Well spacing, productivity, and injectivity

In general, the selection of a suitable flooding pattern for the reservoir depends on the number and location of existing wells. In some cases, producing wells can be converted to injection wells while in other cases it may be necessary or desirable to drill new injection wells. Essentially four types of well arrangements are used in fluid injection projects:

- Irregular injection patterns
- Peripheral injection patterns
- Regular injection patterns
- Crestal and basal injection patterns

Irregular Injection Patterns

Willhite (1986) points out that surface or subsurface topology and/or the use of slant-hole drilling techniques may result in production or injection wells that are not uniformly located. In these situations, the region affected by the injection well could be different for every injection well. Some small reservoirs are developed for primary production with a limited number of wells and when the economics are marginal, perhaps only few production wells are converted into injectors in a nonuniform pattern. Faulting and localized variations in porosity or permeability may also lead to irregular patterns.

Peripheral Injection Patterns

In peripheral flooding, the injection wells are located at the external boundary of the reservoir and the oil is displaced toward the interior of the reservoir, as shown in Figure 14-8. Based on Craig (1971), in an excellent review of the peripheral flood, points out the following main characteristics of the flood:

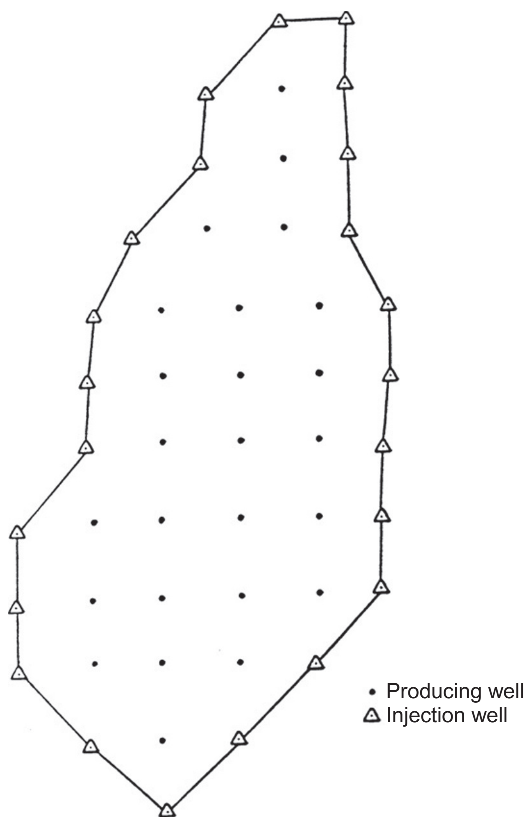

FIGURE 14-8 Typical peripheral waterflood. *(After Cole, F, 1969).*

- The peripheral flood generally yields a maximum oil recovery with a minimum of produced water.
- The production of significant quantities of water can be delayed until only the last row of producers remains.
- Because of the unusually small number of injectors compared with the number of producers, it takes a long time for the injected water to fill up the reservoir gas space. The result is a delay in the field response to the flood.
- For a successful peripheral flood, the formation permeability must be large enough to permit the movement of the injected water at the desired rate over the distance of several well spacings from injection wells to the last line of producers.
- To keep injection wells as close as possible to the waterflood front without bypassing any movable oil, watered-out producers may be
- converted into injectors. However, moving the location of injection wells frequently requires laying longer surface water lines and adding costs.
- Results from peripheral flooding are more difficult to predict. The displacing fluid tends to displace the oil bank past the inside producers, which are thus difficult to produce.
- Injection rates are generally a problem because the injection wells continue to push the water greater distances.

Regular Injection Patterns

Due to the fact that oil leases are divided into square miles and quarter square miles, fields are developed in a very regular pattern. A wide variety of injection-production well arrangements have been used in injection projects. The most common patterns, as shown in Figure 14-9, are the following:

- **Direct line drive**. The lines of injection and production are directly opposed to each other. The pattern is characterized by two parameters: a = distance between wells of the same type, and d = distance between lines of injectors and producers.
- **Staggered line drive**. The wells are in lines as in the direct line, but the injectors and producers are no longer directly opposed but laterally displaced by a distance of a/2.
- **Five spot**. This is a special case of the staggered line drive in which the distance between all like wells is constant, i.e., a = 2d. Any four injection wells thus form a square with a production well at the center.
- **Seven spot**. The injection wells are located at the corner of a hexagon with a production well at its center.
- **Nine spot**. This pattern is similar to that of the five spot but with an extra injection well drilled at the middle of each side of the square. The pattern essentially contains eight injectors surrounding one producer.

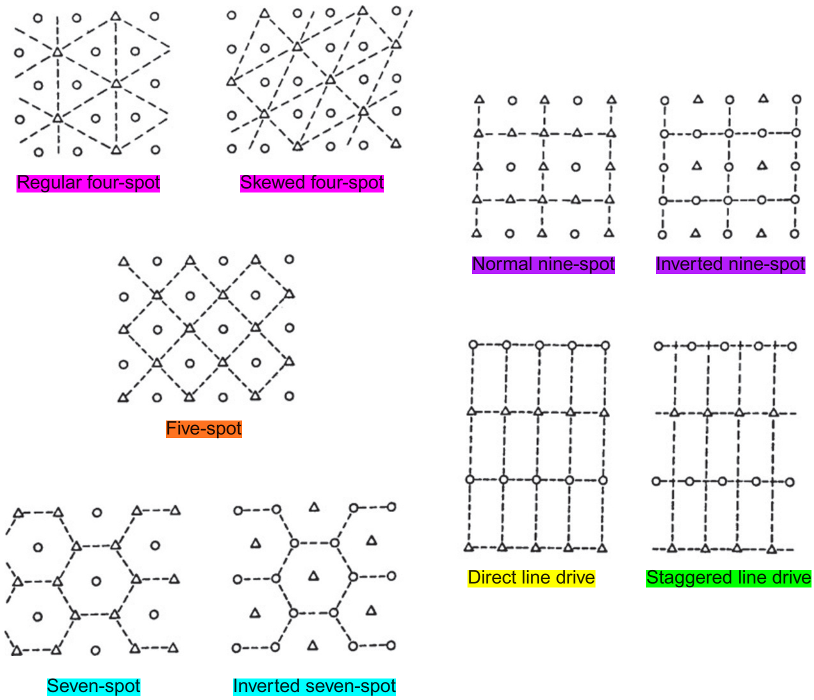

FIGURE 14-9 Flood patterns. *(Permission to publish by the Society of Petroleum Engineers).*

The patterns termed **inverted** have only one injection well per pattern. This is the difference between **normal** and **inverted** well arrangements. Note that the four-spot and inverted seven-spot patterns are identical.

Crestal and Basal Injection Patterns

In crestal injection, as the name implies, the injection is through wells located at the top of the structure. Gas injection projects typically use a crestal injection pattern. In basal injection, the fluid is injected at the bottom of the structure. Many water-injection projects use basal injection patterns with additional benefits being gained from gravity segregation. A schematic illustration of the two patterns is shown in Figure 14-10.

OVERALL RECOVERY EFFICIENCY

The overall recovery factor (efficiency) RF of any secondary or tertiary oil recovery method is the product of a combination of three individual efficiency factors as given by the following generalized expression:

$$RF = E_D\, E_A\, E_V \tag{14-5}$$

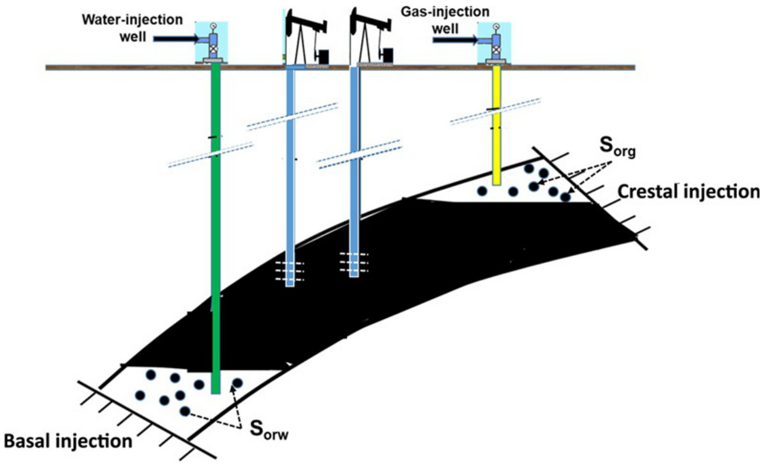

FIGURE 14-10 Well managements for dipping reservoirs.

In terms of cumulative oil production, Equation 14-5 can be written as:

$$N_P = N_S\, E_D\, E_A\, E_V \tag{14-6}$$

Where:

RF = overall recovery factor
N_S = initial oil in place at the start of the flood, STB
N_P = cumulative oil produced, STB
E_D = displacement efficiency
E_A = areal sweep efficiency
E_V = vertical sweep efficiency

The displacement efficiency $\mathbf{E_D}$ is defined as the fraction of movable oil that has been displaced from the swept zone at any given time or pore volume injected. Because an immiscible gas injection or waterflood will always leave behind some residual oil, E_D will always be less than 1.0.

The areal sweep efficiency $\mathbf{E_A}$ is the fractional area of the pattern that is swept by the displacing fluid. The major factors determining areal sweep are:

- Fluid mobilities
- Pattern type
- Areal heterogeneity
- Total volume of fluid injected

The vertical sweep efficiency $\mathbf{E_V}$ is the fraction of the vertical section of the pay zone that is contacted by injected fluids. The vertical sweep efficiency is primarily a function of:

- Vertical heterogeneity
- Degree of gravity segregation
- Fluid mobilities
- Total volume injection