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## Horizontal Injection and Production Wells for EOR or Waterflooding

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### ABSTRACT

This paper describes the potential benefits of using combinations of horizontal injection and production wells for EOR processes or waterflooding.

Our results show that a very favorable configuration occurs when two opposed horizontal wells are drilled from injection and production wells so that the opposed laterals are parallel in the patterns, and extended until the horizontal segments almost meet midway between the like wells. Compared to five-spot patterns with vertical wells, opposed horizontal wells can increase injectivity (injection rate per applied pressure drop) by as much as a factor of ten, depending on well spacing and formation thickness. Areal sweep efficiency can be increased by 25% to 40%. The horizontal-well advantages are greatest for thin formations with wide spacing, and decline significantly for thick formations and/or close spacing. Also, for a given injection pressure, the pressure gradient in the bulk of the reservoir can average several times greater when using opposed horizontal wells than when using vertical wells. This could significantly improve microscopic displacement efficiencies for EOR processes, such as micellar/polymer flooding, that are sensitive to interfacial tensions.

Because of the better sweep efficiencies, faster flooding rates, and/or lower injection pressures that are possible with horizontal wells, all EOR methods should benefit by their use. For example, polymer floods can be improved by the higher injectivity and lower rates of shear at the injection sandface. The advantages of horizontal wells for CO<sub>2</sub> flooding include: (a) delayed CO<sub>2</sub> breakthrough because of the better sweep efficiency, (b) the potential for maintaining the MMP in more of the reservoir with no increase in the injection pressure, (c) better injectivity at the same pressures, and (d) the opportunity to convert more pumped producers to flowing wells. Thermal EOR was not investigated in this work, but the cited references show that horizontal wells have been successful in several field applications and more projects are being planned.

### INTRODUCTION

The use of horizontal wells has been increasing very rapidly throughout the oil industry as advances in drilling techniques continue. In many reservoirs, horizontal wells can help solve a number of oil production problems. However, in spite of a tremendous increase in literature references, little information is available on horizontal-well applications for EOR methods. A survey of the extensive horizontal-well literature is beyond the scope of this paper, but reviews,<sup>1-5</sup> books,<sup>6-10</sup> SPE Reprint Series,<sup>11,12</sup> and published articles (over one thousand, even excluding newspaper articles) show that horizontal wells are still used primarily in problem reservoirs or to solve specific production problems. These include: low-permeability formations, especially fractured formations such as the Austin Chalk,<sup>13-20</sup> low-permeability gas reservoirs,<sup>21</sup> unusual gas sources such as coal-bed methane<sup>22,23</sup> or Devonian shale,<sup>24-26</sup> gas or water coning,<sup>27,28</sup> thin formations,<sup>29-31</sup> and viscous oil.<sup>32,33</sup>

Most of the EOR activity has been in the area of thermal recovery, primarily for steam stimulation and steam drives,<sup>34-39</sup> where both horizontal injection wells and production wells have been tried. A potential for gas EOR projects with horizontal wells is indicated by recent simulation and model studies for inert gas<sup>40</sup> and CO<sub>2</sub> injection.<sup>41</sup> The interest in horizontal-well waterflooding is very recent with most reports or publications appearing in 1991 and 1992.<sup>42-46</sup>

Although there is relatively little published information on the use of horizontal injection wells, other than for thermal recovery, the need for patterns of both horizontal injection and production wells, or opposed vertical fractures, to increase the rate of flooding in EOR processes has been mentioned.<sup>47-50</sup> This paper describes the improvements in sweep efficiency and flooding rates that are possible if horizontal wells are used for waterflooding or for any EOR method which requires the use of both injection and production wells. In addition, the potential for increased microscopic displacement efficiency at the faster rates (with no increase in well-head pressure) is examined for some of the EOR methods.

### INCREASED INJECTION AND PRODUCTION RATES FOR HORIZONTAL-WELL PATTERNS

A relationship between the rate of flooding and the amount of oil displaced by surfactant solutions was observed many years ago.<sup>51</sup> In general, faster displacement rates increased the oil recovery for almost all laboratory experiments with surface active agents. Although later work showed that there is a specific minimum rate for the displacement of oil with surfactants, flooding at rates above this critical value always produced more oil.<sup>48,52</sup> Therefore, different possibilities for increasing the rate of flooding (or the average pressure gradient) for surfactant floods in the field were examined. A major obstacle to efficient oil recovery was the inefficient radial flow between injection wells and production wells. As early as 1933, studies showed that the available pressure gradient for about 75% of a waterflood pattern was only 1/4 of the average pressure gradient.<sup>53</sup> To avoid high pressure losses from radial flow near wells, other geometric arrangements were considered. The two best possibilities appeared to be opposed lateral drainholes (now usually termed "horizontal wells") and opposed vertical fractures. Because lateral drainholes had not been drilled more than 100 feet in the fifties (although Eastman claimed that they could be extended to greater distances),<sup>54</sup> and the costs were much greater than vertical wells, the parallel and opposed vertical fractures (to create a linear flood) were given more attention.<sup>47</sup>

#### Maximum Flooding Rates for Linear Floods

Before discussing the benefits of horizontal injection wells, it is instructive to examine the difference between the flooding rates in a normal five-spot pattern and the theoretical rate that could be achieved by a full linear flood (possibly with vertical fractures) with the same spacing.

The steady-state rate of water injection in a five-spot pattern is given by:<sup>55</sup>

$$q_5 = \frac{1.54 kh \Delta p}{\mu \left( \log_{10} \frac{W}{r_w} - 0.420 \right)} \quad (1)$$

where:

- $q_5$  = rate of water injection, bbls/day
- $k$  = permeability, darcies
- $h$  = sand thickness, ft
- $\Delta p$  = pressure difference between injection and producing wells, psi
- $\mu$  = viscosity, cp
- $W$  = distance between like wells, ft
- $r_w$  = radius of injection well, ft

The linear rate in the same units is given by

$$q_L = \frac{1.13 kA \Delta p}{\mu L} \quad (2)$$

In this equation,  $A$  is the rectangular cross-section area of the sandface between two like wells. In Fig. 1, if the entire

face could be opened to the water (for example if precise vertical fractures replaced the lateral holes),  $A$  will be equal to  $hW$ . On the other hand, if the formation thickness is close to the diameter of the lateral holes shown in Fig. 1, Eq. 2 should be a good approximation for the almost-linear flow between the horizontal injection and producing wells in the pattern.

In Fig. 1,  $L$  is  $1/2 W$ , and again,  $A$  is equal to  $hW$  if the entire sandface is open to flow. Since the total rate in the five-spot includes flow in both directions from the horizontal wells (or vertical fractures), the total linear rate in terms of  $h$  and  $W$  is

$$q_{L(5)} = 2 \left( \frac{1.13 khW \Delta p}{\mu 1/2 W} \right) \quad (3)$$

Therefore, the linear rate for the five-spot becomes

$$q_{L(5)} = \frac{4.52 kh \Delta p}{\mu} \quad (4)$$

Note that the rate depends only on the thickness of the sand for a given  $k$ ,  $\mu$ , and  $\Delta p$ . Thus, the linear rate will be completely independent of the well spacing in five-spot patterns.

Eqs. 1 and 4 can be combined to express the linear rate in terms of the five-spot rate. The result is

$$q_{L(5)} = 2.93 q_5 \left( \log \frac{W}{r_w} - 0.420 \right) \quad (5)$$

Eq. 5 was used to prepare Table 1, which shows the amount that the linear rate exceeds the five-spot rate at various spacings. Theoretically, the rates are equal when the injection wells are 1.9 ft apart. However, the five-spot rate drops off so rapidly with increasing distance between wells, that the linear rate is 8.4 times as fast as the five-spot rate at a spacing of 10 acres and can be more than 10 times as fast at wider spacings.

#### Horizontal-Well Flooding Rates Approach Linear Rates in Thin Formations

The horizontal-well rate differs only slightly from the linear rate in very thin formations. To determine the amount that the rate differs from the full linear rate, an approximate solution can be obtained by solving the flow problem in a manner similar to determining the rate of flow for different permeabilities in series.

In Fig. 2, flow is radial between the well and the radius,  $r_{e1}$ . From  $r_{e1}$  to  $r_{e2}$ , the flow will be linear, and from  $r_{e2}$  to  $r_{e3}$ , the flow again is radial. The same permeability exists in all regions, so  $q$  can be expressed in terms of the pressure drop across each section. In addition, the total pressure drop ( $p_1 - p_4$ ) will equal the sum of the pressure differentials in the other three sections or

$$(p_1 - p_4) = (p_1 - p_2) + (p_2 - p_3) + (p_3 - p_4) \quad (6)$$

The flow in the entire matrix can be expressed as

$$q_{HW} = \frac{k^* A (p_1 - p_4)}{\mu L} \quad (7)$$

where  $k^*$  is the average or effective permeability if the flow is assumed to be linear with the end sections showing a reduced permeability caused by the radial flow patterns.  $q_{HW}$  is the rate for the combination of radial and linear flow between the two lateral holes.

In Fig. 2,  $A$  is actually  $W(2r_e)$  (neglecting well radius), so Eq. 7 is rewritten as

$$q_{HW} = \frac{2k^* W r_e (p_1 - p_4)}{\mu L} \quad (8)$$

The flow for each of the other sections is written in similar units and each equation is solved for the pressure differential. The results along with Eq. 8 are substituted into Eq. 6 and solved for  $k^*$ . The result is

$$k^* = \frac{\pi k L}{4 r_e \ln \frac{r_e}{r_w} + \pi L} \quad (9)$$

Substitution of this value of  $k^*$  into Eq. 8 and multiplying by 2 to give the total flow in both directions yields

$$q_{HW} = \frac{4 \pi k W r_e \Delta p}{\mu (4 r_e \ln \frac{r_e}{r_w} + \pi L)} \quad (10)$$

Eq. 10 is an approximation of the flow capacity of a five-spot pattern wherein the distance between like wells is spanned by lateral holes. After obtaining the above equation, J.E. Warren noted that the problem is comparable to Muskat's line-drive flood<sup>56</sup> if the distance between injection wells is replaced by the formation thickness in Fig. 2. Muskat's line-drive solution using our symbols is

$$q \text{ (or now } q_{HW}) = \frac{2 \pi \frac{k}{\mu} W \Delta p}{\frac{\pi L}{2 r_e} - 2 \ln 2 \sinh \frac{\pi r_w}{2 r_e}} \quad (11)$$

Rearranging Eq. 10 to the same form gives

$$q_{HW} = \frac{2 \pi \frac{k}{\mu} W \Delta p}{\frac{\pi L}{2 r_e} + 2 \ln \frac{r_e}{r_w}} \quad (12)$$

Eqs. 11 and 12 are similar, as long as  $L$  is much greater than the formation thickness. To determine how closely the

flow between the lateral holes approaches a linear flood,  $q_{HW}$  can be expressed in terms of  $q_{L(s)}$  (after substituting  $2L$  and  $\frac{1}{2}h$  for  $W$  and  $r_e$  in Eq. 12). The result, after changing to  $\log_{10}$ , is

$$q_{HW} = q_{L(s)} \left[ \frac{\pi L}{\pi L + 4.6 h \log \left( \frac{1/2 h}{r_w} \right)} \right] \quad (13)$$

The approximate relationship in Eq. 13 shows that  $q_{HW}$  and  $q_{L(s)}$  are almost equal for very wide spacing and/or thin formations. Thus, if five-spot patterns can be drilled with the opposed and parallel horizontal wells as shown in Fig. 1, the linear rates in Table 1 may be taken as the theoretical maximum rates for very thin formations. For thick pay zones and/or close spacing, the horizontal-well rate departs appreciably from the linear-flow maximum as more of the injected fluid follows the radial-flow regime.

Fig. 3 was prepared to provide a direct comparison between the flow rates of horizontal wells and vertical wells in five-spot patterns. Horizontal-well rates were calculated with Eq. 11 (from Muskat) and compared to the five-spot rates (Eq. 1) for different spacings and as a function of formation thickness. The flow-rate advantage of horizontal wells for thin formations and wide spacing is clear in Fig. 3. For example, for ten-ft formations, the horizontal-well flow rates are eight to ten times the rates for the usual five-spot, vertical-well patterns. The advantage of horizontal wells is relatively insensitive to increasing formation thickness until the pay zones exceed 100 feet. Even with 1000-foot formations, horizontal-well flow rates are double those of the usual five-spot waterflooding patterns unless the spacing is closer than 20 acres. The horizontal net rate could be even faster than that indicated by Fig. 3 if the water enters the formation from the vertical portion of the well along with the water entering the lateral hole. For the simple geometry in Figs. 1 and 2, it is assumed the vertical portion of the well is cased and water enters the lateral hole only. The potential for improved oil recovery and better operating conditions with these faster rates (at no increases in injection pressure) will be examined in later sections.

#### SWEEP EFFICIENCY WITH OPPOSED HORIZONTAL INJECTION AND PRODUCTION WELLS

In this section, we compare sweep efficiencies expected in opposed horizontal wells with those in vertical wells. Craig<sup>57</sup> has extensively reviewed areal sweep efficiencies for various patterns of unfractured vertical wells. In a developed, homogeneous five-spot pattern with a unit-mobility displacement, the areal sweep efficiency at breakthrough is about 70%, according to most authors. For example, Muskat predicted a sweep efficiency of 71.5% for vertical wells in a homogeneous five-spot pattern.<sup>56</sup>

Muskat also developed an equation to predict sweep efficiency for a unit-mobility displacement in a direct-line drive. In Eq. 14, we have adapted Muskat's direct-line-drive equation to estimate sweep efficiency ( $E_p$ ) for opposed

horizontal wells as a function of formation thickness ( $h$ ) and pattern size ( $L$ ).

$$E_h = 1 - \frac{0.441 h}{2L} \quad (14)$$

Eq. 14 was used to generate Fig. 4, which compares anticipated sweep efficiencies (at breakthrough for unit-mobility displacements in homogeneous formations) for opposed horizontal wells with those for vertical wells in a five-spot pattern. In this idealized comparison, sweep efficiencies for the vertical wells are independent of well spacing and formation thickness. In contrast, for the horizontal wells, sweep efficiency decreases with increased formation thickness and with decreased well spacing. Using opposed horizontal wells, sweep efficiencies can exceed 90% for formation thicknesses up to 100 ft. However, as formation thickness increases above 300 ft., sweep efficiencies quickly fall below those for the vertical wells, especially for tighter well spacings.

Much has been published on the effects of vertical fractures on areal sweep efficiency.<sup>58-71</sup> In concept, parallel vertical fractures in both injection and production wells could provide areal sweep efficiencies approaching 100% if the fractures have the proper orientation, length, and height, so that flow is linear between opposed vertical fractures. Unfortunately, fracture orientation, length, and height are often difficult to control during fracturing.<sup>72</sup> With recent advances in the precise placement of horizontal wells,<sup>73,74</sup> the use of opposed horizontal wells may now offer advantages over vertical fractures, with respect to improved areal sweep efficiency.

Previous analyses of the impact of fractures on sweep efficiency can be of value in assessing the merits of horizontal versus vertical wells. When comparing fractured versus unfractured vertical wells, some important published conclusions are:<sup>58,61</sup>

1. Fracture orientation can strongly affect sweep efficiency.
2. The impact of fractures on sweep efficiency increases as the mobility ratio increases. In particular, for a given adverse mobility ratio, the presence of an opposed vertical-fracture well pattern would improve the areal sweep efficiency compared to that for unfractured vertical wells.
3. The greatest impact on areal sweep efficiency occurs when both producers and injectors are fractured, while the smallest effect occurs when only the producers are fractured.
4. The ratio of fracture length to interwell distance,  $x_f/L$ , must be greater than 0.1 (and sometimes greater than 0.4) in order to significantly affect sweep efficiency.

By analogy, we anticipate that similar conclusions can be demonstrated for horizontal wells.

In stratified reservoirs, the performance of a horizontal well will be affected by its vertical placement, especially in

thick reservoirs with barriers to vertical flow. This will be an important area for future research.

## USE OF HORIZONTAL WELLS TO IMPROVE DISPLACEMENT EFFICIENCY OF EOR PROCESSES

All EOR or waterflooding projects should benefit from the faster injection-production rates and better sweep efficiencies that are possible with horizontal well patterns such as shown in Fig. 1. However, for those processes which exhibit higher recoveries because of improved microscopic displacement efficiencies at higher rates, the horizontal injection wells should provide a significant additional benefit.

In Fig. 5, the EOR methods are arranged in order of the API gravities of the oils to be displaced.<sup>50</sup> The figure can be used as a very general screening guide to match the oil gravity (or corresponding oil viscosity) to the most effective EOR method. The range of API gravities for most of the EOR field projects listed in recent surveys<sup>75</sup> are given by the limits of the solid lines which enclose the name of each method. A rough indication of the importance of the method (in terms of incremental oil production) is shown by the relative size of the letters.

Fig. 5 indicates that additional benefits should be observed for each of the three general types of EOR methods: miscible, water-based chemical, and thermal. The reasons for the improvements that accompany the faster rates and/or lower pressures that are possible with horizontal wells are examined in the next section for some of the EOR processes.

### Polymer Flooding

The use of horizontal injection wells can improve injectivity and reduce polymer degradation during polymer floods and other chemical floods. Because of the viscous nature of polymer solutions, injectivity in unfractured wells can be substantially less during a polymer flood than during a waterflood.<sup>76</sup> The higher injectivities allowed by horizontal injection wells can help to alleviate this problem.

For a given injection pressure, the fluid velocity at the wellbore sandface can be significantly less in a horizontal well than in a vertical well. Fig. 6 demonstrates that this difference is most pronounced in thin formations and with large well spacings. The reduced sandface velocity allowed by horizontal injectors could significantly reduce mechanical degradation of polymer solutions.

The higher injection rates associated with horizontal wells could also help to mitigate the effects of chemical and thermal degradation of polymers and other chemicals during floods in high-temperature reservoirs. Since higher injection rates lead to lower residence times for injected fluids, the requirements for long-term stability for the chemicals can be relaxed.

### Micellar/Polymer (Surfactant or Low IFT) Flooding

In this section, we discuss the potential for increased microscopic displacement efficiency when the faster rates of

horizontal wells are used for those processes that produce oil by virtue of low oil-water interfacial tensions (IFT).

The aforementioned relationship between the flooding rate and oil recovery by surfactant solutions is often correlated by a dimensionless group termed the capillary number, designated  $N_{CA}$ ,  $N_{VC}$ , or  $N_C$ . The number is useful for expressing the magnitude of the ratio between viscous and capillary forces during the displacement of one phase by another in porous media, such as water, polymer, or surfactant floods. Fig. 7 shows examples of experimental and calculated (by Stegemeier) capillary desaturation curves.<sup>48,52,77,78</sup> The oil saturations are normalized so that the displacements that started at high oil saturations (continuous oil) can be compared to the displacements of residual oil. Many capillary desaturation curves for water or surfactant solutions have appeared in the literature (for examples, see Refs. 48, 52, 77-83). All of the curves for the displacement of residual oil, by increasing the capillary number, have characteristics similar to the experimental results shown in Fig. 7. For sandstones similar to Berea, residual oil displacement starts at a "critical"  $N_{CA}$  value of  $10^{-5}$ - $10^{-4}$ , and about 50% of the oil is usually recovered by an order of magnitude increase in the capillary number. At least 95% of the oil is normally recovered if the  $N_{CA}$  value reaches  $10^{-3}$  to  $10^{-2}$ . The high  $N_{CA}$  values required for this improved oil recovery are achieved in the field by adding surfactants to reduce the oil-brine interfacial tension, since field flooding rates (and pressure gradients) are normally significantly below that required to be in the critical desaturation region in Fig. 7. Maintaining low IFTs throughout the reservoir is difficult because of adsorption and/or dilution of components in the surfactant slug. This fact partly explains why oil recovery has been very disappointing for many micellar/polymer field projects. However, if horizontal wells could be used to increase the flooding rate, and thus the capillary number, some increase in oil recovery would be expected. For example, a tenfold increase in flooding rate should double the oil recovery for a dynamic system that has an  $N_{CA}$  value of  $3 \times 10^5$  before the increase in rate (see Fig. 7).

Laboratory data for the displacement of residual oil from 15 sandstones with permeabilities ranging from 40 to 2,190 md are presented in Table 2.<sup>81</sup> Although the dimensionless "critical" capillary numbers (the minimum  $N_{CA}$  value at which residual oil is displaced) are similar for the different rocks, the "critical" pressure gradient per unit of interfacial tension ( $\Delta P/L\sigma$ ) was much higher for the low-permeability rocks. Since horizontal wells can raise the average pressure gradients in the reservoir, horizontal wells could extend surfactant flooding to tighter sandstones.

#### CO<sub>2</sub> and Hydrocarbon-Miscible Methods

The greater areal sweep and faster flooding rates that are possible with horizontal wells can provide a number of economic and operational improvements for two so-called "miscible" EOR methods: i.e., CO<sub>2</sub> flooding and hydrocarbon-miscible methods. The hydrocarbon processes include high-pressure (vaporizing) gas drives and enriched (condensing) gas drives. The horizontal-well benefits apply primarily to those processes which generate miscibility in the

reservoir by one of the multiple-contact processes. CO<sub>2</sub> flooding is the fastest growing EOR method today<sup>50,75,84</sup> and much of the following discussion of the horizontal-well improvements applies primarily to CO<sub>2</sub>-miscible flooding. The horizontal-well advantages and operational improvements include:

- Better areal sweep and delayed breakthrough of CO<sub>2</sub>.
- Increased injection rates (with no increase in pressure).
- Minimum miscibility pressure (MMP) maintained in wider area of reservoir.
- More production wells converted to flowing wells.
- Better oil recovery in near-miscible areas (just below MMP) because of higher  $N_{CA}$  values from faster injection rates.

Important aspects of these five projected improvements with horizontal wells for CO<sub>2</sub>-miscible projects will be discussed briefly.

Better sweep and delayed breakthrough of injected gas. Although much of the flush oil production in CO<sub>2</sub> flooding comes after CO<sub>2</sub> breakthrough, the early gas breakthrough at production wells adds to the project costs and causes various operational problems. Increased areal sweep efficiency, illustrated in Fig. 4, should delay the CO<sub>2</sub> breakthrough for new CO<sub>2</sub> projects that use horizontal injection wells. If the operator must decide between horizontal injectors or producers, horizontal injection wells should provide the most improvement of areal sweep. This suggestion follows from the work of Bargas and Yanosik,<sup>58</sup> who investigated the use of vertical fractures to improve sweep efficiency during displacements with unfavorable mobility ratios.

Increased injection rates with no increase in pressure. Fig. 3 shows that injection rates for CO<sub>2</sub> floods can be increased several fold with no increase in wellhead pressure when horizontal wells are used instead of vertical-well, five-spot patterns. Injectivity is often a serious problem in tertiary CO<sub>2</sub> floods. Although operators have experienced injectivities that are both higher and lower than predicted from water and CO<sub>2</sub> viscosities (or mobilities),<sup>85-89</sup> a loss of injectivity for both CO<sub>2</sub> and water, especially after switching WAG cycles, is common. The potential for faster injection rates, with no increase in pressure, could mitigate various injectivity problems, especially for those CO<sub>2</sub> floods which are operated with a pressure constraint, i.e., at pressures near the formation parting pressure.

MMP maintained in wider area of reservoir. Operators should be able to maintain more uniform pressure distributions in CO<sub>2</sub> floods that utilize horizontal wells. Because less pressure is lost near the wellbore, higher pressures (at or above MMP) can be achieved in a much broader area of the reservoir, perhaps with even a lower injection pressure. Most CO<sub>2</sub>-miscible floods are operated at injection pressures well above the MMP to try to include as much of the reservoir as possible in the multi-contact-miscible flow regime. Horizontal injection and production wells should reduce significantly the amount of over-pressure required. Again, if it is necessary to decide between injectors or producers, the switch to horizontal

injection wells should be more useful for maintaining MMP uniformly at lower injection pressures.

More production wells converted to flowing wells. The possibility for much faster flooding rates, with no increase in wellhead pressure, should provide operators with more opportunities to convert pumped producers to flowing wells for savings in operational costs.

Better oil recovery in near-miscible pressure areas (just below MMP) because of higher  $N_{CA}$  values from faster injection rates. Shyeh-Yung has shown that the near-miscible pressure regions may be very important in  $CO_2$  displacements of oil.<sup>90</sup> In laboratory studies from outcrop samples, she showed that the  $CO_2$  mobility is less at pressures just below the MMP, and that oil recovery is quite good, i.e., only a little less than the high recoveries above the MMP. She attributes some of these high oil recoveries to the very low IFT values and attendant high  $N_{CA}$  values at pressures near the MMP. Therefore, one would expect even higher recoveries at the higher rates possible with horizontal wells, if the IFTs and  $CO_2$  displacement rates are already in the sensitive part of a capillary desaturation curve (as shown in Fig. 7). Shyeh-Yung has compared  $CO_2$  displacement with surfactant-flood displacement (see Fig. 4 of Ref. 90) and finds that more oil is displaced by  $CO_2$  than by surfactants at the equivalent capillary numbers shown. However, it appears that she did not vary  $N_{CA}$  values by flooding at different rates, but obtained her values by calculating the  $N_{CA}$  value for the IFTs expected at different flooding pressures near the MMP. To make a direct comparison, experiments at different rates at each pressure would be helpful.

Although  $CO_2$  displacements have been performed at various rates above the MMP, we are not aware of  $CO_2$  experiments where the displacement rates have been varied at pressures below, and at, the MMP. However, oil-recovery-versus-rate experiments have been conducted with all-liquid miscible displacements (alcohol displacing oil with connate water present), and oil recovery improved markedly at higher rates.<sup>91</sup> The higher oil recoveries were attributed to reduced trapping and/or increased immiscible displacement of the oil phase as miscibility was approached with the oil-water IFT at very low values, and therefore at even higher  $N_{CA}$  values, as the displacement rates were increased.

We postulate that similar increased oil recovery would be experienced with faster rates for  $CO_2$ -miscible displacements near the MMP. Stern<sup>92</sup> did observe a small decrease in  $S_{orm}$  (an increase in oil recovery) when going from a rate of 0.3 ft/day to 1.0 ft/day, but this was followed by an increase in  $S_{orm}$  when the rate was raised to 5 ft/day. Watkins<sup>93</sup> showed an even greater adverse effect of higher rates on oil recovery. However, both Stern and Watkins performed their  $CO_2$  floods at pressures much higher than the MMP, where the contribution from high-capillary-number, immiscible-displacement mechanisms would be relatively less, and the contribution from extraction would be greater.<sup>90</sup> Thus, the competing effects—improved recovery from high  $N_{CA}$ , and decreased recovery from poorer extraction at high rates—can explain the optimum recovery observed by Stern at 1 ft/day (based on only three different rates) even though his

experiments were well above MMP, because the rate was still slow enough for effective extraction.

Therefore, until more  $CO_2$  displacements are conducted at many different rates (especially at pressures near the MMP), a definitive conclusion cannot be reached on the effect of rate on the microscopic displacement efficiency of  $CO_2$  floods. In any event, if the optimum conditions of pressure and flooding rate are ever determined more precisely for  $CO_2$  floods, horizontal wells would be very useful to establish those optimum conditions in the field.

### Thermal Recovery

In a recent article in the SPE Technology Today series, Joshi pointed out that most of the applications of horizontal wells for EOR to date have been for steam projects.<sup>34</sup> Recent reviews and other publications explain that horizontal wells should provide the same types of benefits for thermal recovery as for waterflooding and other EOR methods, i.e., better sweep efficiency and faster injection/production rates.<sup>33-39</sup> In addition, horizontal-well systems can be devised to permit the injection of the required heat into more parts of the reservoir, and in a shorter time than with the usual vertical wells. However, reservoirs with viscous oils present different challenges and opportunities for horizontal well systems. For example, thermal projects have used more horizontal producing wells than injectors, whereas we anticipate that horizontal injectors should be more beneficial than producers for most other EOR processes. One problem with long horizontal steam injectors is the condensation of steam in the cold part of the well so that steam enters the formation from only a fraction of the injector's full length. Preheating the long wellbore should reduce or eliminate this problem.<sup>34</sup>

Because of the need for early heat to reduce the oil viscosity before it can flow at a useful rate, many different patterns and arrangements of horizontal wells have been tried or suggested, especially configurations designed to place the horizontal injectors and producers close together. For additional information, the reader is referred to some of the literature on the subject.<sup>32-39,94-96</sup>

## HORIZONTAL WELLS FOR WATERFLOODING

Although most of this paper deals with the potential of horizontal wells for EOR methods, the benefits of using horizontal wells for waterflooding should not be overlooked. Many improvements in waterflooding operations should come from the faster injection rates and better sweep efficiencies that are possible with horizontal wells as illustrated in Figs. 3 and 4.

### Potential Benefits of Faster Flooding Rates and/or Lower Injection Pressures

The faster rates, shown in Fig. 3 for horizontal-well patterns, should provide significant operating and economic advantages for waterfloods, especially if the horizontal wells can be drilled in thinner formations at wide spacing for reasonable costs. (A recent survey showed that horizontal wells cost only 17% more per foot even though the average total measured "depth" of the horizontal well was almost twice that for vertical wells.<sup>97</sup>) We emphasize that the increased flooding rates shown in Fig. 3 are achieved with no increase

in pressure, i.e. the rates are compared to standard five-spot rates at the same pressure and spacing.

Since the flow rate is directly proportional to pressure differences between the bottom-hole pressures of the injection and production wells, Fig. 3 could also be used to estimate the lower pressures that would result for a horizontal-well waterflood compared to an equivalent five-spot flood at the same rate. In general, the pressure required for horizontal-well flooding at the same rate as an equivalent vertical five-spot pattern should be the reciprocal of the rate ratio shown on the ordinate of Fig. 3. For example, in a 10-ft formation at 80-acre spacing, the pressure required to maintain the same injection rate with horizontal wells would be about one-tenth the pressure required for normal five-spot floods. Maintaining equivalent rates at lower pressures would have many advantages for waterflood operators. For floods where injection rates are limited by the parting pressure of the formation, much higher rates could be achieved at acceptable pressures. In practice, some combination of lower pressures and faster rates would probably be selected as the optimum condition to maximize oil recovery and profits.

#### Fewer Wells Needed for the Efficient, Wide-Spacing Patterns with Horizontal Wells

Figures 3, 4, and 6 show that the advantages of combinations of horizontal injection and production wells for waterflooding are greatest for patterns with wide spacing. Therefore, equivalent (or better) water injection and oil production rates can be achieved with far fewer horizontal wells than with vertical wells. Although individual horizontal wells cost more, the total drilling costs could be much less than for vertical-well patterns because fewer wells are drilled at the wider spacing. From Table 1 and Figures 3 and 4, it appears that only one horizontal well would be needed in place of about 10 vertical wells to achieve the same overall flooding rate in thin formations at wide spacing. However, a ratio of one horizontal well for each three to eight vertical wells is probably a better estimate to achieve the equivalent production rates and better sweep efficiencies in thicker formations. One operator, who has already drilled at least one horizontal injector and producer in Southeast Texas, estimates that "two horizontal wells could take the place of six vertical wells, allowing higher injection/production rates and boosting oil recovery."<sup>46</sup>

#### Sweep Efficiency and Horizontal Wells Versus Infill Drilling

The sweep-efficiency advantage of horizontal-well, flooding patterns would be observed best for new waterfloods or an expanded development of existing floods. The higher sweep efficiencies shown in Fig. 4 (especially for thin formations) should delay water breakthrough for new floods and provide much higher net oil recovery in a shorter time.

For existing waterfloods, infill drilling is showing promise as a good method for recovering the oil that is bypassed by the poor areal sweep of normal, vertical-well waterflooding patterns.<sup>98-104</sup> Horizontal-well systems should compare favorably with new infill wells, even in mature floods, especially if the costs of horizontal wells continue to fall while the techniques become more versatile. Methods are now available for drilling a horizontal well from an existing well so that a pattern geometry similar to Fig. 1 could be achieved even in older waterfloods. An alternative would be to drill two

horizontal wells from a new infill well to approach the pattern type shown by Fig. 1. In this case, the lateral segments would not need to extend as far towards the existing injection wells to recover most of the pattern-bypassed oil. Careful economic studies are needed to determine if any of these retrofit possibilities could recover oil profitably from existing floods. At present, it appears that some type of horizontal-well application should compare very favorably with the infill drilling of vertical wells, either in new or mature waterfloods.

#### CONCLUSIONS

1. The faster flooding rates and improved sweep efficiencies that are possible with combinations of horizontal injection and production wells should be very beneficial for waterflooding and the following EOR processes: thermal recovery, CO<sub>2</sub> flooding, hydrocarbon-miscible flooding, micellar/polymer (low IFT) flooding, and polymer flooding. An especially favorable configuration of parallel and opposed horizontal injection and production wells is shown in Fig. 1.
2. Injection/production rates can be increased by as much as ten times (with no increase in pressure) by using combinations of horizontal injection and production wells in thin formations and at wide spacing. The advantage of faster rates with horizontal wells (compared to vertical-well patterns) decreases for thicker formations and/or closer well spacing.
3. Compared to vertical wells, fewer horizontal injection/production wells are needed to maintain the fast flooding rates possible in patterns with wide spacing.
4. Significant increases in areal sweep efficiency are possible with horizontal injection and production wells. The sweep advantage is greatest (up to 99% areal sweep) for thin formations and wide spacing. For very thick formations and closer spacing, it appears that there will be no advantage over vertical-well patterns.
5. The faster rates possible with horizontal wells should increase the microscopic displacement efficiencies for EOR methods such as micellar/polymer (surfactant) flooding, that show increased recoveries at higher capillary numbers.
6. Polymer floods should be improved by the higher injectivity and lower rates of shear at the injection sandface (see Fig. 6) that are possible with horizontal wells.
7. Advantages of horizontal wells for CO<sub>2</sub> flooding include: (a) delayed CO<sub>2</sub> breakthrough because of the better sweep efficiency, (b) the potential for maintaining the MMP in more of the reservoir with no increase in the injection pressure, (c) better injectivity at the same pressures, and (d) the opportunity to convert more pumped producers to flowing wells.
8. Further research, development, and economic studies are needed to determine the most beneficial ways for the application of horizontal-well technology to all injection methods and EOR processes.

## NOMENCLATURE

- $A$  = cross-sectional area of the sandface, ft  
 $E_h$  = areal sweep efficiency  
 $k$  = permeability, darcies  
 $k^*$  = average permeability, darcies  
 $h$  = formation thickness, ft  
 $L$  = distance between opposed horizontal wells in five-spot pattern (Fig. 1), ft  
 $N_{CA}$  = dimensionless capillary number (also  $N_C$  or  $N_{VC}$ ), defined as  $\frac{hk_r \Delta p}{\mu L \sigma}$  or  $\frac{v \mu}{\sigma}$  (several other forms listed in Ref. 49)  
 $p$  = pressure, psi  
 $q$  = flow rate, bbls/day  
 $q_{HW}$  = flow rate between opposed parallel horizontal wells, bbls/day  
 $q_L$  = linear flow rate between parallel faces of a reservoir block, bbls/day  
 $q_{L(S)}$  = linear flow rate in five-spot pattern, bbls/day  
 $q_s$  = water injection rate for five-spot pattern, bbls/day  
 $r_e$  = radius to external boundary, ft  
 $r_w$  = wellface radius, ft  
 $S_{orm}$  = miscible flood residual oil saturation  
 $W$  = distance between like wells, ft  
 $x_f$  = fracture length, ft  
 $\mu$  = viscosity, cp  
 $\sigma$  = interfacial tension (IFT) between oil and water or between oil and CO<sub>2</sub>-rich phase, dyne/cm

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Table 1. The Ratio of the Linear Rate to the Vertical-Well Five-Spot Rate at Various Spacings

Spacing (Acres)	W (Feet)	$q_L/q_5$
	1.9	1.0
0.625	165.0	6.7
1.000	209.0	7.0
2.500	330.0	7.5
5.000	467.0	8.0
10.000	660.0	8.4
20.000	935.0	8.9
40.000	1320.0	9.3
80.000	1859.0	9.7
160.000	2640.0	10.2
320.000	3734.0	10.6

$$q_{L(s)} = 2.93 q_5 \left( \log \frac{W}{r_w} - 0.420 \right)$$

W = distance between like wells

$q_5$  = five-spot rate for vertical wells

$r_w$  = well radius = 0.33 ft.

Table 2. The Displacement of Residual Oil from Sandstone and Alundum Cores

Core Number	Core Type*	Porosity (%)	Permeability To Air (millidarcies)	Initial Residual Oil Saturation (%)	Percent of Residual Oil Recovered at Maximum $\Delta P/L_0$	Maximum $\Delta P/L_0$ (psi/ft) (dyne/cm)	Critical Value of $\Delta P/L_0$ (psi/ft) (dyne/cm)	Critical Value of $N_{CA}$
2-269	-----	11.1	40.8	41.7	17.8	52.3	13.60	$1.23 \times 10^{-5}$
2-205	-----	13.1	52.1	42.4	9.3	52.8	20.10	$2.33 \times 10^{-5}$
D-8-9	-----	17.3	95.5	55.6	4.8	82.6	23.80	$5.05 \times 10^{-5}$
J-13	Jelm	17.2	189.0	37.1	7.9	61.3	16.30	$6.85 \times 10^{-5}$
S-12	-----	17.6	242.0	40.4	15.7	61.9	11.40	$6.13 \times 10^{-5}$
ON-2	-----	18.3	320.0	33.0	28.2	86.7	4.03	$2.87 \times 10^{-5}$
T-4	Tensleep	18.6	381.0	36.6	22.4	56.2	5.12	$4.34 \times 10^{-5}$
Ber-1	Berea	19.1	346.0	40.5	25.1	46.2	6.13	$4.72 \times 10^{-5}$
D-1-8	-----	19.7	503.0	49.5	17.1	26.3	1.71	$1.91 \times 10^{-5}$
SP-6	St. Peters	22.1	533.0	45.3	24.8	15.2	1.90	$2.25 \times 10^{-5}$
JK-1	Alundum	28.2	585.0	34.1	11.7	20.4	3.81	$4.96 \times 10^{-5}$
SP-5	St. Peters	23.1	613.0	48.6	27.2	30.9	1.12	$1.53 \times 10^{-5}$
DOT	-----	29.9	635.0	32.1	29.8	21.5	2.01	$2.84 \times 10^{-5}$
21X	Berea	21.6	752.0	45.3	26.4	30.9	1.66	$2.78 \times 10^{-5}$
80	-----	14.4	1450.0	49.7	34.1	24.2	0.73	$2.35 \times 10^{-5}$
MG-6	-----	16.6	2190.0	49.3	48.2	12.2	0.31	$1.51 \times 10^{-5}$

\*All cores except Alundum ( $Al_2O_3$ ) were sandstone. Many were from oil-producing reservoirs and the oil companies asked that the names not be released. Data from Ref. 81.

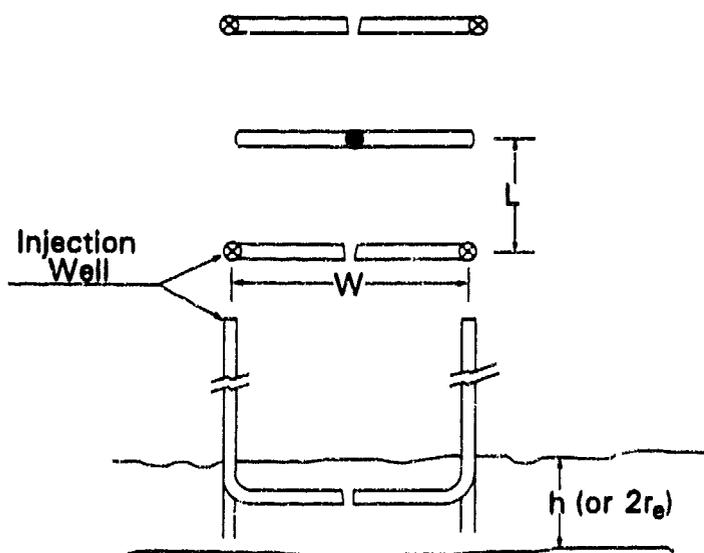


Fig. 1. Five-spot pattern with horizontal injection and production wells.

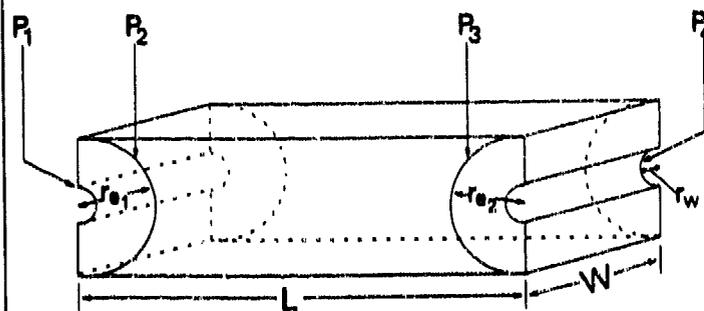


Fig. 2. Segment of parallel and opposed horizontal injection and production wells.

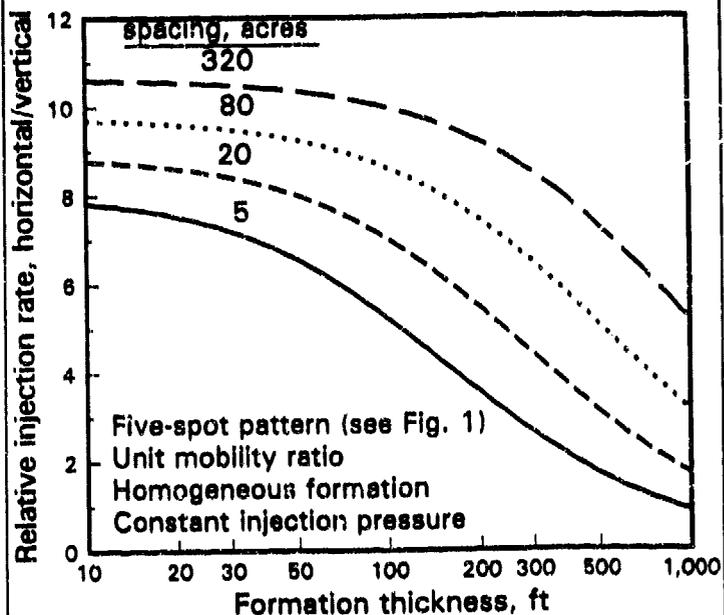


Fig. 3. Comparison of injection rates for horizontal wells relative to vertical wells

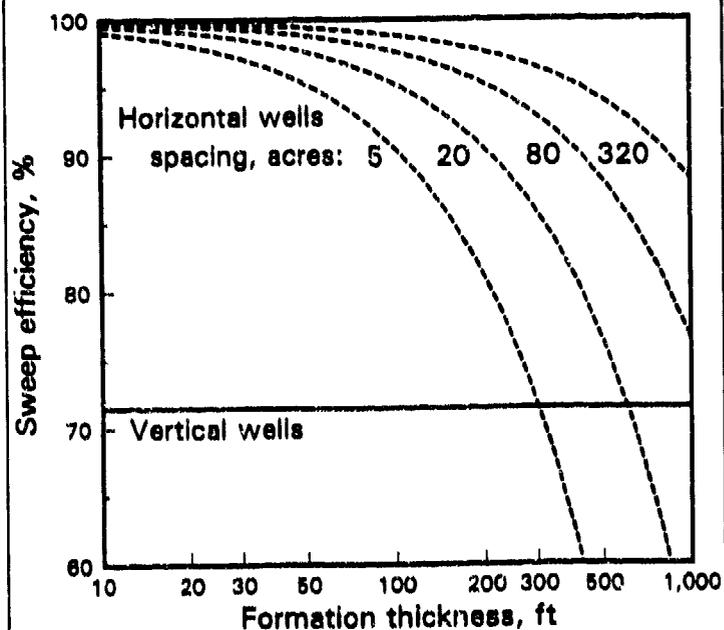


Fig. 4. Comparison of sweep efficiencies for vertical wells versus horizontal wells (parallel and opposed) in a five-spot pattern, unit mobility ratio)

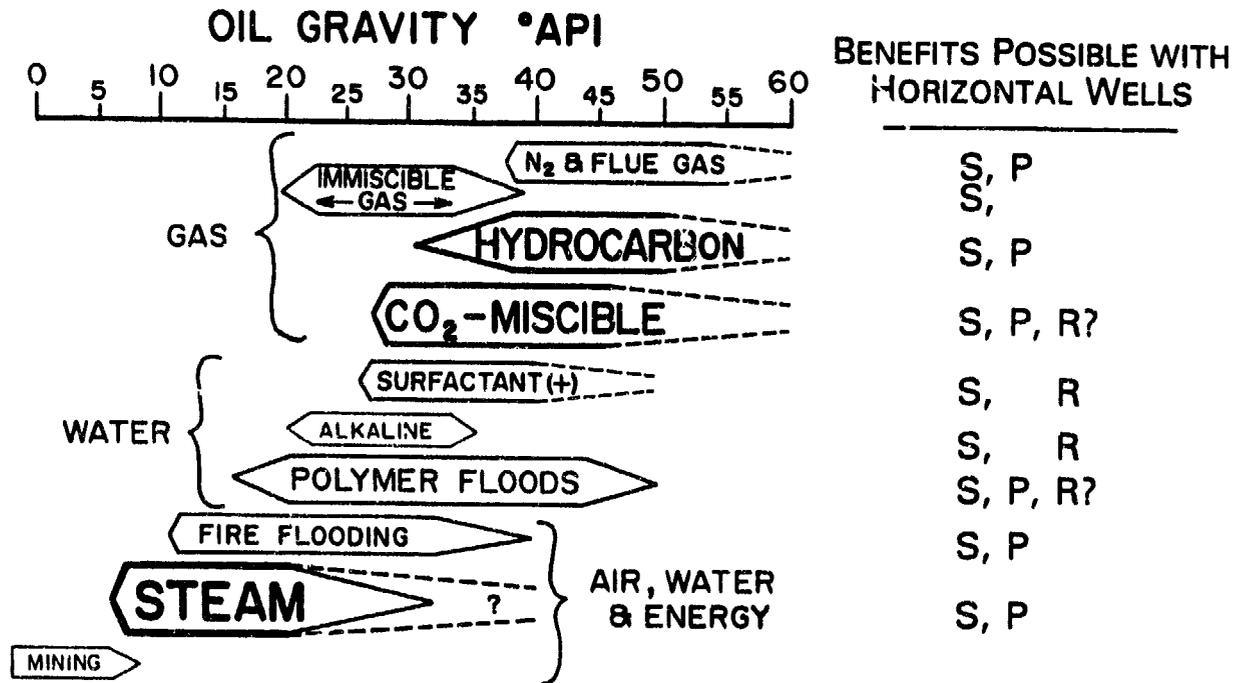


Fig. 5. Possible benefits from horizontal wells for EOR methods:

- Better areal sweep (S),
- Improved recovery from faster flooding rates (R),
- Lower injection pressures (P).

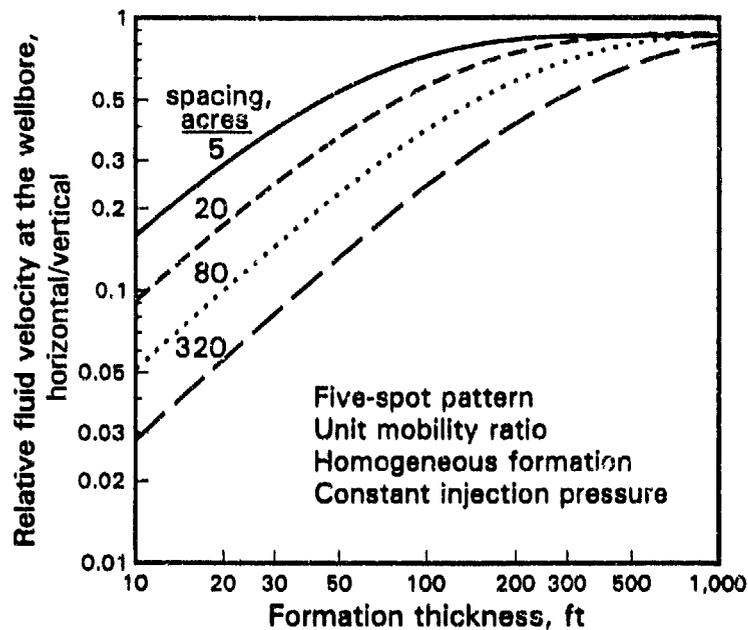


Fig. 6. Comparison of fluid velocities at the wellbore for horizontal versus vertical wells

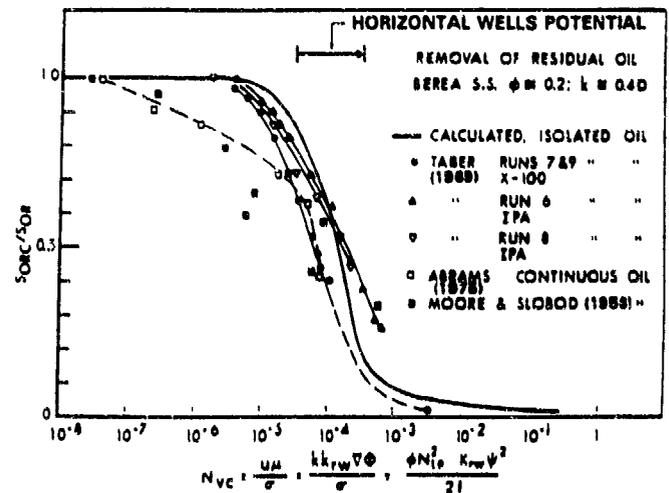


Fig. 7. Potential for improved oil recovery from faster flooding rates with horizontal injection and production wells. Original figure with calculated capillary number values (and definitions of symbols) from Stegemeier;<sup>78</sup> data from Refs. 48, 52, and 77.