Formation Damage Effects on Horizontal-Well Flow Efficiency

Gérard Renard, SPE, Inst. Français du Pétrole, and
J.M. Dupuy,* SPE, Horwell

SPE 19414

Summary. Wellbore damage commonly is accounted for by an apparent skin factor. A better relative index for determining the efficiency with which a well has been drilled and completed is the "flow efficiency," the ratio of a well's actual PI to ideal PI. The flow efficiency of horizontal wells is derived assuming steady-state flow of an incompressible fluid in a homogeneous, anisotropic medium. A comparison between the flow efficiencies of vertical and horizontal wells indicates that permeability reduction around the wellbore is less detrimental to horizontal wells. This paper shows that the effect of damage around a horizontal wellbore is reduced slightly by increasing the well length. Conversely, if the vertical permeability is less than the horizontal permeability, the anisotropy ratio, $\sqrt{k_H/k_V}$, magnifies the influence of formation damage near the horizontal wellbore. Examples of flow efficiency calculations assuming a formation damage or a formation collapse around a liner in poorly consolidated formations are provided for horizontal and vertical wells.

Introduction

Many technical aspects of horizontal wells have been compared with more-conventional wells (vertical or deviated) to determine their effectiveness as a new alterative to reach and produce oil and gas reservoirs. The most obvious comparison, well-documented in the literature,[1,2] is the productivity performance of horizontal wells vs. unstimulated or fully stimulated (acidized/fractured) vertical wells. Two of the newest application areas to compare horizontal and vertical wells and to adapt methods applied to conventional wells to horizontal wells are hydraulic fracturing and matrix acidizing.

Recent papers have expressed different viewpoints on the role of formation damage in the performance of horizontal wells. Some[3,4] suggest that, as horizontal-well length, L, increases, the influence of formation damage on total pressure drop can become negligible, resulting in an additional advantage over vertical wells. Others[5] indicate that the damaged zone may affect productivity more in horizontal wells than in vertical wells, and that skin damage sometimes can prevent horizontal-well projects from succeeding. These two opposing interpretations of the influence of formation damage on horizontal-well productivity come from a lack of well-defined criteria (reservoir and well characteristics) to quantify the effect of formation damage on the flow efficiency of horizontal wells.

The objective of this paper is to provide a basis for comparing the flow efficiencies of vertical and horizontal wells. Analytical expressions are derived assuming steady-state flow of an incompressible fluid in a homogeneous anisotropic medium. Both the top and bottom horizontal boundaries of the reservoir have no-flow conditions. The comparison considers an altered zone of the same radius and reduced permeability around the vertical and horizontal wellbores.

Flow Efficiency of Vertical Wells

van Everdingen[6] and Hurst[7] quantified the pressure drop caused by a permeability reduction near and at the wellbore in terms of the skin factor, s_V:

$$\Delta p_s = s_V(q\mu B/2\pi k_H h). \quad (1)$$

Hawkins[8] showed that this skin factor could be related to the altered zone of permeability k_s, which extends to the distance r_s into the formation, by

$$s_V = [(k/k_s)-1]\ln(r_s/r_w) \quad (2)$$

and that the flow efficiency, E_V, the ratio of actual well PI to ideal PI (the PI if the permeability were unaltered all the way to the well's sandface), could be expressed in terms of Δp_s and the total drawdown, Δp_{wf}, as

$$E_V = J_{\text{actual}}/J_{\text{ideal}} = (\Delta p_{wf} - \Delta p_s)/\Delta p_{wf} \quad (3)$$

or

$$E_V = \ln(r_{eV}/r_w)/\ln(r_{eV}/r_w)+s_V$$

$$= \ln(r_{eV}/r_w)/\ln(r_{eV}/r_{we}). \quad (4)$$

Flow Efficiency of Horizontal Wells

Merkulov[9] originally reported the expression for the ideal PI of a horizontal well in an isotropic reservoir. Giger[1] and Joshi[2] presented the pressure profile created by 3D steady-state flow to a horizontal well located inside an ellipsoidal drainage area (**Fig. 1a**). Their solution, which is suitable for horizontal wells that have small lengths compared with the drainage radius, was extended by Giger[1] to the case of a rectangular drainage area fed laterally (**Fig. 1b**) to account for wells that have large lengths compared with the distance to the feeding boundary. As indicated in Appendix A, the ideal PI of a horizontal well for both geometries in a reservoir of permeability anisotropy ratio β can be written as

$$(J_H)_{\text{ideal}} = 2\pi k_H h/\mu B \times \{1/[\cosh^{-1}(X)+\beta(h/L)\ln(h/2\pi r_w')]\}, \quad (5)$$

with $r_w' = [(1+\beta)/2\beta]r_w$ and X depending on the shape and dimensions of the area drained by the well.

*Now with Inst. Français du Pétrole.

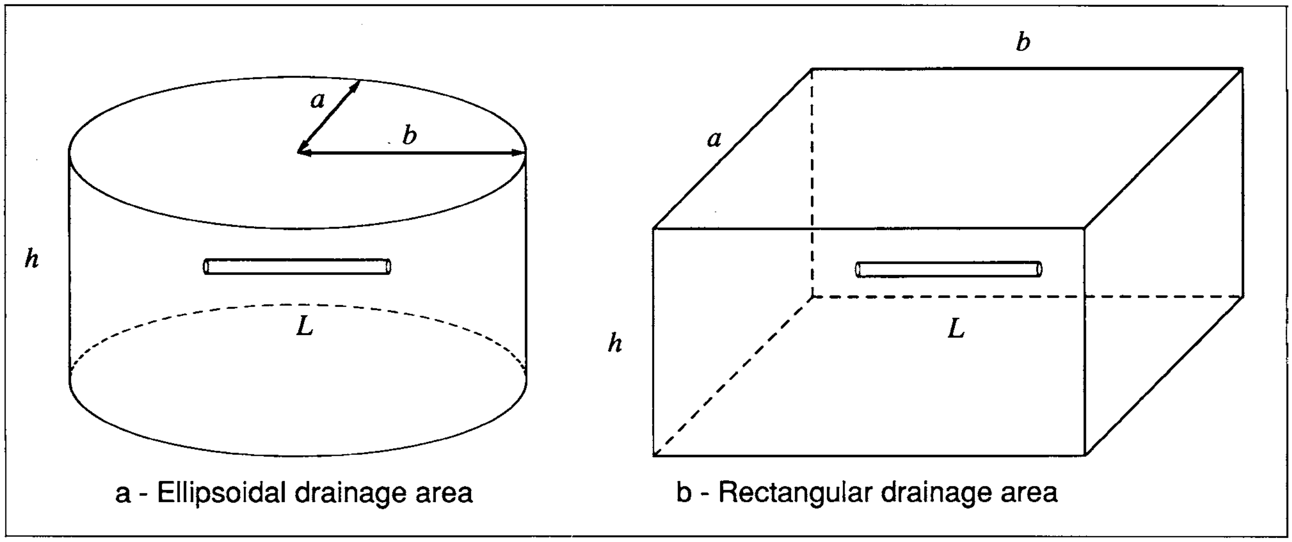

Fig. 1—3D flow to a horizontal well.

Taking into account a skin damage in the vicinity of the well leads to the actual PI for the horizontal well derived in Appendix B.

$$(J_H)_{\text{actual}}=2\pi k_H h/\mu B\times\{1/[\cosh^{-1}(X)+\beta(h/L)\ln(h/2\pi r_w')+s_H]\}, \quad (6)$$

where $s_H=(h/L)\beta s_V$. ....(7)

From Eqs. 5 and 6, we get $E_H=$

$$\frac{\cosh^{-1}(X)+\beta\dfrac{h}{L}\ln\left(\dfrac{h}{2\pi r_w'}\right)}{\cosh^{-1}(X)+\beta\dfrac{h}{L}\ln\left(\dfrac{h}{2\pi r_w'}\right)+\beta\dfrac{h}{L}s_V} \quad (8)$$

or $E_H=$

$$\frac{\dfrac{L}{h\beta}\cosh^{-1}(X)+\ln\left(\dfrac{h}{2\pi r_w'}\right)}{\dfrac{L}{h\beta}\cosh^{-1}(X)+\ln\left(\dfrac{h}{2\pi r_w'}\right)+s_V}. \quad (9)$$

In this form, the expression for the flow efficiency of a horizontal well is similar to that for a vertical well (Eq. 4) with $\ln(r_{eV}/r_w)$ replaced by

$$\Sigma_1=\frac{L}{h\beta}\cosh^{-1}(X)+\ln\left(\frac{h}{2\pi r_w'}\right).$$

Consequently, as **Fig. 2** indicates, flow efficiencies for both vertical and horizontal wells can be represented on the same plot as function of the skin factor.

Flow Efficiency Comparison

From the previous result, flow efficiencies of vertical and horizontal wells are identical, whatever the s_V value, when

$$\ln\left(\frac{r_{eV}}{r_w}\right)=\frac{L}{h\beta}\cosh^{-1}(X)+\ln\left(\frac{h}{2\pi r_w'}\right) \quad (10)$$

$$\text{or } \ln\left(\frac{r_{eV}}{r_w}\right)=\frac{L}{h\beta}\ln\left(X+\sqrt{X^2-1}\right)+\ln\left(\frac{h}{2\pi r_w'}\right),\ \text{with } X\geq 1. \quad (11)$$

If we assume that the horizontal well is located inside a circular drainage area of radius $r_{eH}=\alpha r_{eV}$ with $X=2r_{eH}/L$ such that $\ln\left(X+\sqrt{X^2-1}\right)$ can be approximated by $\ln(2X)$, implying that $X\gg 1$, then Eq. 11 can be written as

$$\ln\left(\frac{r_{eV}}{r_w}\right)=\frac{L}{h\beta}\ln\left(\frac{4r_{eH}}{L}\right)+\ln\left(\frac{h}{2\pi r_w'}\right) \quad (12)$$

so that

$$2\frac{r_{eH}}{L}=½\exp\left[\frac{\ln\left(\dfrac{L}{h}\dfrac{\pi}{4\alpha}\dfrac{1+\beta}{\beta}\right)}{\dfrac{L}{h\beta}-1}\right], \quad (13)$$

which expresses $2r_{eH}/L$ as a function of L/h, α, and β to get the identity $E_V=E_H$, assuming that $X\gg 1$.

The curves in **Fig. 3** are plots of Eq. 13 for β values from 3.16 to 10—i.e., k_H/k_V values from 10 to 100—assuming that $\alpha=1$ ($r_{eH}=r_{eV}$). As Fig. 3 indicates, for instance by Point M ($L/h=20.2$ and $2r_{eH}/L=3$), up to a limiting value of β (7.75 at Point M, which corresponds to $k_H=60\ k_V$), formation damage influences the flow efficiency of a horizontal well less than that of a vertical well of the same radius, whatever the s_V value.

Fig. 3 indicates that for many reservoirs with horizontal/vertical permeability ratio smaller than a few tens, formation damage is less detrimental for horizontal wells than for vertical wells. Moreover, assuming that the superficial extent of the volume drained by a horizontal well is greater than that of a vertical well, the limiting value of β increases as α increases. Note that the identity $E_V=E_H$ is obtained when the ratio of ideal productivities, J_H/J_V, is equal to $L/h\beta$.

Table 1 gives flow efficiencies from Eqs. 4 and 8 for both vertical and horizontal wells for different s_V and β values and $r_w=0.33$ ft, $h=50$ ft, $r_{eV}=r_{eH}=1{,}000$ ft ($\alpha=1$), and $L=500$ ft.

With these data, the identity $E_V=E_H$ is obtained for $\beta=4.8$, or $k_H/k_V\simeq 23$. Consequently, for anisotropy ratios lower than this limiting value, the loss in productivity owing to formation damage is always greater for the vertical well. A well-known result shown in this example is that the productivity improvement, J_H/J_V, with a horizontal well decreases as the permeability anisotropy ratio increases.

E_H values calculated in Table 1, however, show that even though the productivity loss is smaller, it can be very important for the horizontal well also. Moreover, this productivity loss is related to a "lost" production rate,[10] and the main question is whether skin damage can be removed or at least reduced so that a rate increase can justify the workover expense. A given percent change increase in E_H means a different, generally much higher, incremental rate than the same change in E_V. The ratio of "lost" production rates for horizontal and vertical wells is given[10] by $(q_H)_{\text{lost}}/(q_V)_{\text{lost}}=(J_H/J_V)_{\text{ideal}}\times(1-E_H)/(1-E_V)$ and depends mainly on the $L/h\beta$ factor. For example, if the numbers in Table 1 are entered into this equation, the flow rate lost in the horizontal well is greater than that lost in the vertical well. This means that, in this case, skin damage is "costing" more in terms of lost production in the horizontal well than in the vertical well, though E_H is always greater

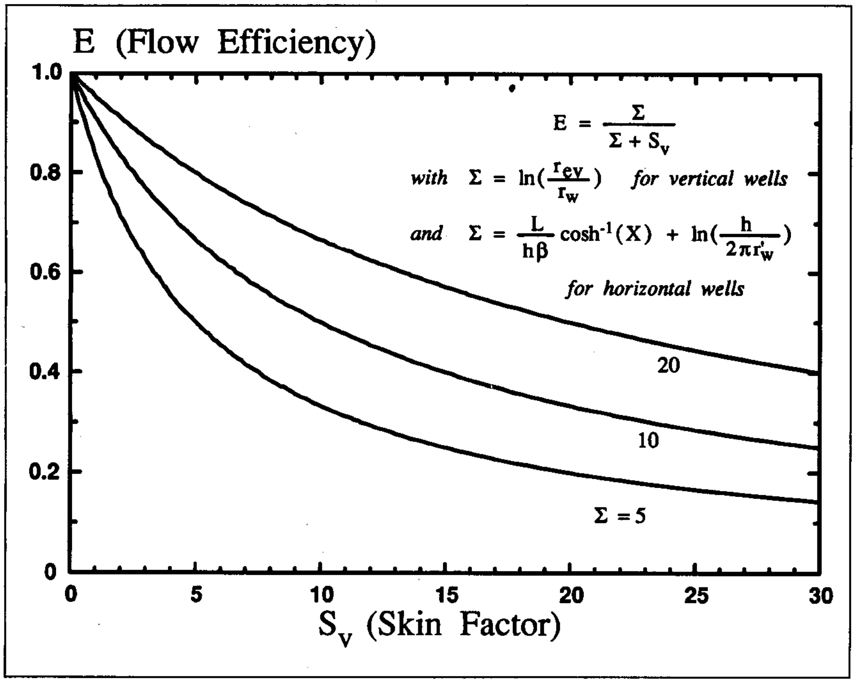

Fig. 2—Flow efficiency for both vertical and horizontal wells.

than E_V. Consequently, to ascertain the maximum profit of horizontal-well production, it is essential to characterize and quantify the productivity loss caused by formation damage near the wellbore. Because of the long sections usually associated with horizontal wells, removal of severe damage will require large quantities of acid,[11] leading to economic-cost and pumping-time considerations. Optimized treatment results and reduced treatment volumes could be obtained by uniform distribution of stimulation fluids along the horizontal well with an adapted acid-placement technique.[12]

Influence of Horizontal-Well Length

From Eq. 8, a first approximation is that the flow efficiency of a horizontal well of length L drilled in a reservoir of anisotropy β is equivalent to the flow efficiency of a horizontal well of length L/β drilled in an anisotropic reservoir of the same thickness. Therefore, increasing the length of the horizontal well must reduce the negative influence of the anisotropy ratio.

Table 2 gives the flow efficiencies of horizontal wells of L=500 to 1,000 ft, with the same assumed data as in the previous example except $\beta=1$ and $r_{eV}=r_{eH}$=2,000 ft. Calculated E_H values indicate that increasing the well length significantly has only a small influence, even for large s_V values and that a major influence is observed on J_H/J_V ratios.

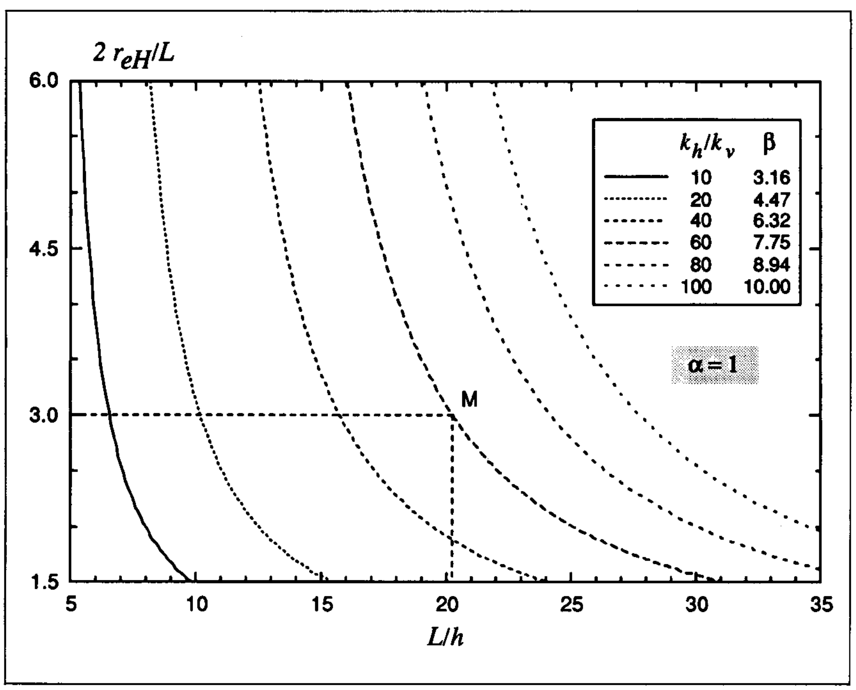

Fig. 3—Plots of Eq. 13 for k_H/k_V values from 10 to 100 ($\alpha=1$).

Effect of Formation Collapse

When an unconsolidated formation is produced, sand production may be a major problem. Usual means of reducing this problem are to use a sand screen or a gravel pack to stabilize the hole. A poorly consolidated formation will probably collapse around the screen, however, filling the screen/drilled-hole annulus. Moreover, experience shows that the screen permeability is damaged eventually by the accumulation of fine particles carried by formation fluids.

The actual PI's of wells when the formation collapses around a screen or slotted liner, assuming no damage into the formation (**Fig. 4a**), can be evaluated through the use of Eqs. 2 and 6, replacing r_w by r_c and r_s by r_w. The flow efficiencies become

$$E_V=\frac{\ln(r_{eV}/r_w)}{\ln(r_{eV}/r_c)+s_V} \quad \text{.......... (14)}$$

and $E_H=$

$$\frac{\cosh^{-1}(X)+\beta\frac{h}{L}\ln\left(\frac{2\beta}{1+\beta}\frac{h}{2\pi r_w}\right)}{\cosh^{-1}(X)+\beta\frac{h}{L}\left[\ln\left(\frac{2\beta}{1+\beta}\frac{h}{2\pi r_c}\right)+s_V\right]}, \quad \text{................ (15)}$$

with $s_V=[(k/k_c)-1]\ln(r_w/r_c)$. ..... (16)

Combined effects of formation damage and collapse around a screen modify the expressions for flow efficiencies for vertical and horizontal wells. Assuming an isotropic reservoir and using the notations of **Fig. 4b**, we obtain

$$E_V=\frac{\ln(r_{eV}/r_w)}{\ln(r_{eV}/r_s)+\frac{k}{k_s}\ln(r_s/r_w)+\frac{k}{k_c}\ln(r_w/r_c)} \quad \text{................ (17)}$$

$$\text{and } E_H=\frac{\cosh^{-1}(X)+\frac{h}{L}\ln\left(\frac{h}{2\pi r_w}\right)}{\cosh^{-1}(X)+\frac{h}{L}\Sigma_2}, \quad \text{................ (18)}$$

where $\Sigma_2=$

$$\ln\left(\frac{h}{2\pi r_s}\right)+\frac{k}{k_s}\ln\left(\frac{r_s}{r_w}\right)+\frac{k}{k_c}\ln\left(\frac{r_w}{r_c}\right).$$

Table 3 shows an application of these formulas for different values of k/k_s and the following data: r_w=0.33 ft, r_c=0.208 ft, r_s=3 ft, k/k_c=10, h=50 ft, r_e=1,000 ft

TABLE 1—EXAMPLE OF COMPARISON OF FLOW EFFICIENCIES, E_V AND E_H, FOR DIFFERENT VALUES OF s_V AND k_H/k_V (β^2)

		E_H		
s_V	E_V	$k_H/k_V=1$ and $\beta=1$	$k_H/k_V=2$ and $\beta=1.41$	$k_H/k_V=10$ and $\beta=3.16$
1	0.89	0.96	0.94	0.91
5	0.62	0.83	0.76	0.67
10	0.44	0.71	0.61	0.50
20	0.29	0.55	0.45	0.34
$(J_H/J_V)_{ideal}$		3.34	3.14	2.49

TABLE 2—EXAMPLE OF THE INFLUENCE OF HORIZONTAL-WELL LENGTH ON THE FLOW EFFICIENCY E_H ($\beta=1$)

	E_H		
s_V	$L=500$ ft	$L=750$ ft	$L=1{,}000$ ft
1	0.97	0.97	0.98
5	0.86	0.89	0.90
10	0.76	0.79	0.82
20	0.61	0.66	0.69
$(J_H/J_V)_{ideal}$	2.82	3.38	3.89

". . . to ascertain the maximum profit of horizontal-well production, it is essential to characterize and quantify the productivity loss caused by formation damage near the wellbore."

(circular drainage area), and $L=500$ ft. For large values of k/k_s, this example indicates that the reduction of flow efficiency of a vertical well caused by the combined effects of damage and collapse around a screen can be twice that of a horizontal well.

An important advantage of horizontal wells is that fluid velocity at the wellbore will be much lower than for a vertical well. This point and usually smaller influence of skin damage suggest that, in many cases, sand control may not be as essential for horizontal production as for vertical wells. The possibility of sand production is reduced by the lower water cuts, lower pressure drawdowns, and lower fluid velocities that horizontal wells experience.[13,14]

Conclusions

Considering the steady-state flow of an incompressible fluid and assuming an altered zone of the same radius around horizontal and vertical wellbores, we can draw the following conclusions.

1. Up to relatively large permeability ratio values, skin damage is less detrimental to horizontal wells than to vertical wells.
2. Severe damage, however, can dramatically reduce the flow efficiency of horizontal wells. Therefore, as with vertical wells, it is essential to be able to quantify the possible loss of productivity caused by formation damage in horizontal wells and, if necessary, to remove or to reduce the damage in the vicinity of horizontal wellbores. Both tasks are more difficult to perform in horizontal wells and require adapted methods.
3. The anisotropy ratio magnifies the influence of the skin damage for horizontal wells.
4. Increasing the horizontal-well length slightly reduces the influence of skin on flow efficiency.

Nomenclature

a,b = half major and minor axes of drainage ellipse, or sides of drainage rectangle parallel and perpendicular to fracture or horizontal well, ft
B = FVF, dimensionless
E = flow efficiency, dimensionless
h = reservoir height, ft
i = complex number variable
J = PI, STB/(D-psi)
J_{actual} = actual PI with skin s
J_{ideal} = ideal PI ($s=0$)
k = permeability, md
k_{eq} = $\sqrt{k_H k_V}$
L = horizontal well length, ft
p = pressure, psia
Δp_s = pressure drop caused by skin, psia
Δp_{wf} = pressure drawdown in flowing well, psia
q = flow rate, STB/D
r = radius, ft
r' = $r[(1+\beta)/2\beta]$
r_e = drainage radius, ft
r_w = wellbore radius, ft
r_{we} = effective wellbore radius $[r_w \exp(-s)]$, ft
s = skin factor, dimensionless
x,y,z = distances along x, y, and z axes, ft
X = parameter depending on shape and dimensions of area drained by well
Z = affix in complex plane $[Z=r\exp(i\theta)]$
α = r_{eH}/r_{eV}
β = $\sqrt{k_H/k_V}$, permeability anisotropy ratio
θ = coordinate in cylindrical coordinate system, degrees
μ = fluid viscosity, cp
Φ = real part of complex flow potential
Ψ = imaginary part of complex flow potential
Ω = complex flow potential ($\Phi+i\Psi$)

Subscripts

c = collapsed zone around well
e = external
F = fracture
H = horizontal

(To Page 868)

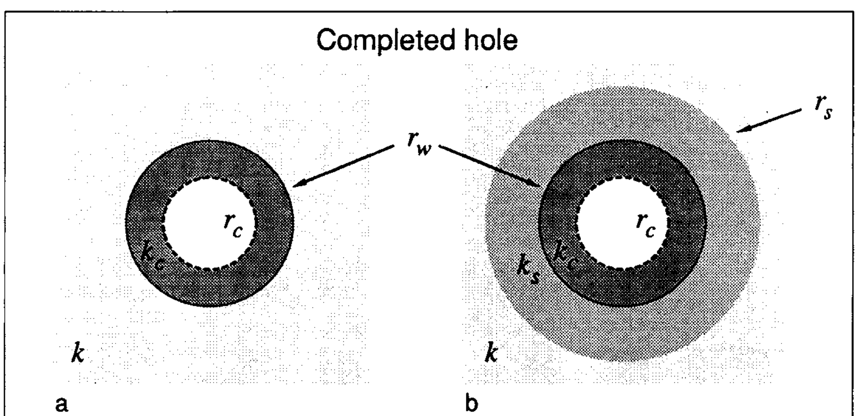

Fig. 4—Schematic of altered zones around a wellbore: (a) undamaged formation and collapse around the screen or slotted liner and (b) damaged formation and collapse around the screen or slotted liner.

TABLE 3—COMBINED EFFECTS OF FORMATION DAMAGE AND COLLAPSE AROUND A SCREEN		
k/k_s	E_V	E_H
1	0.63	0.84
2	0.54	0.78
4	0.41	0.68
10	0.25	0.49

Formation Damage Effects on Horizontal-Well Flow Efficiency

(From Page 789)

s = altered zone around well
V = vertical
w = well

Acknowledgment

We thank Yvonne Tarac for her help in the preparation of this manuscript.

References

1. Giger, F.: "Low Permeability Reservoir Development Using Horizontal Wells," paper SPE 16406 presented at the 1987 SPE Joint Low-Permeability Reservoir Symposium/ Rocky Mountain Regional Meeting, Denver, May 18-19.
2. Joshi, S.D.: "Augmentation of Well Productivity Using Slant and Horizontal Wells," *JPT* (June 1988) 729-39; *Trans.*, AIME, **285.**
3. de Montigny, O. and Combe, J.: "Horizontal Well Operations—3, Hole Benefits, Reservoir Types Key to Profit," *Oil & Gas J.* (April 1988) 50-56.
4. Mauduit, D.: "Determining the Productivity of Horizontal Completions," *World Oil* (Dec. 1989) 55-61.
5. Sparlin, D.D. and Hagen, R.W.: "Controlling Sand in a Horizontal Completion," *World Oil* (Nov. 1988) 54-60.
6. van Everdingen, A.F.: "The Skin Effect and Its Influence on the Productive Capacity of a Well," *Trans.*, AIME, **198** (1953) 171-76.
7. Hurst, W.: "Establishment of the Skin Effect and Its Impediment to Fluid Flow Into a Well Bore," *Pet. Eng.* (Oct. 1953) B6-B16.
8. Hawkins, M.F.: "A Note on the Skin Effect," *Trans.*, AIME (1956) **207,** 356-57.
9. Merkulov, V.P.: "The Flow of Slanted and Horizontal Wells," *Neft. Khoz.* (1958) **6,** 51-56.
10. Gilman, J.R.: "Discussion of Formation Damage Effects on Horizontal-Well Flow Efficiency," *JPT* (July 1991) 870.
11. McLennan, J.D., Roegiers, J-C., and Economides, M.J.: "Extended Reach and Horizontal Wells," *Reservoir Stimulation,* M.J. Economides and K.G. Nolte (eds.), Prentice Hall Inc., Englewood Cliffs, NJ (1989).
12. Economides, M.J., Ben-Naceur, K., and Klem, R.C.: "Matrix Stimulation Methods for Horizontal Wells," paper SPE 19719 presented at the 1989 SPE Annual Technical Conference and Exhibition, San Antonio, Oct. 8-11.
13. Murphy, P.J.: "Performance of Horizontal Wells in the Helder Field," *JPT* (June 1990) 792-800.
14. Coffin, P.: "Pelican Lake and Winter Field Horizontal Well Projects," paper presented at the 1989 Horizontal Well Seminar, Calgary, April 20.
15. Muskat, M.: *The Flow of Homogeneous Fluids Through Porous Media,* Intl. Human Resources Development Corp., Boston (1937).
16. MacDonald, C.J.: "Horizontal Wells: An Application in the North Sea," paper SPE 18342 presented at the 1988 SPE European Petroleum Conference, London, Oct. 17-19.

Appendix A—3D Flow to an Undamaged Horizontal Well

For both geometries in Fig. 1, the pressure distribution caused by steady-state flow to the horizontal well is approximated by subdividing the 3D flow problem into two 2D problems:

$$\underbrace{p_e-p_H(r_w)}_{3\text{D}-xyz}=\underbrace{p_e-p_F}_{2\text{D}-xy}+\underbrace{p_F-p_H(r_w)}_{2\text{D}-xz}. \quad \text{(A-1)}$$

In the first zone, located far from the well, flow is studied in a horizontal plane as if it were a flow to a vertical fracture of the same length as the horizontal well. The pressure drop in this 2D xy-flow has been determined by Giger[1] and Joshi[2] from the potential-fluid-flow theory. For both geometries,

$$p_e-p_F=\frac{q\mu B}{2\pi k_H h}\cosh^{-1}(X), \quad \text{(A-2)}$$

with $X=2a/L$ if the drainage area is ellipsoidal. The other expression of the $\cosh^{-1}$, assuming $X\geq 1$, leads to a more frequent presentation of the solution,[2]

$$p_e-p_F=\frac{q\mu B}{2\pi k_H h}\ln\left[\frac{2a}{L}+\sqrt{\left(\frac{2a}{L}\right)^2-1}\right], \quad \text{(A-3)}$$

that simplifies to

$$p_e-p_F=\frac{q\mu B}{2\pi k_H h}\ln\left(\frac{4a}{L}\right) \quad \text{(A-4)}$$

if $a\gg L$, and $X=[\cosh(\pi a/2b)]/[\sin(\pi L/2b)]$ if the drainage area is rectangular with a lateral feeding at $x=a/2$. The solution tends to the solution of a fully developed fracture when the length of the well tends to the dimension of Side b of the rectangle:

$$p_e-p_F=\frac{q\mu Ba}{4k_H hL} \quad \text{(A-5)}$$

if $L=b$.

In the second zone, in the immediate vicinity of the well, flow is studied in a vertical plane perpendicular to the well axis. The additional pressure drop caused by the convergence of streamlines toward the horizontal well compared with the flow toward a fully penetrating vertical fracture can be written as

$$p_F-p_H(r_w)=p_F-p_e+p_e-p_H(r_w). \quad \text{(A-6)}$$

The first pressure drop gives the 2D flow to a vertical fracture (Eq. A-5), while the second term, $p_e-p_H(r_w)$, gives the 2D vertical flow to the horizontal well. This last term is also derived from the fluid-flow-potential theory, as indicated by Giger[1] and Joshi.[2] These authors have used two different complex flow potentials:

$$\Omega_G=\frac{q\mu B}{2\pi k_H L}\ln[\sin(i\pi Z/h)] \quad \text{(A-7)}$$

and $$\Omega_J=\frac{q\mu B}{2\pi k_H L}\ln[\sinh(\pi Z/h)], \quad \text{(A-8)}$$

which have, however, the same real part, Φ (potential), because $\sin(i\pi Z/h)=i\sinh\times(\pi Z/h)$ and $\ln i=\pi/2$. So,

$$\Omega_G=\Omega_J+i\frac{\pi}{2}\frac{q\mu B}{2\pi k_H L} \quad \text{(A-9)}$$

and, from Giger,

$$p_e-p_H(r_w)=\frac{q\mu B}{2\pi k_H h}\left[\frac{\pi a}{2L}+\frac{h}{L}\ln\left(\frac{h}{2\pi r_w}\right)\right]. \quad \text{(A-10)}$$

The expression presented by Joshi, though it gives quite the same result, is slightly different because the factor π is omitted in the second term. It seems that the expansion of the function $\sinh(\pi Z/h)$ proposed by Joshi in Eq. B-3 of his paper can be used only for small values of the argument of the function and cannot be used at the wall; that is, for $Z=ih/2$, which gives $\Omega_J(h/2)-\Omega_J(r_w)=-q\ln(h/2r_w)$ (Eq. B-4) instead of $-q\ln\times(h/\pi r_w)$ when the complex flow potential (Eq. B-1) is used.

The additional pressure drop in the vicinity of the well when producing a horizontal well compared with the production of a fracture from Eqs. A-5 and A-10 is then

$$p_F-p_H(r_w)=\frac{q\mu B}{2\pi k_H L}\ln\left(\frac{h}{2\pi r_w}\right). \quad \text{(A-11)}$$

The approximate solution for the total pressure drop, Eq. A-1, becomes

$$p_e-p_H(r_w)=\frac{q\mu B}{2\pi k_H h}\left[\cosh^{-1}(X)+\frac{h}{L}\ln\left(\frac{h}{2\pi r_w}\right)\right], \quad \text{(A-12)}$$

with X as previously defined, and the ideal PI is

$$(J_H)_{\text{ideal}}=\frac{2\pi k_H h}{\mu B}\times\left[\frac{1}{\cosh^{-1}(X)+\frac{h}{L}\ln\left(\frac{h}{2\pi r_w}\right)}\right]. \quad \text{(A-13)}$$

To account for any vertical anisotropy $\beta=\sqrt{k_H/k_V}$, the transformation introduced by Muskat[15] has to be applied to the 2D vertical flow to the horizontal well. The

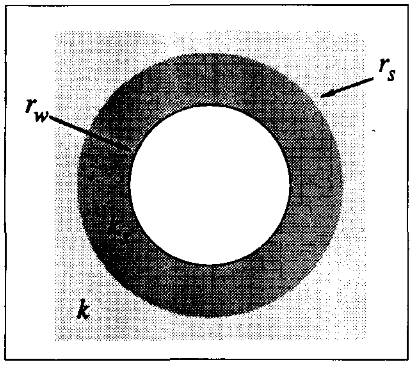

Fig. B-1—Schematic of altered zone around a wellbore, open hole, damaged formation.

distances along the axes have to be multiplied by $\sqrt{k_{eq}/k_H}$ and $\sqrt{k_{eq}/k_V}$ where $k_{eq} = \sqrt{k_H k_V}$. In the transformation, the well becomes elliptical and its radius, r_w, has to be changed to $r_w(1+\beta)/2\sqrt{\beta}$ to have the same section.[16] So,

$$p_e - p_H(r_w) = \frac{q\mu B}{2\pi k_H h} \times \left[\cosh^{-1}(X) + \beta\frac{h}{L}\ln\left(\frac{h}{2\pi r'_w}\right)\right] \quad \text{(A-14)}$$

and $$(J_H)_{\text{ideal}} = \frac{2\pi k_H h}{\mu B} \times \left[\frac{1}{\cosh^{-1}(X) + \beta\frac{h}{L}\ln\left(\frac{h}{2\pi r'_w}\right)}\right], \quad \text{(A-15)}$$

with $r'_w = [(1+\beta)/2\beta]r_w$.

Appendix B—3D Flow to a Damaged Horizontal Well

The altered zone that extends to r_s around the well affects only the pressure near the well. The skin factor must be introduced through the calculation of the pressure drop in the close vicinity of the well (2D xz flow in **Fig. B-1**). In an isotropic reservoir, from Eqs. A-10 and A-11,

$$p_e - p_H(r_w) = p_e - p(r_s) + p(r_s) - p_H(r_w)$$
$$= \frac{q\mu B}{2\pi kh}\left[\frac{\pi a}{2L} + \frac{h}{L}\ln\left(\frac{h}{2\pi r_s}\right)\right] + \frac{q\mu B}{2\pi k_s L}\left[-\ln\left(\frac{h}{2\pi r_s}\right) + \ln\left(\frac{h}{2\pi r_w}\right)\right], \quad \text{(B-1)}$$

which can be written as

$$p_e - p_H(r_w) = \frac{q\mu B}{2\pi kh}\left[\frac{\pi a}{2L} + \frac{h}{L}\ln\left(\frac{h}{2\pi r_w}\right) + s_H\right] \quad \text{(B-2)}$$

to introduce the skin factor s_H. So,

$$s_H = \frac{h}{L}\left(\frac{k}{k_s} - 1\right)\ln\left(\frac{r_s}{r_w}\right) = \frac{h}{L}s_V. \quad \text{(B-3)}$$

Accounting for the anisotropy ratio, the PI of a damaged horizontal well is then expressed by

$$(J_H)_{\text{actual}} = \frac{2\pi k_H h}{\mu B} \times \left[\frac{1}{\cosh^{-1}(X) + \beta\frac{h}{L}\ln\left(\frac{2\beta}{1+\beta}\frac{h}{2\pi r_w}\right) + \beta\frac{h}{L}s_V}\right] \quad \text{(B-4)}$$

or $$(J_H)_{\text{actual}} = \frac{2\pi k_H h}{\mu B} \times \left[\frac{1}{\cosh^{-1}(X) + \beta\frac{h}{L}\ln\left(\frac{h}{2\pi r'_{we}}\right)}\right], \quad \text{(B-5)}$$

with $r'_{we} = [(1+\beta)/2\beta]r_w \exp(-s_V)$.

Authors

Renard Dupuy

Gérard Renard is a research engineer at Inst. Français du Pétrole (IFP) in Rueil Malmaison, France. His research interests are in reservoir engineering aspects of horizontal wells and EOR. He graduated from Ecole Natl. Supérieure d'Electronique, d'Electrotechnique, d'Informatique, et d'Hydraulique de Toulouse (ENSEEIHT) in fluid mechanics and from Ecole Natl. Supérieure du Pétrole et des Moteurs (ENSPM) in petroleum engineering. Jean-Marc Dupuy is business development manager for the Industrial Div. at IFP. He previously was technical manager of Horwell and vice president of reservoir engineering at Elf Horizontal Drilling & Production in Houston. He holds an MS degree in fluid mechanics from ENSEEIHT.

SI Metric Conversion Factors

ft × 3.048*	E−01	= m
md × 9.869 233	E−04	= μm^2

*Conversion factor is exact.

Provenance

Original SPE manuscript, **Influence of Formation Damage on the Flow Efficiency of Horizontal Wells,** received for review Feb. 22, 1990. Paper accepted for publication March 15, 1991. Revised manuscript received Jan. 24, 1991. Paper (SPE 19414) first presented at the 1990 SPE Formation Damage Control Symposium held in Lafayette, Feb. 22-23.

JPT

Discussion of Formation Damage Effects on Horizontal-Well Flow Efficiency

J.R. Gilman, SPE, Marathon Oil Co.

This discussion refers to the concept of "lost" production because of skin damage in vertical or horizontal wells.

For a well with skin damage limited by a bottomhole pressure constraint, an important question to consider is whether the skin damage can be removed, or at least reduced, so that a rate increase can justify the workover expense. Therefore, I feel that Tables 1 and 2 in "Formation Damage Effects on Horizontal-Well Flow Efficiency" would be more informative with an additional column that shows the relative amount of production "lost" because of skin damage. The amount of lost production is the amount of additional rate that a well could produce at a fixed drawdown, Δp_{wf}, if the skin damage was removed. The lost production in terms of efficiency factor and ideal (non-damaged) productivity index for a vertical well is

$$q_{V,\text{lost}}=J_{V,\text{ideal}}(1-E_V)\Delta p_{wf}, \quad \text{(D-1)}$$

and similarly for a horizontal well,

$$q_{H,\text{lost}}=J_{H,\text{ideal}}(1-E_H)\Delta p_{wf}. \quad \text{(D-2)}$$

The ratio of horizontal- to vertical-well lost production, assuming the same drawdown, then becomes

$$(q_H/q_V)_{\text{lost}}=(J_H/J_V)_{\text{ideal}} \times(1-E_H)/(1-E_V). \quad \text{(D-3)}$$

Tables D-1 and D-2 show this loss ratio and the efficiency factor ratio for the data given in Tables 1 and 2. For all the data given in Table D-1, the loss ratio is greater than unity. Therefore, for a given amount of damage, the horizontal well has a greater amount of "lost" production than the vertical well, even though horizontal well efficiency, E_H, is greater than vertical well efficiency, E_V. Table D-2 shows that this loss ratio can also be less than unity.

TABLE D-1—EFFICIENCY FACTOR AND LOST PRODUCTION RATIOS FOR DAMAGED HORIZONTAL AND VERTICAL WELLS AS A FUNCTION OF PERMEABILITY RATIO

	$\beta=1$		$\beta=1.41$		$\beta=3.16$	
s_V	E_H/E_V	$(q_H/q_V)_{\text{lost}}$	E_H/E_V	$(q_H/q_V)_{\text{lost}}$	E_H/E_V	$(q_H/q_V)_{\text{lost}}$
1	1.08	1.21	1.06	1.72	1.02	2.04
5	1.34	1.49	1.23	1.98	1.08	2.16
10	1.61	1.73	1.39	2.19	1.14	2.22
20	1.90	2.12	1.55	2.43	1.17	2.31

TABLE D-2—EFFICIENCY FACTOR AND LOST PRODUCTION RATIOS FOR DAMAGED HORIZONTAL AND VERTICAL WELLS AS A FUNCTION OF HORIZONTAL WELL LENGTH ($\beta=1$)

	$L=500$ ft		$L=750$ ft		$L=1{,}000$ ft	
s_V	E_H/E_V	$(q_H/q_V)_{\text{lost}}$	E_H/E_V	$(q_H/q_V)_{\text{lost}}$	E_H/E_V	$(q_H/q_V)_{\text{lost}}$
1	1.08	0.85	1.08	1.01	1.09	0.78
5	1.34	1.10	1.39	1.03	1.41	1.08
10	1.62	1.28	1.68	1.34	1.74	1.32
20	2.03	1.57	2.20	1.64	2.30	1.72

Generally the cost of removing skin damage from horizontal wells is much greater than the cost for vertical wells. Therefore, the benefit of removing skin damage must be considered for each individual well. This discussion and the subject paper point out, however, that removing or preventing skin damage in horizontal wells can be very beneficial.

Nomenclature

E = flow efficiency, dimensionless
J_{ideal} = well productivity index without skin damage, STB/D-psi
k = permeability, md
L = horizontal well length, ft
Δp_{wf} = pressure drawdown in a flowing well, psi
q_{lost} = lost production rate because of skin damage, STB/D
s = skin factor, dimensionless
β = permeability anisotropy ratio (k_H/k_V), dimensionless

Subscripts

H = horizontal
V = vertical

(SPE 23526)

JPT

Discussion of Formation Damage Effects on Horizontal-Well Flow Efficiency

M.J. Economides, SPE, Mining U. Leoben,
and **C.A. Ehlig-Economides,** SPE, Schlumberger

The general thrust in Renard and Dupuy's paper (July 1991 *JPT,* Page 786) and in the associated discussion by Gilman (July 1991 *JPT,* Page 870) is useful because it indicates the profound effects of damage on horizontal-well performance. Also, Gilman shows the greater flow-rate loss that damage inflicts on horizontal wells compared with vertical wells. Some theoretical and practical considerations, however, are not addressed in Renard and Dupuy's paper.

Fig. D-1 shows two conceptual models for horizontal-well damage.[1] When the vertical/horizontal permeability anisotropy is significant, the damage shape is not radial. Furthermore, the damage caused by drilling and completion filtrate invasion is maximized near the vertical section of the borehole and decreases down the length of the well. Flow-profile measurements in horizontal wells indicate that in some wells the flow contribution along the well is limited to a small fraction of the drilled length.[2] Clearly, the nature of the damage must be correctly characterized to quantify its effect on production adequately and to design an appropriate damage-removal treatment.

Fig. D-1 shows the damage shape, normal to and along the well, for three values of the permeability anisotropy ratio, $I_{ani}=\sqrt{k_H/k_V}$. In their Eq. 6, Renard and Dupuy add the Hawkins[3] skin effect to a Merkulov[4]-type equation. As such, they have included a skin value derived for an isotropic formation in a flow equation that otherwise accounts for anisotropy.

To account for anisotropy, the analogy to Hawkins' formula is

$$s'_{eq}=\left(\frac{k}{k_s}-1\right)\ln\left[\frac{1'}{(I_{ani}+1)}\times\sqrt{\frac{4}{3}\left(\frac{a^2{}_{H,\max}}{r_w^2}+\frac{a_{H,\max}}{r_w}+1\right)}\right], \quad \text{(D-1)}$$

where $a_{H,\max}$ is the horizontal axis of the damage ellipse near the vertical section (as shown in Fig. D-1). Eq. D-1 assumes that the permeability damage ratio is equivalent in the vertical and horizontal directions. This expression can be used in place of s_V, defined by Renard and Dupuy. For example, when $a_{H,\max}=4$ ft and $k/k_s=10$, $s'_{eq}=12$ for $r_w=0.3$ ft, and $I_{ani}=3$. For $r_s=1$ ft, the value for s_V, as defined in Eq. 2 from Renard and Dupuy, is 11.

In the case study by Ahmed and Badrey,[2] analysis of both production-log and transient test data indicated that oil was produced through only 16% of the completed well length, with most of the production coming from the end of the borehole away from the vertical section of the well. The theoretically derived form of the skin distribution down the length of a horizontal well is shown in Fig. D-1 as a truncated elliptical cone. This skin distribution may inhibit cleanup in all but a small fraction of the borehole length because, once a portion

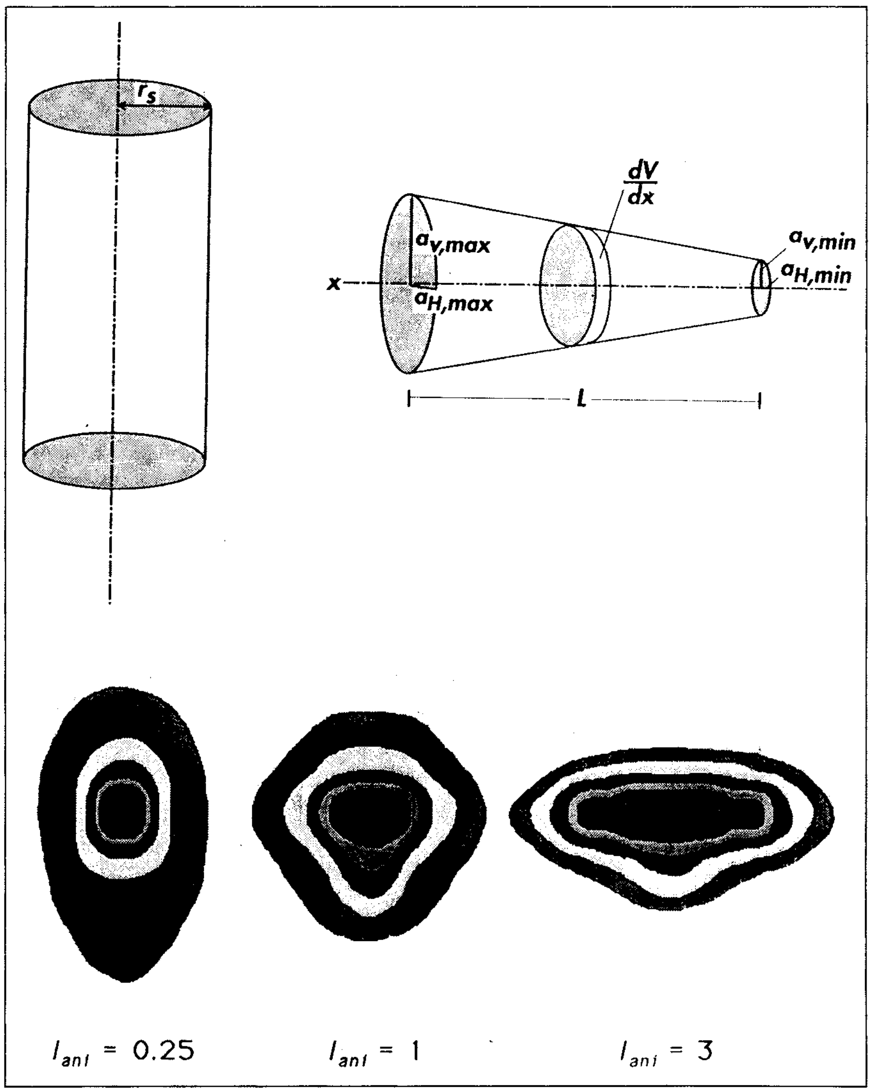

Fig. D-1—Damage shape along vertical and horizontal wells and cross section of damage around a horizontal well for different permeability anisotropies.

of the well begins to flow, the pressure drop is too low to provide sufficient gradient to clean up the rest of the borehole.

For the case study in Ref. 2, the skin along the producing interval was determined to be −3.3 from the transient test, which also provided values of k_H=618 md, k_V=3.2 md, and an effective wellbore length of 219 ft, for a drilled length of 1,411 ft. For this case, I_{ani}=14, and the well productivity computed with Eq. 10 from Kuchuk *et al.*[5] is only 17% of what it would be in the ideal case of production along the entire drilled length with no damage. The horizontal well was drilled despite an unusually large I_{ani} value to avoid coning from an underlying aquifer.

As in vertical wells, production logs in horizontal wells[6] help to explain observed productivity and provide essential information for effective treatment placement and design. The same condition that may result in cleanup of only a small fraction of the drilled length can threaten the success of a stimulation treatment. The use of coiled tubing, either with mechanical zonal isolation or chemical diverters, allows treatment fluids to be placed where they are needed and economically justified.

After the flow profile verifies that flow is fairly uniform along the horizontal borehole, if lower-than-expected productivity suggests significant damage, treatment that mimics the more realistic damage model shown in Fig. D-1 can be more cost effective. **Fig. D-2** (from Ref. 1) illustrates the costs of ignoring these effects. The injected volume for uniform or tapered injection is plotted in Fig. D-2 as a function of the resultant skin for a particular example. As shown, the skin is smaller after increased quantities of treatment fluid are injected.

The bottom curve shows the volumetric demand of the stimulation fluid when the injection mimics the damage shape, allowing for larger stimulation volumes near the vertical section and smaller ones away from it. If uniform injection is done (as implied by Renard and Dupuy's skin effect), wasteful overtreatment can result, as the top curve shows. For the example in Fig. D-2, the skin reduction from 20 to 4 would require nearly 60% more acid with uniform injection. The same damage shape can be assumed for the design of a partial stimulation treatment, when total damage removal is not an option either because of economics or out of concern for well tubulars.[1]

Nomenclature

a_H = horizontal axis of damage ellipse, ft
a_V = vertical axis of damage ellipse, ft
I_{ani} = permeability anisotropy variable
k = permeability, md
k_H = horizontal permeability, md
k_s = damage zone permeability, md
k_V = vertical permeability, md
L = length, ft
r_s = radial penetration of damage in isotropic formation, ft
r_w = wellbore radius, ft
s = skin factor, dimensionless
s'_{eq} = anisotropic skin effect
s_V = isotropic vertical skin effect
V_f = fluid volume, gal
x = horizontal coordinate, ft

Subscripts

max = maximum
min = minimum

References

1. Frick, T.P. and Economides, M.J.: "Horizontal Well Damage Characterization and Removal," paper SPE 21795 presented at the 1991 SPE Western Regional Meeting, Long Beach, CA, March 20-22.
2. Ahmed, U. and Badrey, R.: "Production Logging as an Integral Part of Horizontal Well Transient Pressure Test," paper SPE 20980 presented at the 1990 SPE European Offshore Petroleum Conference, The Hague, Oct. 22-24.
3. Hawkins, M.F.: "A Note on the Skin Effect," *Trans.*, AIME (1956) **207,** 356-57.
4. Merkulov, V.P.: "The Flow of Slanted and Horizontal Wells," *Neft Khoz.* (1958) **6,** 51-56.
5. Kuchuk, F.J. *et al.*: "Pressure-Transient Analysis for Horizontal Wells," *JPT* (Aug. 1990) 974-1031; *Trans.*, AIME, **289.**
6. Chauvel, Y.L. and Oosthoek, P.: "Production Logging in Horizontal Wells: Experience to Date," paper SPE 21094 presented at the 1990 SPE Latin American Petroleum Engineering Conference, Rio de Janeiro, Oct. 14-19.

SI Metric Conversion Factors

ft × 3.048*	E−01	= m
gal × 3.785 412	E−03	= m³
md × 9.869 233	E−04	= μm²

*Conversion factor is exact.

(SPE 23833) **JPT**

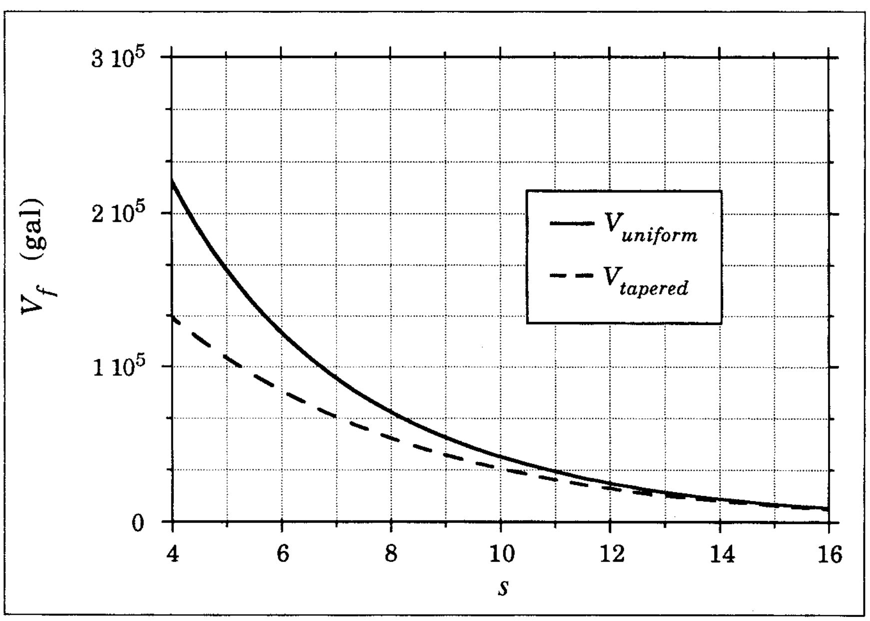

Fig. D-2—Matrix stimulation-fluid demand for uniform and tapered injection.

Authors' Reply to Discussion of Formation Damage Effects on Horizontal-Well Flow Efficiency

Gerard Renard, SPE, and **J.M. Dupuy,** SPE,
Inst. Français du Pétrole

In our paper, we considered a very simple schematization of the distribution of damage surrounding a horizontal well, assuming a radial damaged zone even in anisotropic formations. A more realistic schematization was presented by Frick and Economides,[1] and as a matter of fact, the expression of the skin in Hawkins[2] formula has to be modified if an elliptical damage zone is assumed. Although it is better, the proposed representation is also idealized for at least two reasons.

First, reservoirs are naturally heterogeneous. In the case study[3] invoked by Economides and Ehlig-Economides in their discussion, production logging indicated that a little more than 164 ft [50 m] was contributing to flow from the 1,411 ft [430 m] of the horizontal section, with production coming from the end tip of the borehole and from a central section. Ahmed and Badry[3] explain the production profile with different reasons relevant to this particular well: the entire well may not be within the formation, changes in formation pressure could occur in the lateral direction, and more probably, low-permeability shale streaks are present (Fig. 17 of Ref. 3). Economides and Ehlig-Economides suggest another possibility: the drop is too low to provide sufficient gradient to clean up the nonproductive section of the borehole. To say that this is the reason for limited production, however, is not correct, and more generally, the skin distribution along a wellbore will be dictated by the heterogeneous nature of the reservoir.

Second, as Woodhouse *et al.*[4] indicate, in formations with moderate to high permeability and high k_V/k_H ratios, invaded filtrates will migrate vertically, propelled by density contrasts between the mud filtrate and formation fluid. In such cases, an asymmetric invasion will develop.

As Economides and Ehlig-Economides indicated, the nature of the damage must be characterized correctly to quantify its effect on production adequately. In the future, formation-evaluation-while-drilling logs[4] will provide essential information for this characterization of productive damaged zones.

References

1. Frick, T.P. and Economides, M.J.: "Horizontal Well Damage Characterization and Removal," paper SPE 21795 presented at the 1991 SPE Western Regional Meeting, Long Beach, CA, March 20-22.
2. Hawkins, M.F.: "A Note on the Skin Effect," *Trans.*, AIME (1956) **207**, 356-57.
3. Ahmed, U. and Badry, R.: "Production Logging as an Integral Part of Horizontal Well Transient Pressure Test," paper SPE 20980 presented at the 1990 SPE European Petroleum Conference, The Hague, Oct. 21-24.
4. Woodhouse, R., Opstad, E.A., and Cunningham, A.B.: "Vertical Migration of Invaded Fluids in Horizontal Wells," paper A, *Trans.*, SPWLA 32nd Annual Logging Symposium, Midland (June 16-19, 1991).

(SPE 23839) **JPT**