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A New Approach for Economic Evaluation of Horizontal and Vertical Wells in A Sensitive Formation

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Abstract

Severe formation damage in horizontal wells has been frequently reported. Many theoretical works related to this subject have also appeared in the literature. This indicates that such damage is a serious problem that can considerably affect the economics of horizontal well applications. The purpose of this paper is to present a new approach for evaluating the economic advantage of a horizontal well as compared to the vertical well case in a sensitive formation.

The new approach employs concepts of production loss analysis and the maximum cost ratio (MCR), respectively, to evaluate short and long term production and economic performances. MCR here is defined as the ratio of horizontal-to-vertical well drilling and completion costs arriving at the ratio of net present values of 1.0.

Results demonstrate that, although production performance of a vertical well is generally more sensitive to formation damage, the production loss can be much higher in the horizontal well causing a considerable economic loss when converted to dollars. Based on the analysis of MCR, it is found that (1) the costs limit of a horizontal well is controlled by the degree of damage severity, permeability, and oil price and (2) MCR is well correlated with the standard economic criteria as well as the production performance. In general, the costs limit decreases with damage severity and oil price and as reservoir permeability increases. Overall, the approach proposed can be used as a valuable tool for the economic analysis and provides engineers guidance for optimizing the drilling and completion design when a horizontal well project must go on.

Introduction

Over the past two decades, horizontal wells have become the central issue of the oil industry. Since the mid 1980's the topic has been the interest of major oil companies as well as research institutions as shown by large amount of publications. By the early 1990's, it seemed that every operator had at least a horizontal well project planned or even executed. In this regard, horizontal well has been applied for specialized cases such as layered formation, dipping formations, depleted reservoirs, and EOR processes. For the majority of cases, the main objective of drilling horizontal wells is to offer a larger area of flow. This makes horizontal drilling very attractive in primary production. In addition, for the same flow rate, pressure drop per foot at the horizontal well is smaller than that for a vertical well so that the horizontal well is more attractive than a vertical well in many enhanced oil recovery applications and in situations where water or gas coning is a problem. In Saudi Arabia, horizontal wells have been successfully drilled through reservoirs with different characteristics such as tight to highly permeable limestone, extremely porous and permeable dolomite and dolomitic limestone, and highly permeable unconsolidated sandstone.[1] In the Yowlumne field, the horizontal well has been applied in the thin Stevens Sand that could not be economically developed using vertical wells. In the latter case, the horizontal well has produced at more than three times the rate of previous vertical wells.[2]

Despite the successful applications of horizontal well in many oil and gas fields throughout the world, production results from the horizontal well have been often disappointing due to what is believed to be formation damage. Over the last few years, this problem has been extensively addressed in the literature trying to understand the damage mechanisms since formation damage effects may be more significant in horizontal wells. Numerous studies conducted by service companies, operators, and joint industry-university research projects examining formation damage and completion impairment caused by drilling and completion related operations have been reported.[3-8] The results indicate that such a problem can lead to significant productivity impairment of horizontal wells.

However, little attention has been paid to the economic impact of the poor productivity in horizontal wells due to formation damage. Usual economic justification for a well drilled horizontally is based on productivity improvement of about 2 to 2.5 times without any attention to considerations of effects of formation damage.[9] Specifically, there have been no significant efforts to convert such productivity impairment (meaning loss in production) to the economic loss in horizontal wells compared to that of vertical wells. On the other hand, the results of the economic evaluation on drilling horizontal wells where formation damage is a serious problem should be the key in determining whether to drill a horizontal well or not.

The purpose of this paper is to present an approach for evaluating the economic advantage of a horizontal well as compared to the vertical well case where the impact of formation damage is significant.

The approach presented in this paper uses concepts of production loss analysis and the maximum cost ratio (MCR), respectively, to evaluate short and long term production and economic performances. MCR here is defined as the ratio of horizontal-to-vertical well drilling and completion costs arriving at the ratio of net present values of unity.[9] By this definition, the economic advantage of a horizontal well application over a vertical one will be more significant in the sense of more relaxed expenditure when the MCR value is considerably high.

Theoretical Background

Formation Damage Characterization. To account for the effect of formation damage on well productivity, the distribution of damage should be first examined. In this regard, it is believed that the distribution of damage surrounding a horizontal well is neither radial nor distributed evenly along the well. Using a numerical simulator to model mud filtrate invasion into the formation, Frick and Economides[10] suggested that the damage distribution around a horizontal wellbore would essentially resemble a truncated elliptical cone with the larger base near the vertical section of the well. Their analytical expression for the "equivalent" skin effect in an anisotropic reservoir is derived and given by the following equation.

$$S_h = \left(\frac{k_u}{k_s} - 1\right) \ln\left[\frac{1}{\beta + 1} \times \sqrt{\frac{4}{3}\left(\frac{a_{max}^2}{r_w^2} + \frac{a_{max}}{r_w} + 1\right)}\right] \qquad (1)$$

where a_{max} is the horizontal half-axis of the damage cone near the vertical section. As the truncated-cone shape implies, the above equation assumes that the damage radius at the tip of the horizontal well is negligible and that the damage distribution is not uniform. If the damage is uniform and the formation is isotropic, Eq. (1) would be identical to the following well-known Hawkins formula for the vertical skin factor equation.

$$S_v = \left(\frac{k_u}{k_s} - 1\right) \ln\frac{r_d}{r_w} \qquad (2)$$

Effect of Formation Damage on Well Performance. There are numerous equations for predicting performance of a horizontal well. For the purpose of this study, we used the equation proposed by Permadi for pseudo-steady state flow condition as given by Eq. (3).[11]

$$q_h = \frac{k_h h L (P_e - P_{wf})}{141.2\mu B\left[0.523\left(X_e - Y_e\sqrt{h/L}\right) + \beta h\left\{\ln\left(\frac{Y_e}{2r_w}\sqrt{h/L}\right) - 0.5 + S_h\right\}\right]} \qquad (3)$$

where S_h is given by Eq. (1).

For a vertical well this was calculated based on the semi-steady state flowrate of a well located at the center of a circular drainage area and is given by Eq. (4).

$$q_v = \frac{k_h h (P_e - P_{wf})}{141.2\mu B\left[\ln\left(\frac{r_e}{r_w}\right) - 0.5 + S_v\right]} \qquad (4)$$

where S_v is given by Eq. (2).

Well Production Loss Analysis. Based on the definitions of productivity index and flow efficiency and applying Eqs. (3) and (4), a comparison of horizontal and vertical well production losses due to formation damage at the same pressure drawdown may be defined. This so-called Loss Ratio (LR) is written as[12]

$$\text{Loss Ratio} = \frac{\Delta q_h}{\Delta q_v} = \frac{J_{h-ideal}(1 - FE_h)}{J_{v-ideal}(1 - FE_v)} \qquad (5)$$

where productivity index, J, and flow efficiency, FE, are defined by Eqs. (6) and (7), respectively.

$$J = \frac{q}{\Delta P} \qquad (6)$$

$$FE = \frac{J_{damage}}{J_{ideal}} \qquad (7)$$

Decline Curve Analysis. A common decline curve analysis following Arps' method was used in this study to predict the performance of both vertical and horizontal wells. In this case we used a non-exponentially production decline, *i.e.* $b \neq 0$, as shown by the following equation.[9]

$$\frac{q(t)}{q_{inst}} = \frac{1}{\left(1 + bD_i t\right)^{1/b}} \tag{8}$$

The instantaneous rate, q_{inst}, was determined by Eq. (3) or (4) for horizontal or vertical well cases, respectively.

Following Arps, Fetkovich[9] has defined initial production decline rate as given by Eq. (9).

$$D_i = \frac{\left(q_i\right)_{max}}{N_{pi}} \tag{9}$$

where $(q_i)_{max}$ for either horizontal or vertical well case is taken at P_{wf} equal to zero and P_e equal to P_i in Eqs. (3) or (4), respectively. N_{pi} for vertical wells is given by Eq. (10) and for horizontal wells is given by Eq. (11).

$$N_{pi} = \frac{\pi\left(r_e^2 - r_w^2\right)\phi\, c_t\, h\, P_i}{5.615B} \tag{10}$$

$$N_{pi} = \frac{\left(Ah - \pi\, r_w^2\, L\right)\phi\, c_t\, P_i}{5.615B} \tag{11}$$

Methodology

In essence, this study used a methodology that is similar to our previous work.[9] The exception is that we now include the effects of formation damage. These effects were incorporated into the calculation procedure by applying the skin factors for both horizontal and vertical well performances as shown by Eqs. (1) through (4). Based on the performance of each well with both damaged and undamaged conditions, production losses from which the horizontal-to-vertical production-loss ratio is obtained using Eq. (5) were calculated. A parametric analysis on the production-loss ratio was then conducted based on several reservoir and economic conditions to investigate the effects of formation damage severity on well performances. The maximum cost ratio (MCR), which is defined as in our previous study,[9] was obtained based on the calculation of horizontal-to-vertical well drilling and completion costs ratio at various conditions including reservoir and economic parameters. Such parameters are damage penetration, formation permeability, the ratio of original formation permeability to permeability in the damage zone (k_u/k_s), and oil price. The calculation of MCR was then extended for conditions where the formation damage has been removed by matrix acidizing. For this purpose, the calculation of acid requirements was based on the so-called two-mineral model.[13]

The case we considered in this study for evaluating the economic advantage of horizontal well when the damage can be removed is divided into two parts: (1) the damage is totally removed and (2) the damage is partially removed. Although we believe that the total damage removal is not the case that usually possible in practice, it is certainly the most optimum treatment and extreme situation for comparing the economics of well production gained after treatment. In contrast, the second part of our case is considered as the practicable treatment. To predict the performance of the wells after partial damage removal, we used the skin "equivalent" proposed by Frick and Economides[10] for the horizontal well case and Hawkins formula for the vertical well case provided that the permeability for representing both treated and untreated zones can be approximated using serial flow averaging technique.

Data and Results

The reservoir used in this work is the same as that in our previous work.[9] The pertinent data of both reservoir and economic parameters are shown in **Table 1**. Note that this study is a well-to-well basis comparison meaning that both horizontal and vertical wells produce the oil from the same reservoir. Accordingly, the parametric analysis involved only the well geometry and several reservoir variables that affect the severity of formation damage. These parameters are damage penetration, reservoir permeability, and the ratio of original permeability to damaged permeability (k_u/k_s). Government tax employed was 48 % and the operating cost of the horizontal well was 25 % higher than that of the vertical well as we considered the typical condition of offshore operations in Indonesia. In this particular study, a fixed capital cost of 2 MM US dollars and 4 MM US dollars for drilling and completing a vertical well and a horizontal well, respectively, are assumed. The only economic parameter altered in this study was the oil price.

The ratio of production loss was then calculated for various k_u/k_s at various damage radii. This is shown in **Fig. 1** for isotropic reservoirs. For the same various formation damage conditions, the MCR was then calculated at several reservoir permeability values. Typically, the results are presented in **Fig. 2** for k = 300 mD and **Fig. 3** for k = 60 mD both of which employed the oil price of $15 a barrel. To investigate the effects of market environment, the MCR was also calculated at various oil prices for the same formation damage radii and reservoir permeability with k_u/k_s of 20.0. These are shown in **Fig. 4** for k = 300 mD and **Fig. 5** for k = 60 mD. The MCR was also examined whether it is correlable with the common economic indicator, NPV. For this purpose, the MCR is presented as a function of the present worth at various damage severity and damage radii. The results are shown in **Fig. 6** for k = 300 mD and **Fig. 7** for k = 60 mD. As can be seen on these two figures, we have used a parameter called ΔNPV, which is defined as the difference of the present worth of both wells after the economic abandonment rate has been reached. This is simply obtained by subtracting the NPV of the vertical well from that of the horizontal well. The correlation of MCR to the NPV was also examined for the effect of the oil price as shown by **Fig. 8**. And finally, the production improvement ratio (IR) – defined here as the ratio of horizontal-to-vertical well incremental production as results of damage removal in both wells – and the MCR were calculated for the condition after acid treatment. The results for partial damage removal case are shown in **Fig. 9** and **10.** Fig. 9 shows the LR and the IR plots against damage radius and Fig. 10 shows the MCR versus ΔNPV. We intentionally do not present the results for the case of full damage removal, as we will discuss in the following section. In the case when a reservoir is anisotropic, we run the loss ratio and MCR calculations at the same damage condition. The two parameters were then plotted against damage radius for a particular value of reservoir permeability at a fixed oil price. The results are shown in **Fig. 11** and **12**.

Discussion

Fig. 1 shows the effect of damage radii on the production loss ratio for 300-mD case. For other cases, the results are closely the same. It reveals that the loss ratio decreases as the damage penetration increases. The shape of the curve also suggests that once the damage exist even with very shallow penetration, horizontal wells will suffer the worse condition resulting in sharp drop of production compared to vertical wells. However, the effect of damage condition is much more pronounced in the vertical well compared to that in the horizontal well when the damage penetration is getting deeper. For example, the undamaged condition will provide the horizontal well rate of 17,014.6 STB/d and the vertical well rate of 1,875.9 STB/d. When there is formation damage with a penetration of 0.01 ft with $k_u/k_s = 20$ the rate drops to 9,667.0 STB/d and 1,771.3 STB/d, yielding the production losses of 7,347.6 STB/d and 104.6 STB/d, for the horizontal and vertical wells, respectively. However, if the damage has a penetration of 2.6 ft, the production losses for the horizontal and vertical wells are 10,939.2 STB/d and 1,553.5 STB/d, respectively. When these production losses are converted to dollars, using oil price of US$15 a barrel, the dollar loss would be US$110,214.1 for the horizontal well and US$1,568.8 for the vertical well at the damage penetration of 0.01 ft and US$164,087.8 for the horizontal well and US$23,301.9 for the vertical well at the damage penetration of 2.6 ft. Furthermore, as can be seen on the figure, the smaller the ratio of original permeability to damage permeability, k_u/k_s, the smaller the loss ratio. This means that the production loss due to formation damage in horizontal wells are much more significant than that of vertical wells when converted to dollars especially in the cases of more severe permeability reduction within the damage region.

Fig. 2 and Fig. 3, respectively for 300 mD and 60 mD reservoirs, show the effect of damage penetration on the economic consideration for a horizontal well application in a sensitive formation. As the definition implies, any calculated MCR value, that is higher than the ratio of horizontal-to-vertical drilling and completion costs (or capital cost ratio, CCR), would provide a better economic opportunity in implementing the horizontal well. However, we all believe that formation damage must be prevented in all cases, horizontal and vertical wells. Thus, for our case of a high permeability reservoir (see Fig. 2), the horizontal well application is not economically attractive, except if a very severe damage could not be possibly prevented in the vertical well. Note that this particular study uses a CCR of 2.0. This means that the horizontal well application would be economically attractive when the MCR is greater than 2.0. The magnitude of the difference, *i.e.* (MCR – CCR), may represent a measure of the economic attractiveness. The bigger the difference, the more attractive or the more relax in planning the horizontal well design and future jobs in an effort for improving the production performance.

We have actually calculated for 300, 100, 60, and 15 mD cases. A typical results for a relatively low permeability case is shown in Fig. 3. The interesting results obtained here is that, unlike for the high permeability case as shown in Fig. 2, the calculated MCR for the 60 mD case has values greater than the given CCR of 2.0, at all the damage conditions. In general, results obtained suggest that a horizontal well has a better economic advantage over a vertical well for sensitive reservoirs having low to intermediate permeability.

Overall at this point, although the short-term production loss ratio increases with the degree of damage severity, it appears that a horizontal well is more economically attractive than a vertical well especially in a relatively low permeability reservoir. Besides, from the reservoir management standpoint, the use of a horizontal well can increase producing rate and thus accelerate reserve production.

Fig. 4 and Fig. 5 is the plot of MCR versus oil price for reservoir permeability of 300 mD and 60 mD, respectively. These results demonstrate that the advantage of using horizontal well is more notable at higher oil prices as shown by high values of MCR. A further observation on the figures concludes that the advantage is also affected by the damage penetration. The larger penetration will result in the more significant advantage of the horizontal well. Furthermore, it is shown by these figures that for the smaller permeability of the reservoir, the effect of k_u/k_s on the MCR is also smaller. This means that the effect of damage severity on MCR is less significant for low-permeability reservoirs. Nevertheless, these results demonstrate that the application of a horizontal well to a low permeability, very sensitive reservoir with deep damage would require an oil price of higher than 13 dollars a barrel for the CCR of 2.0.

The MCR used in our approach appears to be correlable with the common economic indicator, NPV. Fig. 6 and Fig. 7 display this evidence for both values of reservoir permeability. An interesting outcome is that the curves for cases with high k_u/k_s's lie on the same line. For cases with low k_u/k_s (see the curves for $k_u/k_s = 2$ and $k_u/k_s = 5$) the curves are off the line and exhibit small range of economic advantage for the same range of damage penetration. Again, the application of horizontal well appears to be more attractive in low-permeability reservoirs as shown by positive ΔNPV and the MCR values of higher than 2.0.

Fig. 8 shows the relation of the MCR and ΔNPV at various oil prices. This figure demonstrates the advantage of using horizontal wells compared to vertical wells when the oil price is considerably higher. This is also shown by the MCR values of higher than 2.0 when the oil price is at least $14/bbl at all damage radii. If the oil price is less than $14/bbl the horizontal well is still attractive as long as the radius of damage is considerably large. However, if the oil price is less than $11/bbl then the horizontal is not attractive at all for any cases of damage penetration.

When the damage has been removed by acidizing, all evidences are completely different. Fig. 9 and Fig. 10 display the results of partial damage removal, which is considered as the more realistic case. For our specific purpose, the case was considered only for r_d of 1.5, 2.0, and 3.0 to depict the formation damage that is unworkable for full removal. As can be observed in Fig. 9, the analysis of production improvement resulted from acidizing treatment can be misleading. The instantaneous production after treatment surely increased by about 3 to 5 times the production before treatment. However, the economic analysis of the project indicates the reduction of the advantage of horizontal wells as shown by negative ΔNPV and the MCR of less than 2.0. This is shown in Fig. 10. Thus, handling sensitive formation when a horizontal well is applied may not always be viable economically. In this regard, to the best of our knowledge, no one has reported the success of horizontal well acidizing and, as a result, underbalanced horizontal drilling may be more effective in handling sensitive formation since the damage, if any, is considered irreparable technically.

As we have noted, we run the calculation of all parameters considered in this study for both partial and full damage removal cases although, as we have also noted, the full damage removal is beyond the viable practice. For several reasons, however, we presented only the results for the case of partial removal. In our experience, the volume of mud acid requirement determined by the two-mineral model was occasionally unrealistic for full removal. This indeed affected the economics of horizontal well acidizing. Regardless this problem, we found that the partial removal is economically more attractive than full removal due to the lower cost of acid. In addition, we also found that the loss ratio is higher than that of full removal case, as expected. Nevertheless, these findings are subject to further study.

Fig. 11 and 12 demonstrate the results of an anisotropic reservoir case. Here we present results for a reservoir with the horizontal permeability of 60 mD and vertical permeability of 20 mD. All evidences in the isotropic case are also observed in the anisotropic one. For example, the plot of production loss ratio versus damage radius exhibits similar appearance. The only difference between the two cases is that the loss ratio is slightly higher when the anisotropy exists, as shown by Fig. 11, especially for low k_u/k_s. The effect of damage severity on the MCR performance is shown in Fig. 12. As compared to the isotropic case (see Fig. 3), reservoir anisotropy with k_h/k_v = 3.0 reduces the MCR, depending on the damage condition. The reduction in MCR increases with the damage severity, implying that the long term production loss in a vertical well due to wellbore damage gets even bigger than that in a horizontal well as the damage condition gets severe. However, this typical degree of anisotropy still yields a good economic shape for a low permeability case.

Concluding Remarks

The following are the summary and the conclusions withdrawn from this work.

1. A new approach for economic evaluation of horizontal well advantage in a sensitive formation has been developed using concepts of production loss analysis and maximum cost ratio, MCR.
2. Based on the instantaneous production loss analysis, the economic loss due to formation damage can be much higher in horizontal wells when converted to dollars.
3. Based on the MCR analysis, the investment cost limit for drilling horizontal well is controlled primarily by damage penetration (*i.e.* damage severity), reservoir permeability, and market environment (oil price).
4. It has been shown that the horizontal well project would be economically attractive when the calculated MCR is greater than the given capital cost ratio, CCR.
5. The MCR appears to be well correlated with other economic indicators as we have shown its relationship with the NPV.
6. A further study on economics of damage removal should be conducted.

Nomenclature

A = Drainage area, Acres
B = Reservoir formation volume factor, bbl/STB
b = Power of the instantaneous rate, dimensionless
c_t = Total compressibility, psi^{-1}
D_i = Initial production decline rate, t^{-1}
FE_h = Flow efficiency for horizontal well, dimensionless
FE_v = Flow efficiency for vertical well, dimensionless
h = Reservoir thickness, ft
J = Productivity index, STB/d/psi
J_{damage} = Productivity index (with damage), STB/d/psi
J_{ideal} = Productivity index (without damage), STB/d/psi
$J_{h\text{-}ideal}$ = Productivity index for horizontal well without damage, STB/d/psi
$J_{v\text{-}ideal}$ = Productivity index for vertical well without damage, STB/d/psi
k_h = Lateral permeability, mD
k_s = Permeability in the damage zone, mD
k_u = Undamaged zone permeability, mD
k_v = Vertical permeability, mD
L = Horizontal well section length, ft
N_p = Cumulative production, STB
N_{pi} = Maximum recoverable production, STB
P_e = Pressure at the outer edge of drainage area, psi
P_i = Initial reservoir pressure, psi
P_{wf} = Bottomhole flowing pressure, psi

ΔP = Pressure drawdown, psi
$q(t)$ = Production rate, STB/d
$(q_i)_{max}$ = Maximum production rate at $P_{wf} = 0$, STB/d
q_{inst} = Instantaneous production rate, STB/d
Δq_h = Horizontal well production loss due to damage, STB/d
Δq_v = Vertical well production loss due to damage, STB/d
r_e = Radius of drainage area, ft
r_d = Damage radius, ft
r_w = Well radius, ft
S_h = Skin factor for horizontal well, dimensionless
S_v = Skin factor for vertical well, dimensionless
X_e = Drainage area width (perpendicular to the well), ft
Y_e = Drainage area length (parallel to the well), ft
$\beta = \sqrt{k_h / k_v}$
μ = Viscosity, cp
ϕ = Porosity, fraction
π = 3.141 592 654 …

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SI Metric Conversion Factors

cp	× 1.0*	E–03 = Pa.s
ft	× 3.048*	E–01 = m
mD	× 9.869 233	E–04 = μm^2
psi	× 6.894 757	E+00 = kPa
bbl/d	× 1.589 873	E–01 = m^3/d

*Conversion factor is exact

TABLE 1 – DATA USED

Drainage area, A (acres)	= 250	Well radius, ft	= 0.4
Reservoir thickness, h (ft)	= 50	Damage radius, ft	= 0.41, 0.425, 0.45, 0.5, 0.55, 0.6, 0.7, 0.8, 0.9, 1.2, 1.5, 2.0, 3.0
Initial reservoir pressure, P_i (psi)	= 1900		
Flowing bottomhole pressure, P_{wf} (psi)	= 800		
Oil viscosity, μ (cp)	= 7	Ratio of original permeability to damaged permeability, k_o/k_s	= 2, 5, 10, 15, 20
Oil formation volume factor, B_o, (bbl/STB)	= 1.12	Lateral permeability, k_h (mD)	= 15, 60, 300
Porosity, fraction	= 0.28	Vertical permeability, k_v (mD)	= 15, 20, 300
Total compressibility, c_t (psi^{-1})	= 2.50E-05	Oil price, US$/STB	= 10, 11, 12, 13, 14, 15
Production decline curve exponent, b	= 0.3		
Horizontal well length , L (ft)	= 2000		
Government tax, %	= 48		
Capital cost, US$	= 2,000,000 (vert. well) = 4,000,000 (hor. well)		
Operating cost, US$/STB	= 5.00 (vert. well) = 6.25 (hor. well)		

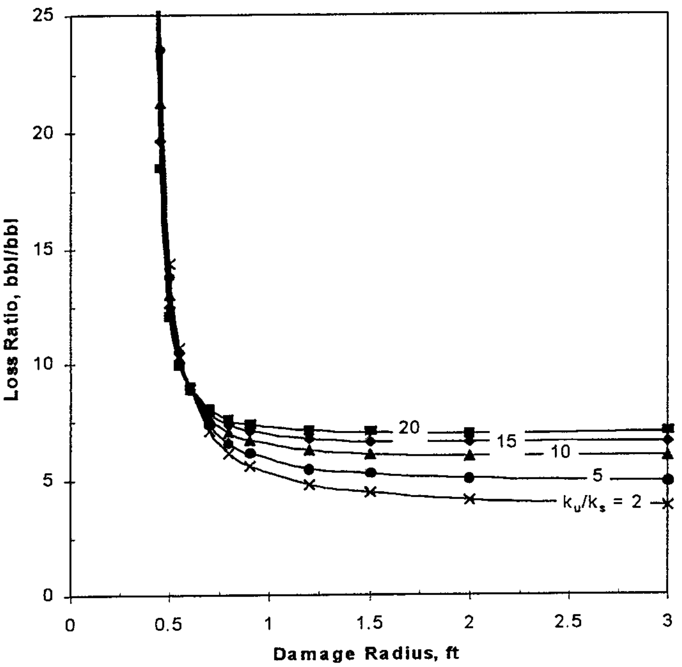

Fig. 1— Production loss ratio vs. damage radius for an isotropic reservoir with permeability of 300 mD and various k_u/k_s.

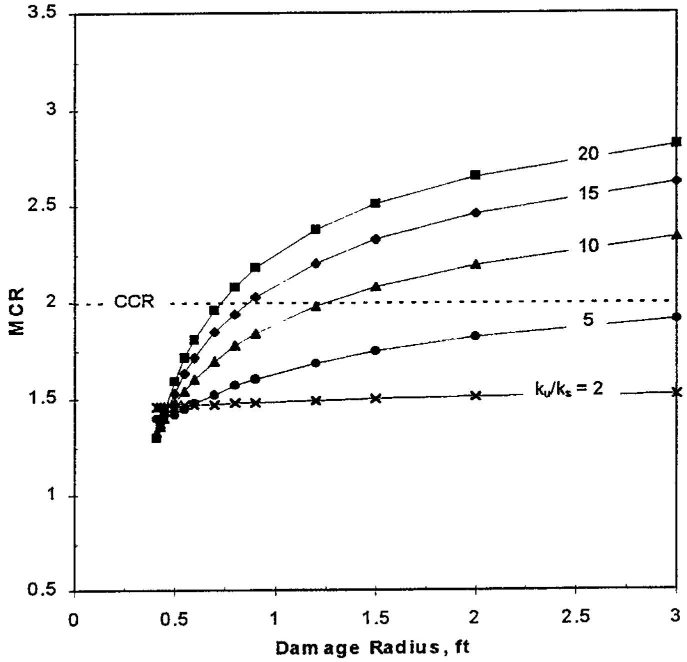

Fig. 2— MCR vs. damage radius for an isotropic reservoir with permeability of 300 mD and various k_u/k_s at oil price of US$ 15.0/bbl.

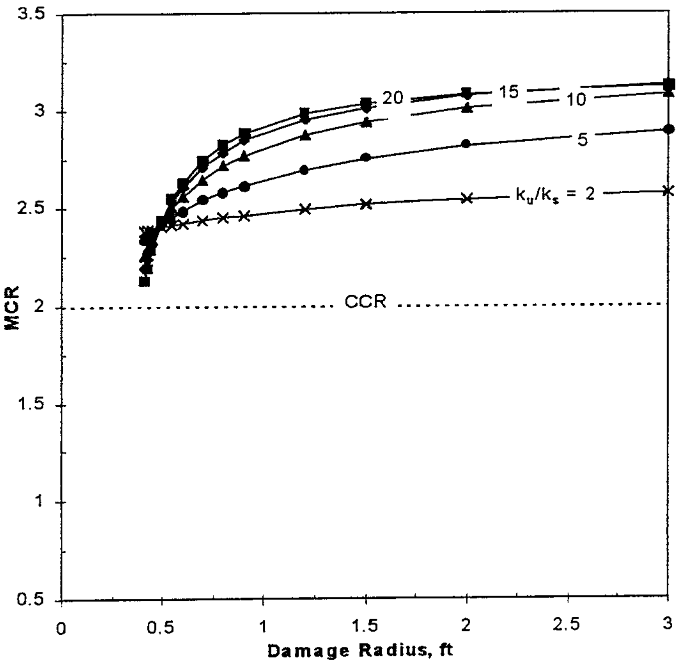

Fig. 3— MCR vs. damage radius for an isotropic reservoir with permeability of 60 mD and various k_u/k_s at oil price of US$ 15.0/bbl.

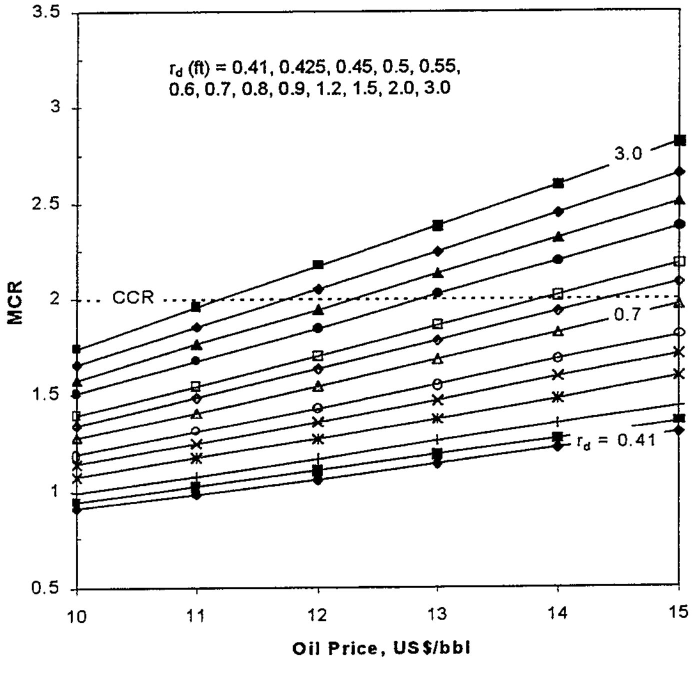

Fig. 4— MCR vs oil price for an isotropic reservoir with permeability of 300 mD, k_u/k_s = 20, and varied damage radius.

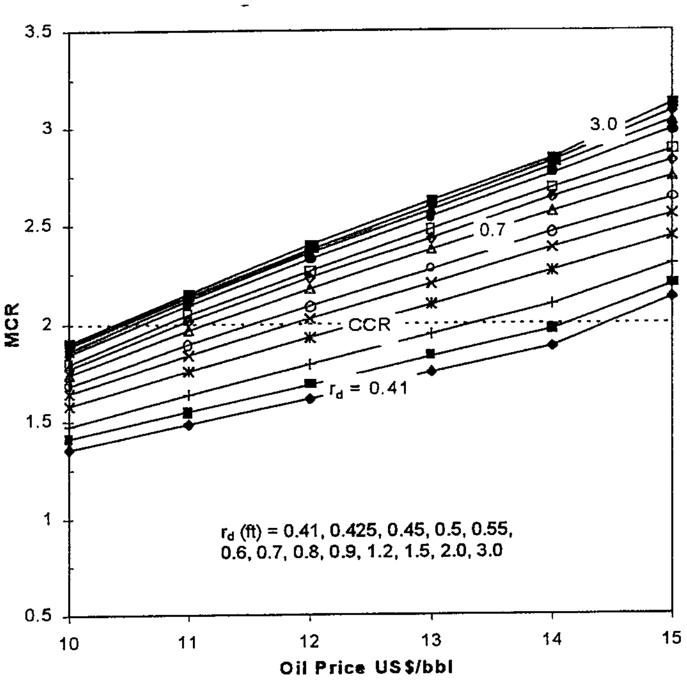

Fig. 5— MCR vs oil price for an isotropic reservoir with permeability of 60 mD, k_u/k_s = 20, and varied damage radius.

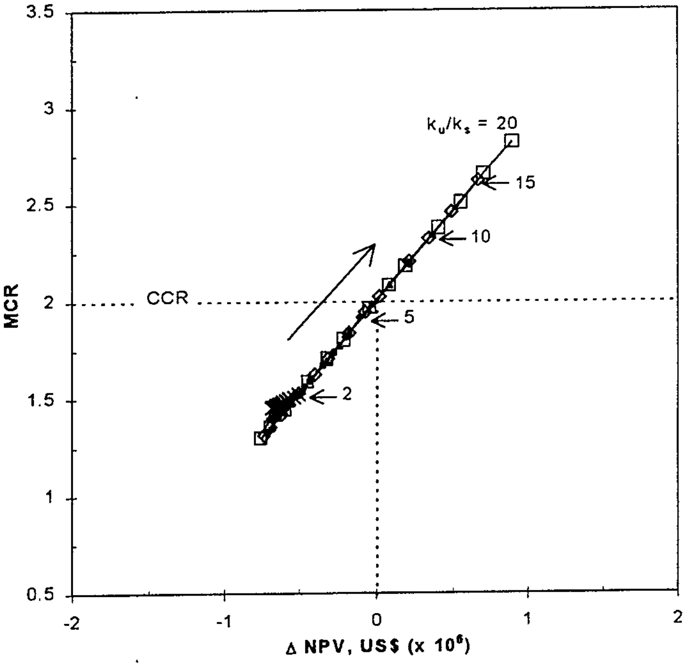

Fig. 6— MCR vs. ΔNPV for an isotropic reservoir with permeability of 300 mD and various k_u/k_s at oil price of US$ 15.0/bbl. Arrow sign indicates increasing r_d from 0.41 to 3.0 ft.

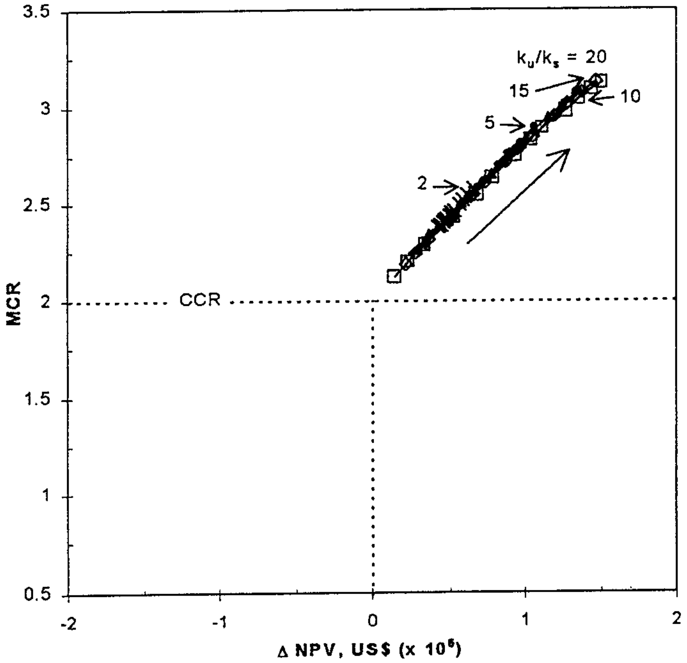

Fig. 7— MCR vs. ΔNPV for an isotropic reservoir with permeability of 60 mD and various k_u/k_s at oil price of US$ 15.0/bbl. Arrow sign indicates increasing r_d from 0.41 to 3.0 ft.

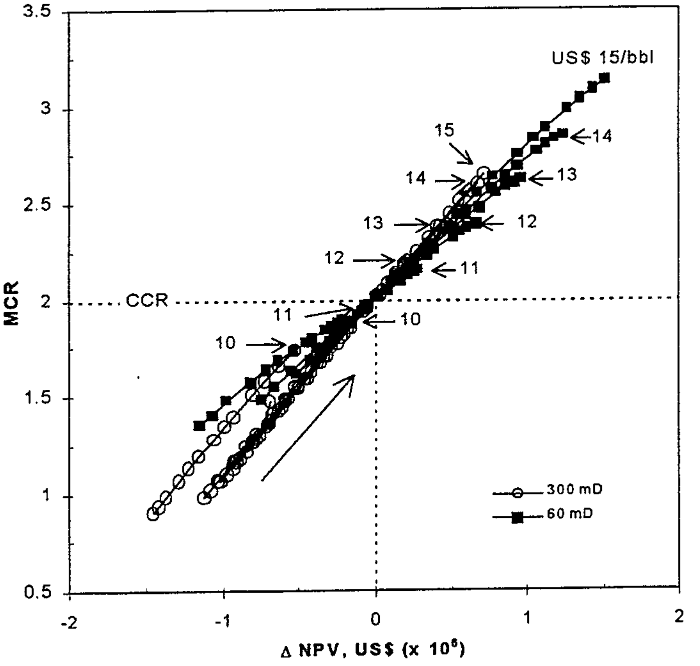

Fig. 8— MCR vs. ΔNPV for two isotropic reservoirs with permeability of 300 and 60 mD and, k_u/k_s = 20, and varied oil price. Arrow sign indicates increasing r_d from 0.41 to 3.0 ft.

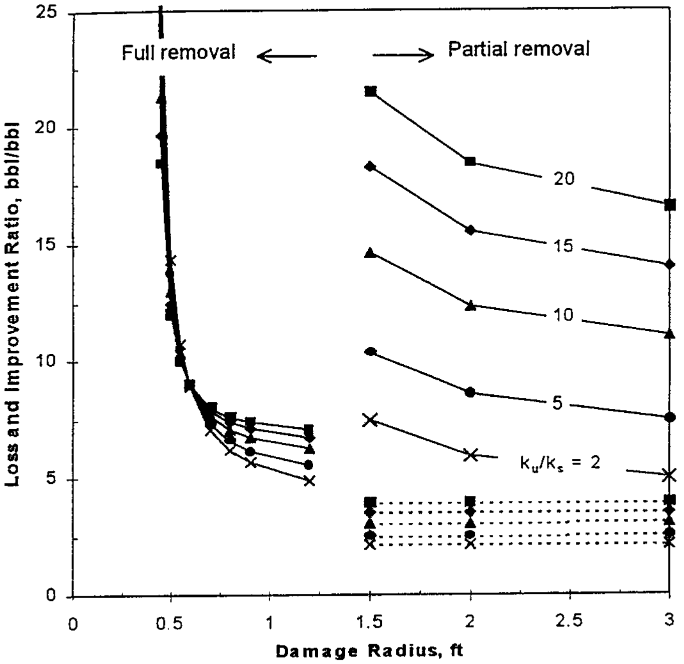

Fig. 9— Loss and improvement ratio vs. damage radius after partial damage removal for an isotropic reservoir with permeability of 300 mD and various k_u/k_s. Solid lines indicate improvement ratio curves and dashed lines indicate loss ratio curves.

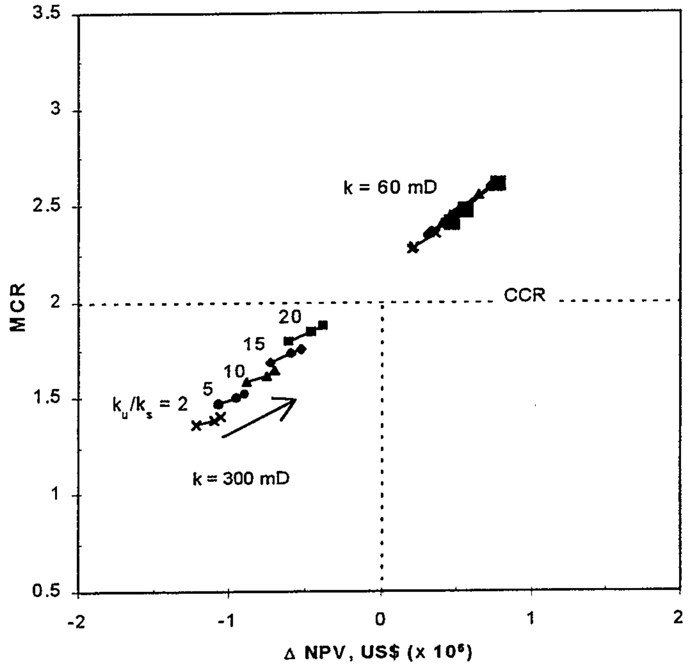

Fig. 10— MCR vs. ΔNPV after partial damage removal for an isotropic reservoir with permeability of 300 dan 60 mD, at oil price of US$ 15.0/bbl, and varied k_u/k_s. Arrow sign indicates increasing r_d from 1.5 to 3.0 ft.

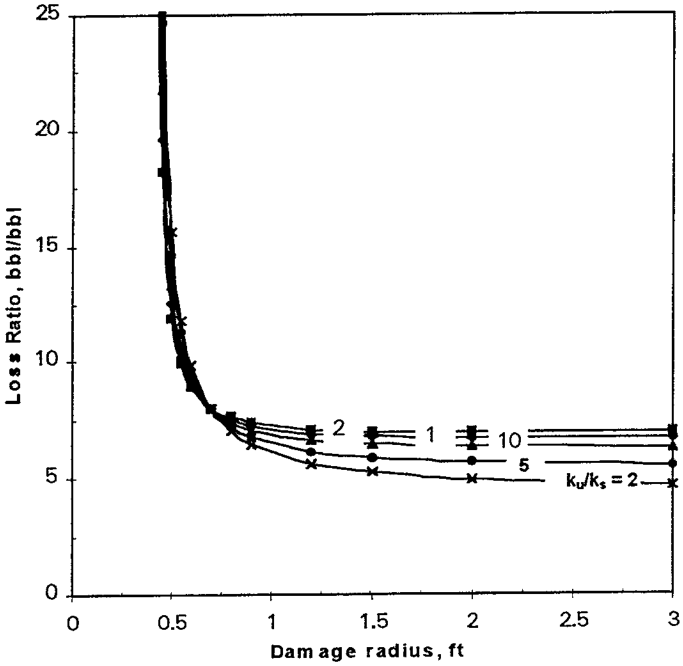

Fig. 11— Loss ratio vs. damage radius for an anisotropic reservoir with k_h = 60 and k_v = 20 mD and various k_u/k_s.

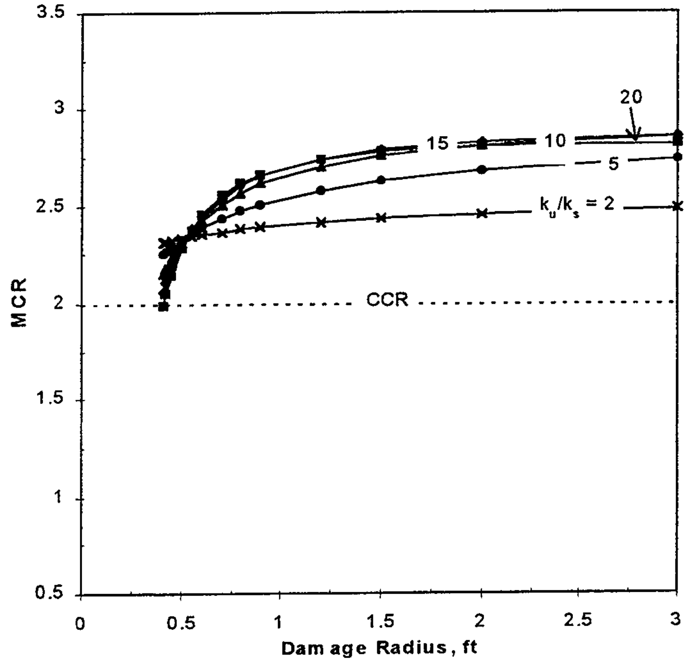

Fig. 12— MCR vs. damage radius for an anisotropic reservoir with k_h = 60 and k_v = 20 mD, at oil price of US$ 15.0/bbl and various k_u/k_s.