# Well Productivity Enhancement by Drilling Multi-Legged Wells A Quantitative Assessment

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*Forked well, multi-legged well, multilateral well, geothermal well productivity, well productivity enhancement*

## ABSTRACT

This paper presents an analysis of the well productivity enhancement possible by drilling multi-legged (or "forked" or "multilateral") wells in geothermal fields at temperatures in the 100 to 250°C range. A parameter, Productivity Enhancement Factor ("PEF"), is introduced to quantify productivity enhancement; it is defined as the ratio of the downhole productivity index of the multi-legged well to that of the original hole before the forked leg was added. Assuming the original hole to be vertical, it is shown that PEF rises sharply with deviation angle of the forked leg upto about 5 degrees; beyond this, PEF continues to increase with deviation angle albeit at a slower rate. A deviation angle of 25 to 30 degrees gives the highest percent increase in PEF per meter drilling of the forked leg (for a two-legged well) or legs (for a three-legged well). PEF is not significantly affected by reservoir temperature and declines rapidly with flow time for a few weeks before the decline rate stabilizes; PEF becomes nearly constant after a year or two of flow. The tighter the reservoir rock the more effective it is, in general, to enhance well productivity by drilling multi-legged wells. PEF of a two-legged well does not exceed a value of 2 unless the skin factor in the forked leg is less than in the original hole, in which case it can reach a value perhaps as high as 2.5. A three-legged well can provide up to 50% more PEF than a two-legged well, everything else being equal. Not only does a three-legged well pose a higher drilling risk, it is less effective in enhancing well productivity per unit drilling cost. Only where the original hole and the first forked leg both prove disappointing in productivity, drilling a second forked leg may be worthwhile.

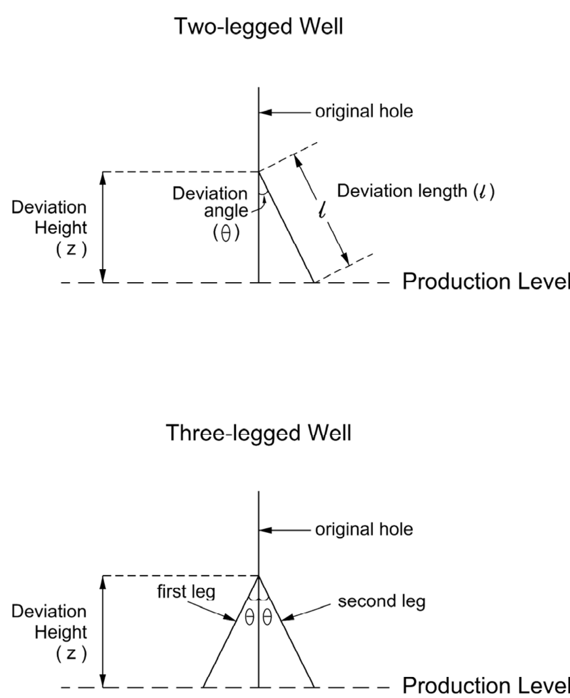


**Figure 1.** Definitions.

## Introduction

Drilling of multi-legged (or "forked" or "multi-lateral") wells, that is, wells with two or more "legs" open to production from the reservoir, is a means of increasing geothermal well productivity. Drilling such wells has been practiced for the past two decades at The Geysers steam field in California (Henneberger *et al*, 1995; Steffen, 1993; Yarter *et al*, 1988). Multi-legged wells have also been drilled at the Raft River hot water field in Idaho. Our experience shows that a 30% to 80% increase in well productivity is typically achievable by forked well drilling for a 30% to 50% incremental increase in drilling cost. However, it is not clear how the reservoir rock and fluid properties or the geometry of deviation of the forked legs affect this productivity enhancement. Unfortunately, the empirical database is not sufficiently extensive to resolve this issue. Therefore, we have conducted in this paper a theoretical analysis of the productivity enhancement achievable from forked wells over the typical ranges of reservoir rock and fluid properties and geometry of deviation of the forked legs.

## Analysis Methodology

For this analysis we have introduced a dimensionless parameter named Productivity Enhancement Factor (PEF). This parameter is defined as the ratio of the downhole productivity index (that is, mass production rate available per unit pressure drawdown) of the multi-legged well to that of the original hole before the forked leg was drilled. In other words, PEF of a multi-legged well, after production for a given time period (t), is given by:

$$PEF(t) = PI(t)/PI_o(t), \tag{1}$$

where PI(t) = downhole productivity index of the multi-legged well after a flow time t , and

$PI_o(t)$ = downhole productivity index of the original hole at flow time t.

We have assumed the original hole to be vertical and the forked leg to be drilled from the original hole from a certain height above the production level in the reservoir; we refer to this height as the deviation height. We refer to the angle between the forked leg and the original hole at the point of deviation as the deviation angle. In reality, the deviation angle is the final angle between the original hole and the forked leg after this angle has been built up over a few tens to a few hundred meters of drilling the leg. The definitions of the parameters introduced above are illustrated in Figure 1. Furthermore, we have assumed for this analysis that the reservoir flow and storage capacities are the same at the production level of the original and forked legs.

We have defined PI as:

$$PI = W/\Delta p, \tag{2}$$

$$\text{Where} \quad \Delta p = p_i - p. \tag{3}$$

In equation (3), $p_i$ is initial static pressure in the reservoir and p is flowing bottom hole pressure at the well, which will decline with time if the well is produced at a constant rate W. It should be noted that Δp is more commonly defined as ($\bar{p}$ -p), where $\bar{p}$ is the average static reservoir pressure. Therefore, for a well flowing at a constant rate, p (and consequently PI) declines with time. This decline trend in PI is a function of the hydraulic properties and boundary conditions of the reservoir, and interference effects between the forked legs and the original hole. For such estimation, it is customary to utilize the so-called Line-Source Solution of the partial differential equation describing transient pressure behavior in a porous medium filled with a single-phase liquid (Earlougher, 1977). This solution gives the PI of a single-legged well in an infinite system using the nomenclature of Earlougher (1997) as:

$$PI = \frac{2\pi\,(kh)\,\rho}{\mu\, p_D}, \tag{4}$$

where kh = reservoir flow capacity,

ρ = fluid density,

μ = fluid viscosity, and

$p_D$ = a dimensionless variable that is a function of time.

In equation (4), $p_D$ is given by:

$$p_D = -\frac{1}{2}Ei\left(\frac{-r_D^{\,2}}{4t_D}\right) \tag{5}$$

where $t_D$ = dimensionless time

$= \frac{(kh)t}{(\phi c_t h)\mu r_w^{\,2}}$,

ϕ cth = reservoir storage capacity,

rD = dimensionless radius

= r/rw,

r = distance between the "line source" and the point at which the pressure is being considered (equal to wellbore radius if flowing wellbore pressure is being considered),

$r_w$ = wellbore radius, and

t. = time.

In equation (5), Ei represents the Exponential Integral, defined by

$$Ei(-x) = -\int_x^\infty \frac{e-u}{u}du \tag{6}$$

Equation (4) is true if the wellbore skin factor is zero, that is, if the wellbore flow efficiency is 100%, the well being neither damaged nor stimulated. Productive geothermal wells usually display a negative skin factors, which implies a "stimulated" well (that is, the wellbore flow efficiency is greater than 100%), because such wells intersect open fractures. If skin factor is negative, for the same flow rate *W,* pressure drop will be lessened by the amount:

$$\Delta p_{skin} = \frac{W\mu}{2\pi(kh)\rho}S \tag{7}$$

From the above discussion, it follows:

$$PEF = \frac{PI_1(t) + PI_2(t)}{PI_o(t)}, \tag{8}$$

where $PI_1(t)$ and $PI_2(t)$ are the downhole productivity indices at flow time t of the original leg and forked leg, respectively, taking into account the interference between the two legs, and $PI_o(t)$ is the PI of the original hole at a flow time t before the well was forked.

Interference between the legs of a multi-leg well will reduce the individual PIs of all legs. From equations (4) through (7) it is possible to calculate the pressure drawdown at a leg, and therefore its PI, in response to both its own production plus the interference effect of simultaneous production from the other legs; this is accomplished by the mathematical process of "superposition in space" of the Line-Source Solution, as describes below.

If n legs produce simultaneously, the PI of a leg *i* will decline with time according to

$$PI_i = \frac{2\pi(kh)\rho}{\mu\left[\sum_{i=1}^{n} W_i p_{Di}(t, r_i) + WS_i\right]}, \tag{9}$$

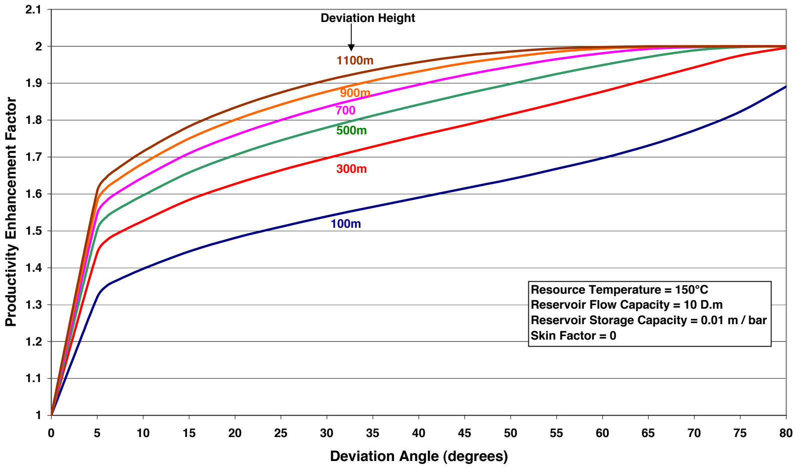


**Figure 2.** Productivity enhancement factor versus deviation angle and deviation height.

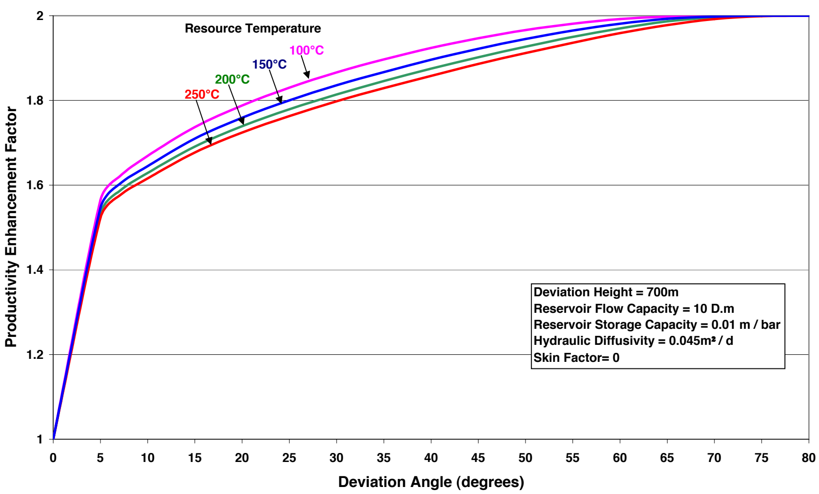


**Figure 3.** Productivity enhancement factor versus deviation angle and reservoir temperature.

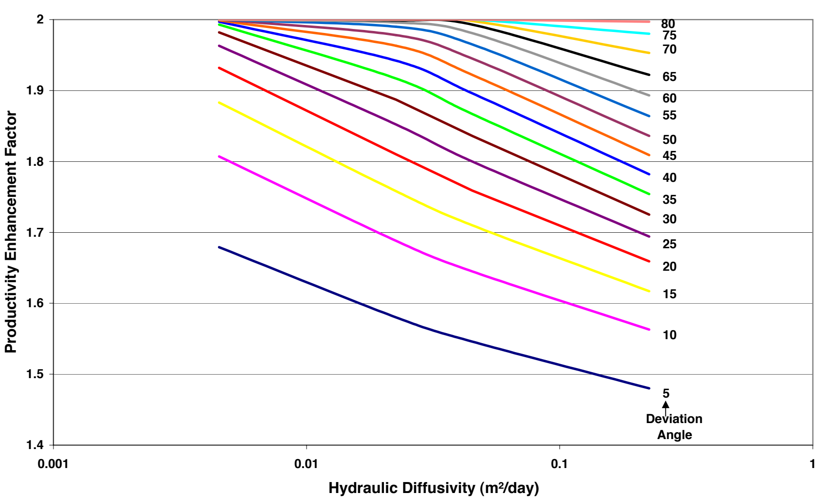


**Figure 4.** Productivity enhancement factor versus hydraulic diffusivity for a range of deviation angle values.

where $W_i$ and $S_i$ are the flow rate and skin factor, respectively, of leg *i,* and $r_i$ is the distance (at the production level) between the subject leg and leg i (i=1,….n). For the purposes of estimating PEF, we have considered the PI values after 7 days of flow, unless stated otherwise.

Based on the above discussion it can be shown that PEF is a unique function of the hydraulic diffusivity (α) of the reservoir, being defined as:

$$\alpha = \frac{kh}{(\phi c_t h)\mu}. \tag{10}$$

## Results for Two-Legged Wells

### *The Base Case*

Figure 2 presents the calculated PEF values as a function of deviation height and deviation angle for conditions typical of a field like Raft River: 150°C hot water reservoir, a reservoir flow capacity of 10 Darcy-meter, a reservoir storage capacity of 0.01 m/bar and skin factor of zero in both the original leg and forked leg. It should be noted that the above combination of reservoir flow and storage capacities and reservoir temperature is equivalent to a reservoir hydraulic diffusivity of 0.045 sq.m/day; we have considered this hydraulic diffusivity value to represent the base case condition for our subsequent analysis. Figure 2 indicates that, for all reasonable deviation heights, PEF rises sharply with deviation angle up to about 5 degrees; beyond this, the rate of increase in PEF with deviation angle slows down.

### *Sensitivity to Resource Temperature*

Figure 3 presents the calculated PEF values versus deviation angle and resource temperature for a deviation height of 700m, a hydraulic diffusivity of 0.045 sq.m/day, and a skin factor of zero in both the original and forked legs. From Figure 3 it is apparent that resource temperature does not affect PEF significantly, at least within the resource temperature range of 100° to 250° C. It should be noted that above a temperature of 250° C the reservoir is likely to have some steam saturation. When the reservoir contains steam saturation, any prediction of PEF is a futile exercise because PEF will be a sensitive function of this saturation, which is nearly impossible to estimate with any confidence. The results presented in this paper become progressively less applicable as reservoir temperature increases beyond 250°C. Although not discussed in this paper, the conclusions in this paper are equally valid for a single-phase steam reservoir.

### *Sensitivity to Hydraulic Diffusivity*

Figure 4 presents the calculated PEF values versus hydraulic diffusivity for a range of deviation angles from a deviation height of 700m, assuming a skin

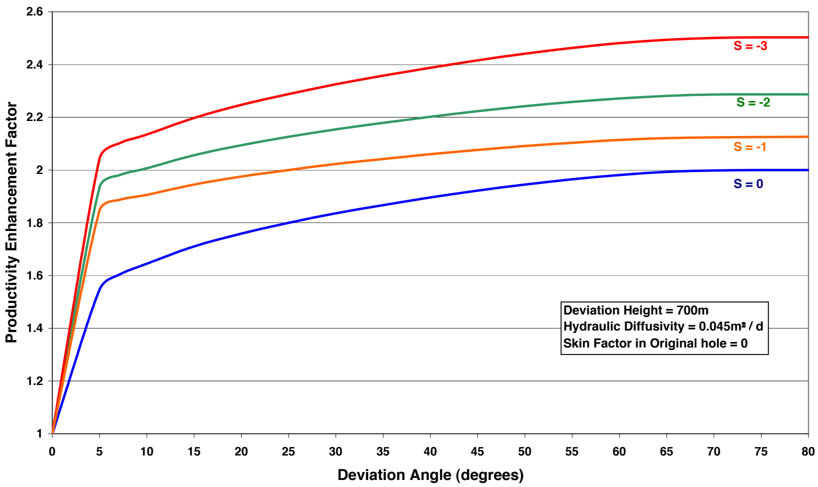


**Figure 5.** Productivity enhancement factor versus deviation angle and skin factor.

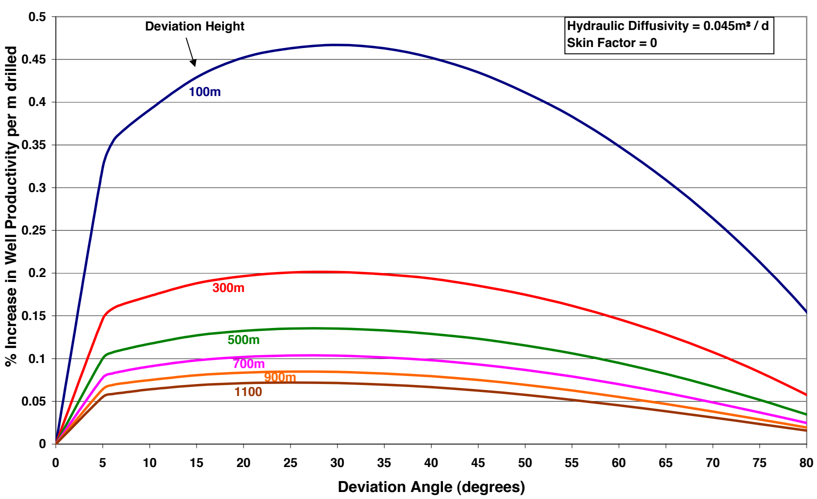


**Figure 6.** Percent increase in productivity per meter of drilling versus deviation angle and deviation height.

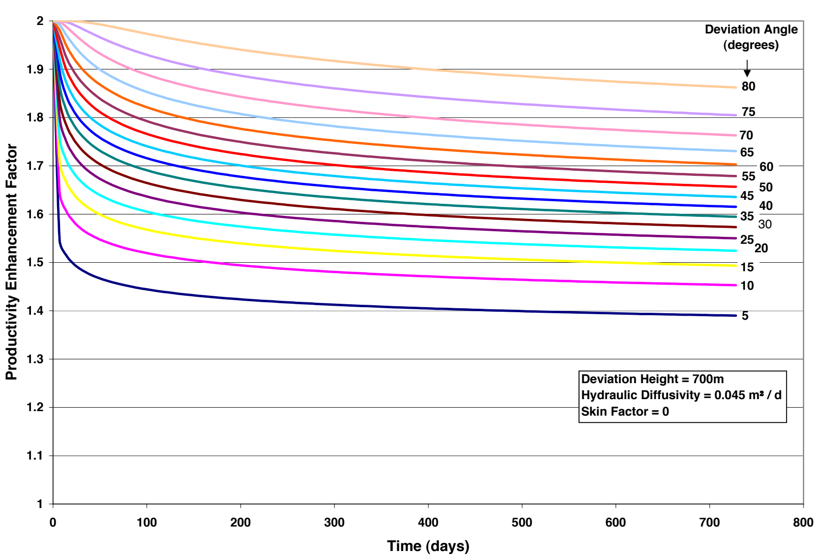


**Figure 7.** Productivity enhancement factor versus time and deviation angle.

factor of zero at both the original hole and forked leg. Figure 4 shows that for a given deviation height and a deviation angle, PEF decreases approximately linearly as a function of logarithm of hydraulic diffusivity of the reservoir. Since tighter rocks typically have smaller diffusivity, it follows that tighter the reservoir the more effective will be the drilling of multi-legged wells as a means of increasing well productivity.

## *Sensitivity to Skin factor*

As Figure 2 shows, PEF does not exceed a value of 2. However, if the forked leg has a negative skin factor, PEF can indeed exceed 2. Figure 5 presents the calculated values of PEF versus deviation angle from a deviation height of 700m for a plausible range of negative skin factor values, assuming a hydraulic diffusivity of 0.045 sq.m/day and a zero skin factor in the original leg. When the forked leg is targeted towards a fault or fracture zone, a lower skin factor in the forked leg compared to that in the original leg is a reasonable expectation; in such a situation PEF can readily exceed a value of 2, and reach a value perhaps as high as 2.5.

## *The Optimum Deviation Angle*

The discussion above indicates that a forked well will always have a higher productivity than encountered in the original hole. But given that drilling a forked leg entails additional drilling and corresponding incremental cost, relative enhancement in well productivity per meter of drilling of the forked leg should be a practical decision criterion. Figure 6 presents the calculated percent increase in PEF per meter of drilling of the forked leg versus deviation angle for a range of deviation heights for the base case (hydraulic diffusivity of 0.045 sq.m/day and skin factor of zero in both legs). Figure 6 shows that, for all deviation heights, a deviation angle of 25 to 30 degrees is the optimum as it gives the highest percent increase in well productivity per meter of drilling of the forked leg.

## *Sensitivity to Flow Time*

As a well, whether forked or not, is produced, its productivity index declines with time due to reservoir pressure drawdown. For a forked well this decline in well productivity should be more pronounced because of the additional detrimental factor of pressure interference between the two legs. But does this fact affect the PEF of the well as a function of time? Figure 7 presents the calculated values of PEF versus flow time for a range of deviation angles from a deviation height of 700m for the base case (hydraulic diffusivity of 0.045 sq.m/day and skin factor of zero in both legs). It is apparent from Figure 7 that PEF declines rapidly with time for the first few weeks before the decline rate stabilizes; PEF becomes nearly constant after a year or so. As mentioned before, for calculating PEF we have consistently used a flow time of 7 days in this paper. It should be noted that beyond a flow time of a year or two the PEF will be dictated by the reservoir boundary conditions and the injection scheme adopted in the field, which are uniquely site-specific issues.

## Results for Three-Legged Wells

At both The Geysers and Raft River a few three-legged wells have been drilled, although such wells have proven mechanically difficult to drill and disappointing as regards productivity enhancement achieved for the incremental drilling cost. In Figure 1 we have shown a schematic of a three-legged well we have considered for analysis, the deviation angle for the two forked legs being equal at the deviation height. Figure 8 shows the calculated PEF values versus deviation angle for both a two-legged well and a three-legged well for a deviation height of 700m for the base case conditions (hydraulic diffusivity of 0.045 sq.m/day and skin factor of zero at all three legs). It is clear from Figure 8 that a three-legged well can provide up to 50% more PEF than a two-legged well, everything else being the same.

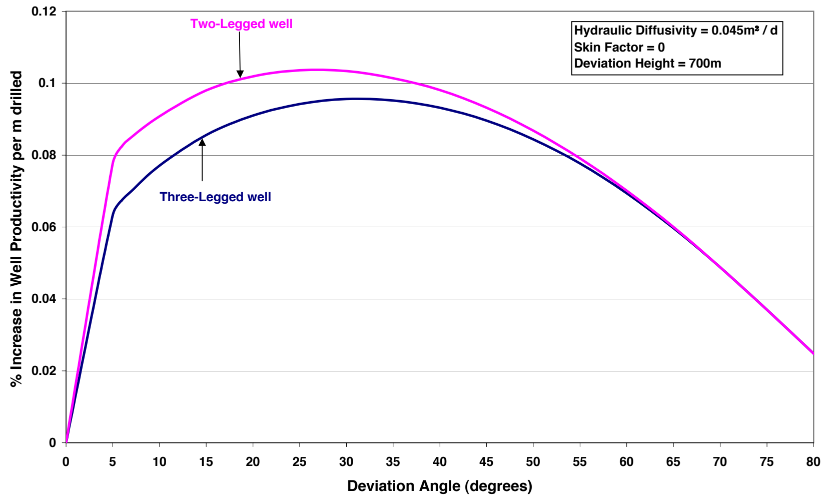


**Figure 9.** Percent increase in productivity per meter of drilling of the forked legs versus deviation angle for two-legged and three-legged wells.

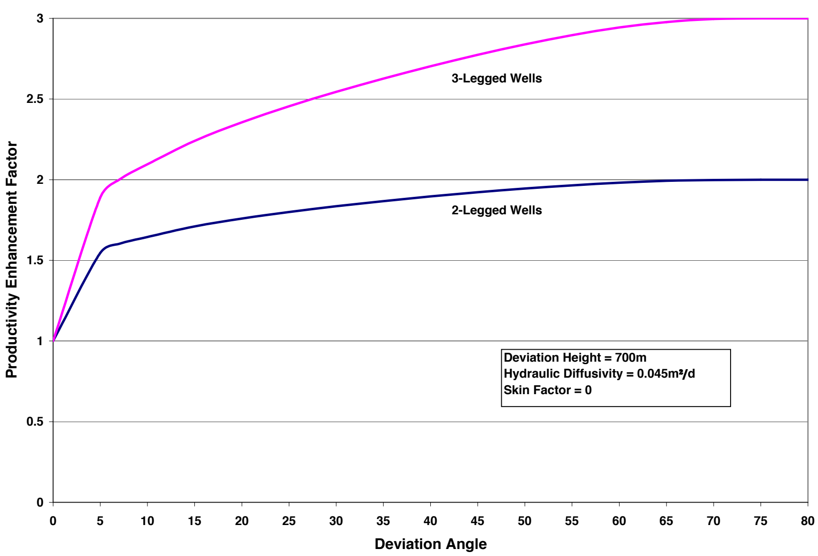


**Figure 8.** Productivity enhancement factor versus deviation angle for 2-legged and 3-legged wells.

Since a three-legged well requires more drilling than a two-legged well, it is worthwhile comparing the percent gain in PEF per meter of drilling of forked legs for both two-legged and three-legged wells (Figure 9). Two important features of Figure 9 are apparent:

1) the percent gain in PEF per meter of the forked legs drilled is optimized at a deviation angle of 25 to 30 degrees for both two-legged and three-legged wells; and

2) for all realistic deviation angles a three-legged well provides a lower percent improvement in PEF per meter of forked legs drilled than does a two-legged well.

Therefore, not only does a three-legged well pose a higher drilling risk, it is less effective in enhancing well productivity per unit drilling cost. Only where the original hole and the first forked leg both prove disappointing in productivity, drilling a second forked leg may be worthwhile; otherwise it appears unreasonable to plan to drill a three-legged well.

## Conclusions

1. For all reasonable deviation heights, PEF rises sharply with deviation angle up to about 5 degrees; beyond this, PEF continues to increase with deviation angle, albeit at a slower rate. A minimum deviation angle of 5 degrees should be used.
2. Resource temperature of a single-phase liquid reservoir does not affect PEF significantly.
3. For a given deviation height and deviation angle, PEF decreases nearly linearly with logarithm of hydraulic diffusivity; tighter the reservoir rock the more effective it is to enhance well productivity by drilling multi-legged wells.
4. PEF of a two-legged well does not exceed a value of 2.0 unless the skin factor in the forked leg is less than in the original hole, in which case it can reach a value perhaps as high as 2.5.
5. For both two-legged and three-legged wells and for all deviation heights, a deviation angle of 25 to 30 degrees gives the highest percent increase in PEF per meter drilling of the forked legs.
6. PEF declines rapidly with flow time for a few weeks before the decline rate stabilizes; PEF becomes nearly constant after a year or two of flow.
7. A three-legged well can provide up to 50% more PEF than a two-legged well, every thing else being equal.
8. For all realistic deviation heights and angles, a three-legged well provides a lower percent increase in PEF per meter drilling of the forked legs than does a two-legged well.

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