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Productivity Index Decline Curve Analysis and Its Application to Well Surveillance

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ABSTRACT

The productivity index (PI) is one useful tool used in assessing well productivity in the oil industry. As the reservoir pressure declines during production, the decline in well productivity becomes inevitable following the depletion of the hydrocarbon in place. Hence, the well productivity index declines over time even as the strength of the predominant drive mechanism deteriorates and becomes less significant in hydrocarbon recovery. Production decline can also result from impairment of the formation and poor completion designs. Therefore, PI decline of wells draining a reservoir suggests reserve depletion while exceptions suggest formation damage for low PI wells. Consequently, the PI values should be compared to the well completion efficiency to know if the decline is normal or induced by formation damage. This study presents procedure for analyzing PI decline curves and its application to well surveillance. Different representative rate of decline curves and their respective critical times were developed for determining stimulation candidate for different sand exclusion types. The possible areas of application include ranking candidates for stimulation as well as predicting the critical time for stimulating wells in order to improve production in oil wells.

Key words: Productivity index, Well surveillance, PI decline, well completion efficiency, sand exclusion, stimulation candidates, critical time

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INTRODUCTION

Production rate decline curves are widely used in the oil and gas industry to assess individual wells, field performance and for forecasting future behaviours. The concept of productivity index in evaluating the performance of different wells and reservoirs across fields has been a subject for investigation by several authors [1-4]. Unless a well's condition progressively deteriorates due to well or reservoir problems, the PI remains constant, even if the well production rate and the reservoir pressure change during the life of the well [5-6]. Constant production is usually noticed at the early life of wells [6]. However, after some period of production, the well would no longer make its allowable as production rate declines. The decline may be caused by formation damage, flow restrictions and reserve depletion.

The productivity index (PI) is the number of barrels of oil produced per day per pound per square inch of differential pressure between the reservoir and the bottom hole of the well [7]. It is a measure of how good a well is producing at its potential. The PI measures the flow rate per psi of pressure drawdown [8]. The pressure drawdown Δp, is the pressure difference between the average reservoir pressure pr, and the bottom hole flowing pressure p_{wf}. The PI can be mathematically expressed as:

$$PI = \frac{Q_L}{p_r - p_{wf}} \tag{1}$$

where Q_L is the liquid flow rate, p_r is the average reservoir pressure and p_{wf} is the bottom hole flowing pressure. The average reservoir pressure is very vital for calculating the drawdown and thus the PI. The value of the average reservoir pressure rarely changes significantly with time during production, unless in situations where the predominant primary drive mechanism is weak. Hence, it is recommended that in estimating the PI, the most recent average reservoir pressure determined from a pressure build-up test evaluation be used [9]. Therefore, the main determinant in evaluating the productivity index to investigate well performance is the bottom hole flowing pressure p_{wf}.

Unlike the average reservoir pressure, the bottom hole flowing pressure is not only commonly available; rather it is measured regularly at time frequency as high as per seconds [9]. The measurement of the bottom hole flow pressure is usually carried out using permanent downhole BHP gauges, although recently, attempts have been made to infer it using surface production data [10-11]. The p_{wf} value depends on several parameters such as permeability, the type of well completion fluid, compressibility of the flowing fluids, formation damage, fluid saturation, flow regimes, turbulence and drive mechanisms [12, 8]. These parameters can contribute to PI decline. For example, the formation permeability is usually reduced by consolidation in the crushed zone and cement squeezing during well completion as well as formation fines migration. Reduced permeability is an indication of formation damage which increases pressure drawdown. Completion fluids also add to increase pressure drawdown particularly if losses were encountered during the completion stage. However, the impact of the completion fluids on the formation depends largely on the type of completion fluid. A comparison of some completion fluids used in Permafrost, Umiat field, Alaska showed that wells completed with oil in-hole are the best, followed by brine and then water-base muds [13]. Moreover, the completion type (sand control method) used contribute to the pressure drop; however, the extent of pressure drop differs from one sand-exclusion type to another.

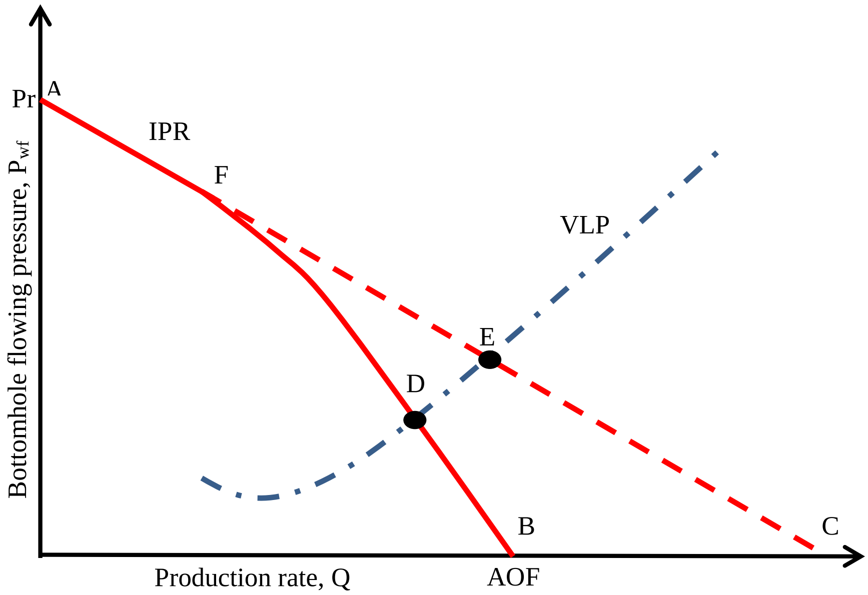

Fig. 1 A typical system plot showing the inflow performance relationship and vertical lift performance curves

Therefore, from Equation 1, the productivity index can be defined as the slope of the functional relationship between the bottom hole flowing pressure and the liquid production rate. This functional relationship between the production rate and the bottom hole flowing pressure is called the inflow performance relationship (IPR) as shown in Figure 1. Figure 1 is a typical system plot, showing the inflow performance relationship (IPR) and the vertical lift performance (VLP) curves. The points of intersection, D and E, represent the well operating points. Figure 1 shows two IPR curves, AFEC and AFDB. The straight line AFEC is a typical IPR for a single phase fluid, producing from an under-saturated reservoir while AFDB which has two sections, a straight line AF, and a curved section FDB is an IPR for a saturated reservoir. The straight line AF section is the region of single phase flow while the curved section is for two-phase flow; an indication that dissolved gas in oil is liberated and thus exists as free gas. The straight line IPR has constant PI while the IPR calculated from curve will vary and decline with time. This part where PI declines with time is what is of interest in this study to determine the rate of decline in order to identify normal (decline due to depletion of reserves) or abnormal (decline due to formation damage or poor completion designs) declines. This would require adequate analysis using reliable well, reservoir and fluid data to unravel candidates for stimulation to improve well productivity.

The monitoring of PI decline is very important as its unusual decline could impair operational economics and cause undue production downtime. Analysing productivity index decline using rate of decline would aid early well problem identification for sick wells, and even for supposedly healthy producers. In the following sections, the application of productivity index in analysing flow efficiency of wells and the development of curve fitting techniques to determine the decline patterns of wells will be illustrated to enhance well surveillance.

METHOD

The flow efficiency and the curve fitting techniques used to obtain well specific decline trends in identifying stimulation candidates is now described below.

Flow Efficiency

One parameter often used to assess the performance of wells is the flow efficiency. The flow efficiency also called productivity ratio, is a dimensionless parameter defined as the ratio of the actual productivity index to the ideal productivity index. The actual and ideal productivity indices can be defined using:

$$\mathrm{PI_a} = \frac{\mathrm{Q_o}}{\mathrm{P_r - P_{wf}}} = \frac{7.08\times10^{-3}\mathrm{k_0 h}}{\mu_o \mathrm{B_o}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s_t\right]}, \qquad \text{for PI actual} \qquad (2)$$

$$\mathrm{PI_i} = \frac{\mathrm{Q_o}}{\mathrm{P_r - P_{wf}}} = \frac{7.08\times10^{-3}\mathrm{k_0 h}}{\mu_o \mathrm{B_o}\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75\right]}, \qquad \text{for PI ideal} \qquad (3)$$

Here k_0 is the effective permeability of oil, h is the reservoir thickness, μ_o is the oil viscosity, B_o is the oil formation volume factor, r_e is the reservoir radius, r_w is the wellbore radius and s_t is the total skin. Hence, the flow efficiency becomes:

$$\mathrm{FE} = \frac{\mathrm{PI_a}}{\mathrm{PI_i}} = \frac{\ln\left(\frac{r_e}{r_w}\right) - 0.75}{\left[\ln\left(\frac{r_e}{r_w}\right) - 0.75 + s_t\right]}. \qquad (4)$$

The main difference between the ideal and the actual PI's is that the ideal PI is defined without the total skin ($s_t = 0$), while the actual PI has the total skin s_t, embedded in it as shown in Equation 2. The flow efficiency can be called either completion or performance efficiency (dimensionless productivity index) depending on when it is being calculated.

The completion efficiency (CE) is the flow efficiency estimated at the onset of production or after re-entry. It is a form of dimensionless PI (PI_D) except that it is the initial PI_D measured and used as a reference against subsequent PI_D's that would be measured and even after re-entry. It also gives an indication of how good the initial completion was. It is a single value that remains in the lifetime of a well until a re-entry is made which may alter it. Subsequent flow efficiencies calculated in-between productions after the completion efficiency has been estimated are called performance efficiencies. The performance efficiency (PE) is an instantaneous flow efficiency measured over the producing period of the well. The completion and performance efficiencies can be estimated using Equation 4.

Rate of Decline

The determination of the decline pattern is very important to ascertain the rate of decline of wells; which is a major criterion for ranking candidates for well stimulation. The decline pattern can take different forms such as exponential, polynomial, linear, logarithmic and power law; depending on the well, reservoir and sand exclusion in-place. For example, a well exhibiting a quadratic polynomial decline pattern, the equation for the dimensionless productivity index as a function of time can be written in the general form:

$$\mathrm{PI_D} = at^2 + bt + c \qquad (5)$$

Differentiating Equation 5 with respect time gives the rate of decline as:

$$\frac{\mathrm{DPI_D}}{\mathrm{DT}} = 2\mathrm{AT} + \mathrm{B} \qquad (6)$$

where a, b, and c are constants to be determined for each well that exhibits a particular polynomial trend. The best-fit trend line in this work is selected on the basis of the highest coefficient of determination (R^2). Hence, the trend types are determined specifically for wells and selected by proper regression analysis. Once a correlation has been selected, the equation describing the trend is noted which on differentiation gives the rate of decline. Fig. 2 is a typical PI_D decline rate plot showing the critical period (the area shaded with red) when stimulation is required for a well with a given sand control type. Any attempt to allow production below this critical region would make it uneconomical.

Procedure for Developing PI Decline Curve Models

- Applies only to well PI in-between re-entry. It does not apply to PI outside re-entry. In other words, the PI trend is useful to predict the time for the next re-entry and rate of decline.
- It does not apply to wells where PI increases with water breakthrough and increasing water cut, i.e wells with $\mu o/\mu w > 1$[14].

Procedure:

- Set up a table of data of bottomhole flowing pressure P_{wf}, time t, productivity index PI, drawdown ΔP, and basic sediment & water BS&W. Where t is the date converted to producing time, starting with the first P_{wf} at t = 0.
- Calculate PI actual and ideal using Equations 2 and 3
- Determine the completion and performance efficiencies using Equation 4
- Plot PI_a and the performance efficiency against time.
- Fit trend lines to PI and the dimensionless PI plots and determine R^2. Do this for exponential, linear, logarithmic, polynomial, and power law models.

- Note the trend with highest R^2 and select the equation of best fit.
- Determine the rate of decline by differentiating the equation with the highest R^2 value with time as shown in Equation 6, and ascertain the critical time using current reservoir average PI for sand control type.

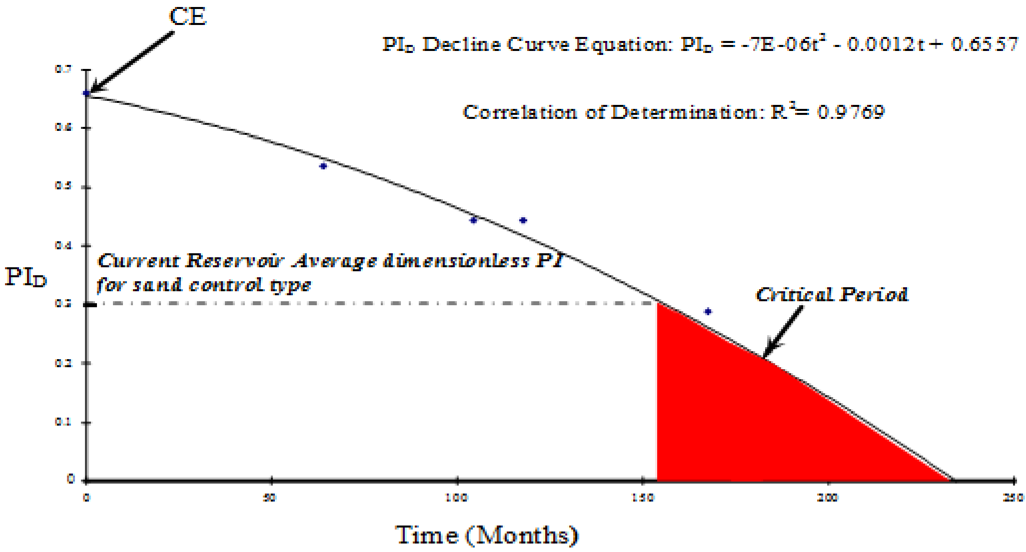

Fig. 2 A typical dimensionless PI decline curve showing the critical period for selecting stimulation candidates

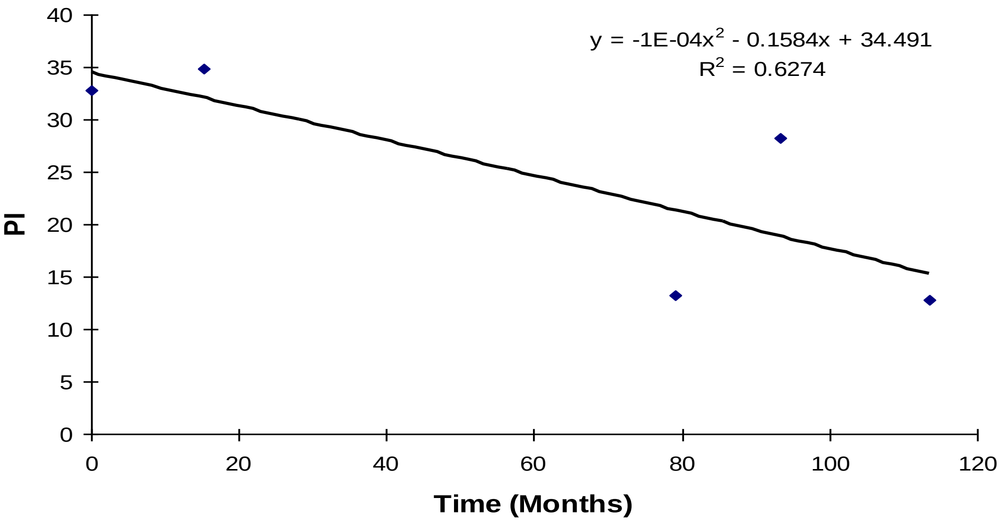

Fig. 3 PI decline trend for W-1 (SCON)

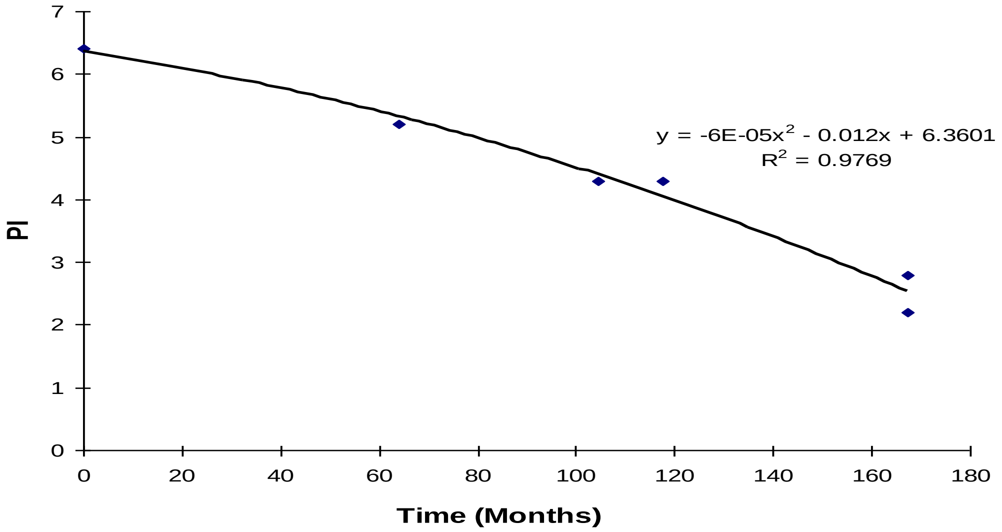

Fig. 4 PI decline trend for W-2 (IGP)

RESULTS AND DISCUSSIONS

Below are decline profiles of PI versus time and PI_D versus time for five wells with different sand exclusion types. Four sand exclusion types were considered in this investigation and they include: chemical consolidation (SCON), internal gravel parking (IGP), untreated completion (UNTR) and the external gravel parking (EGP) completion respectively. Figures 3 to 7 are plots of PI versus time for each sand exclusion type in the wells considered. The profiles are fitted with different trend lines and the trend line that gives the highest R^2 value was chosen to model the PI trend for that particular well. For example, Figure 3, 4, 5 for wells W-1, W-2, and W-3 which are completed with SCON, IGP, and SCON are best fitted with quadratic polynomials, while Figure 6 for well W-4, which is completed UNTR is best fitted with a Power Law model. Well W-5 completed with EGP as shown in Figure 7, the PI trend is best fitted with a quadratic polynomial.

Table -1 shows five wells (W-1, W-2, W-3, W-4, and W-5), whose PI decline trends have been fitted with different models and their corresponding R^2 values determined. The values superscripted with asterisks are the selected models for each well. Four out of the five wells exhibited quadratic polynomial decline trend while well W-4 exhibited a power law model. As can be seen in Table 1, the Logarithmic and Power Law models least describe the PI trends for the sand exclusion types in the wells except for the untreated completion where high R^2 values were seen. An R^2 value less than 0.5 is an indication of poor correlation of the PI's measured in a well during production to risk designating a particular production decline trend for any well. However, higher R^2 values indicate good correlation existing amongst calculated PI's and hence, future performance efficiencies can be estimated from such plots. As can be seen across the figures, the strongest correlation was seen in W-2, completed with internal gravel parking having a coefficient of determination (R^2) of 0.9769, while the least correlation was seen in W-3 with R^2 of 0.4957.

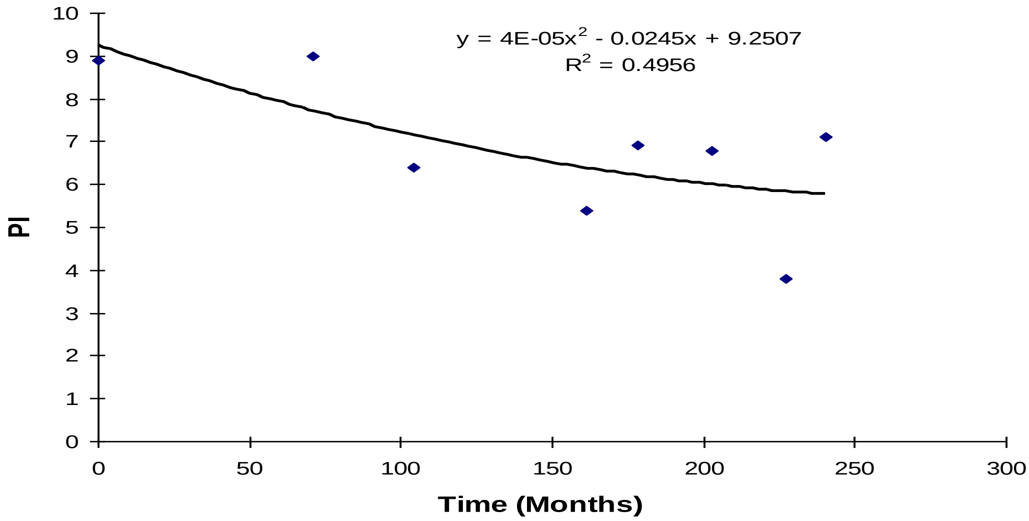

Fig. 5 PI decline trend for W-3 (SCON)

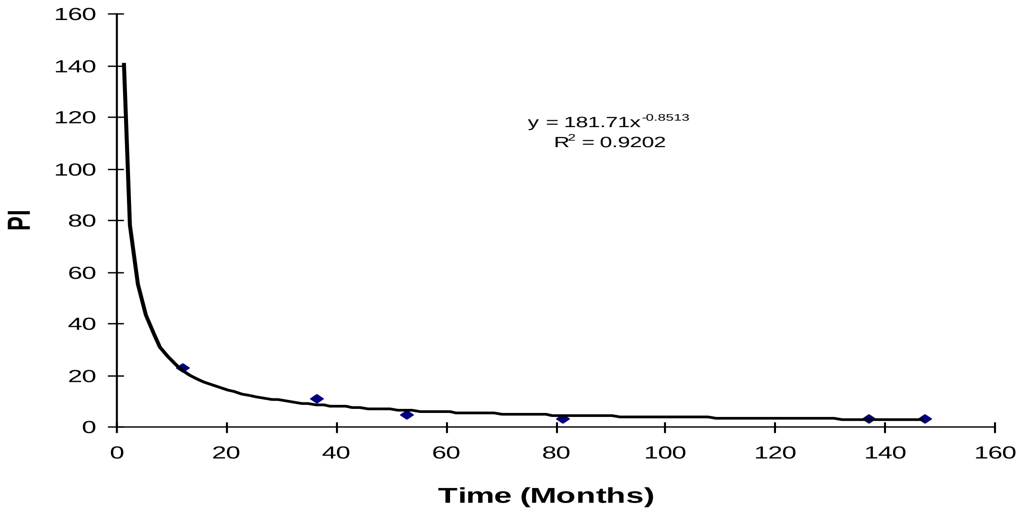

Figure 6: PI decline trend for W-4 (UNTR)

Table -1 Correlation Selection for PI Decline

Well	Sand Control Type	Coefficient of Determination (R^2)				
		Exponential	Linear	Logarithmic	Polynomial	Power Law
W-1	SCON	0.5773	0.6273	N/A	0.6274*	N/A
W-2	IGP	0.8739	0.956	N/A	0.9769*	N/A
W-3	SCON	0.4074	0.4756	N/A	0.4957*	N/A
W-4	UNTR	0.7171	0.5819	0.8736	N/A	0.9202*
W-5	EGP	0.5949	0.5887	N/A	0.6747*	N/A

*Selected Correlation, N/A: not applicable

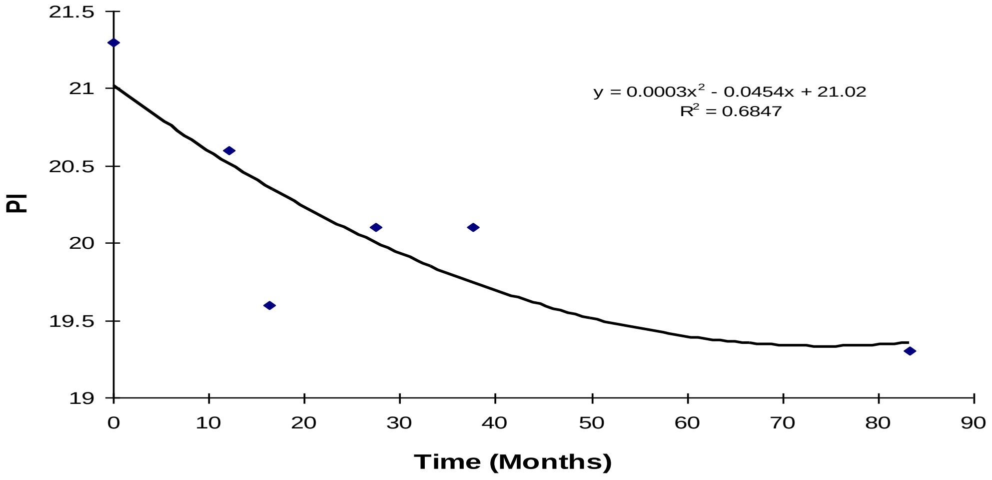

Fig .7 PI decline trend for W-5 (EGP)

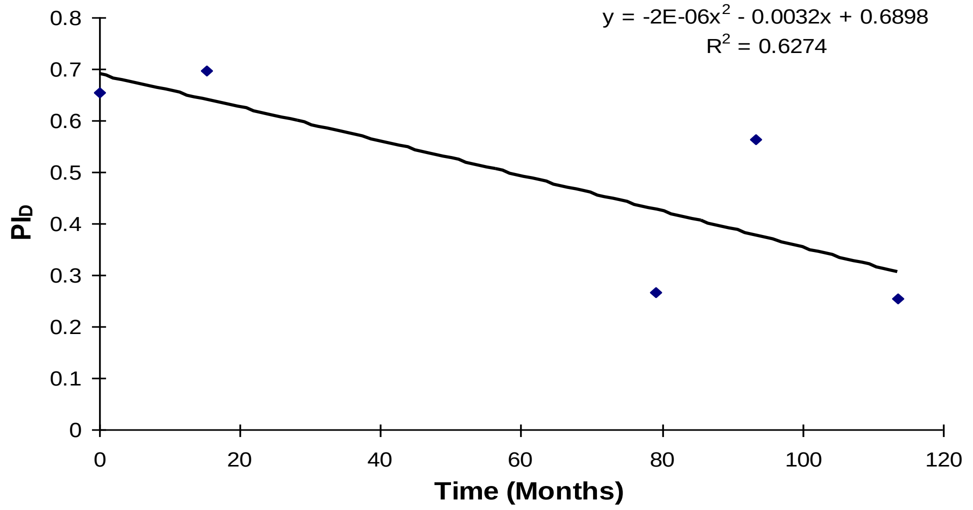

Fig. 8 PI_D decline trend for W-1 (SCON)

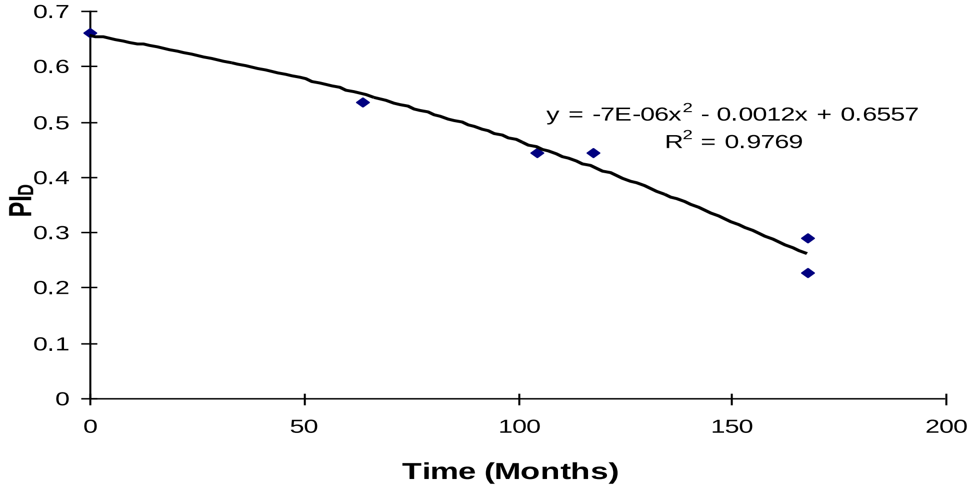

Fig. 9 PI_D decline trend for W-2 (IGP)

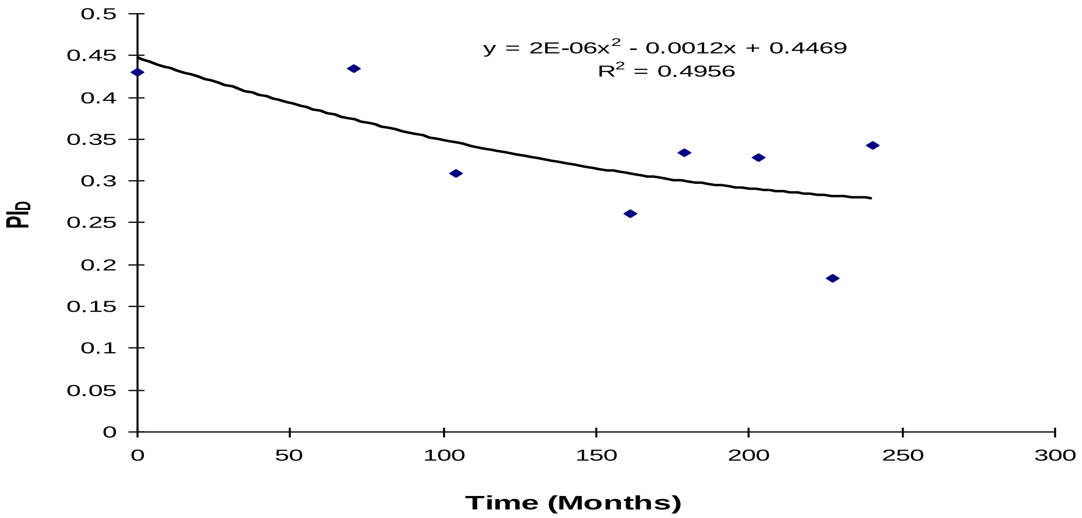

Fig. 10 PI$_D$ decline trend for W-3 (SCON)

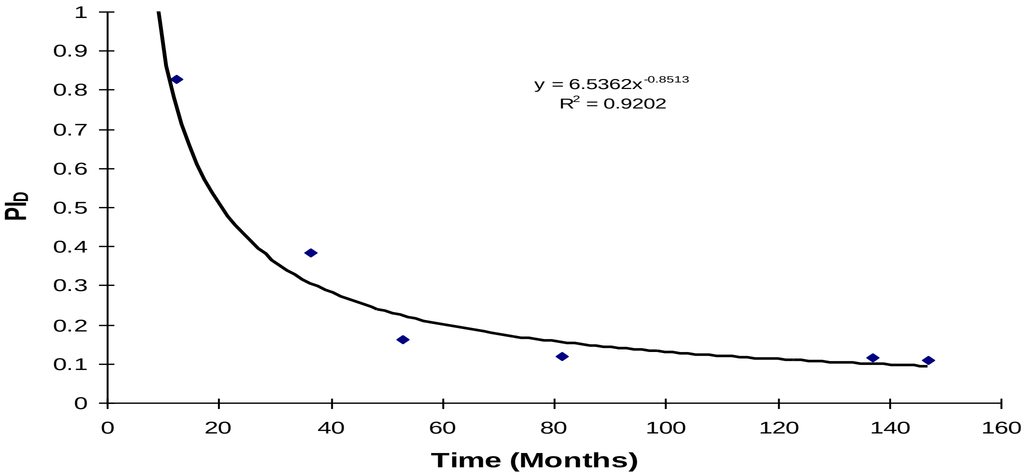

Fig. 11 PI$_D$ decline trend for W-4 (UNTR)

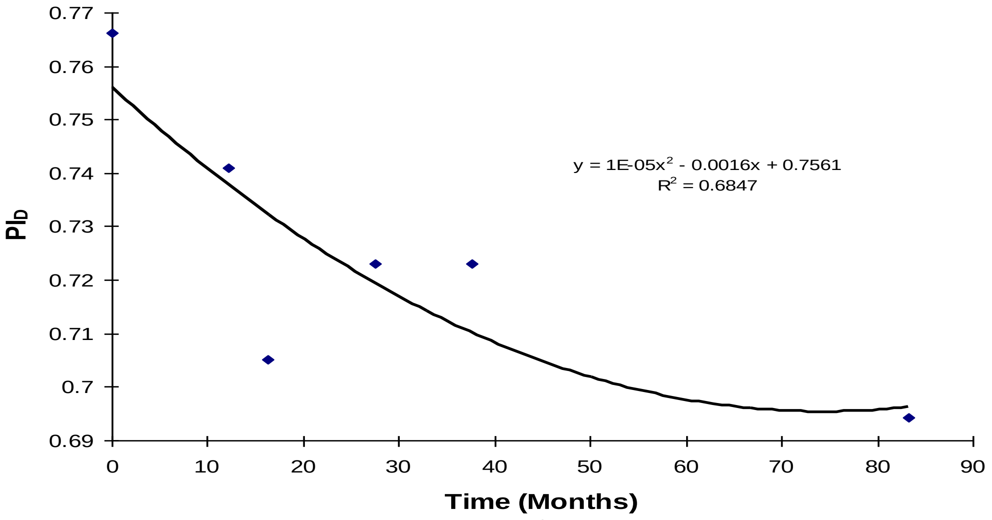

Fig.12 PI$_D$ decline trend for W-5 (EGP)

Figs 8 to 12 are the plots for the dimensionless PI (PI$_D$) for the four sand exclusion types of the different wells. As can be seen in Figures 8 to 12, the dimensionless PI plots follow similar trend with that of the PI except that their polynomial coefficients and the coefficient of correlations are different.

Rate of Decline and Critical Time

Having determined the equation for the line of best-fit, the rate of decline and the critical time was determined by differentiating the respective selected equations with respect to time using the procedure illustrated in Equations 5 and 6 and the results shown in Table 2. Assuming all the wells are producing from the same reservoir and the current average reservoir performance efficiency is 0.3 as shown in Figure 2. The current critical time to stimulate a well and the rate of PI decline can be determined; and the wells can be ranked for stimulation purposes. Looking at Table 2, except for well W-5 which was not applicable because the minimum dimensionless PI's calculated in this well was 0.695, all other wells would reach critical time to be recommended for stimulation. For example, it will take W-1 more than 115 months, W-2, more than 150 months and more than 170 months of production for W-3 to attain the critical time while well W-4 will produce barely for less than 40 months to reach the critical time of production. In ranking the wells for stimulation based on the critical time, the order of priority would be W-4, W-1, W-3, W-2 and W-5 respectively. As far as the critical time has not been reached, this method of ranking is favoured since we do not have interest to attain the critical time unless where nothing could be done. In addition, the sand control technique in the well also affects the rate of decline as each method would exhibit different pressure drops around the wellbore. Hence, comparison made for similar sand control types will yield more reliable result than comparison for all sand exclusion types.

Planning candidates for stimulation requires ranking the wells in the order of priority. Some of these wells are presently healthy producers, but may need stimulation in future. The ranking criteria used are the rate of PI decline and the predicted future PI's of wells. Wells with higher rate of decline will require stimulation in the near future subject to the reservoir average PI. However, the remaining reserve as well as potential gains may affect the overall ranking. The following solution steps can be used in developing well specific surveillance procedures:

- Draw a line of the current average reservoir dimensionless PI until it intersects the PI_D decline curve as shown in Figure 2. Read the intersection point in months, which is the critical time shown in Table 2. The future PI and dimensionless PI can also be determined by a simple trace to the decline curve. Note that if nothing is done, the PI may decline to zero.
- Calculate the rate of decline, which is the slope of the PI decline curve. The rate of decline is obtained as in equation 5.
- Using Figure 8, screen and rank wells in order of priority for stimulation.

Table -2 Rate of Decline and Critical Time for Five Wells

Well	Sand Control Type	Best-Fit Correl.	Equation of best-fit	Rate of decline (PI/Month)	Critical time (Months)	Drive Mech.
W-1	SCON	Poly	$-1E(-04)t^2 - 0.1584t + 34.491$	$-2E(-04)t - 0.1584$	>115	water
W-2	IGP	Poly	$-6E(-05)t^2 - 0.012t + 6.3601$	$-1.2E(-04)t - 0.012$	>150	Water
W-3	SCON	Poly	$2E(-06)t^2 - 0.0012t + 0.4469$	$4E(-06)t - 0.0012$	>170	Water
W-4	UNTR	Power	$181.71t^{-0.8513}$	$-154.68t^{-1.8513}$	<40	water
W-5	EGP	Poly	$0.003t^2 - 0.0454t + 21.02$	$0.0006t - 0.0454$	N/A	Water

Applications to Well Surveillance

The disparity between the performance efficiencies (PE) and the completion efficiency (CE) readily brings two things into mind. First is that the well is cleaning up (if the PE is greater than the CE). Second is that the well productivity is declining. The decision tree in Figure 13 shows that irrespective of the production rate of the well, it may still be producing below potential due to impairment. However, in practice, high flowing rate wells are not easily stimulated because of the potential of being at risk. The decision tree is strictly for wells with known pressure drawdown from bottom hole pressure (BHP) survey. For planning purposes, establishing trend lines for wells will be useful in predicting the likely time the well PI may drop so low that it will need to be stimulated. Note that decline in PI automatically results to decline in PI_D unless workover job was done on the well.

Since PI declines with time, extrapolating the decline curve will give the expected value of PI (PI_D) in future. The predicted PI value is used in the decision tree for the identification of possible stimulation candidates. Before the actual job is to be carried out, the predicted PI values must be confirmed with actual well BHP survey. However, some factors can prevent this work from being done in practice even when the formation has been certified impaired. These include the remaining reserve, price of crude, water and gas production rates among others.

CONCLUSIONS

The trend of the PI's and the performance efficiencies (PE) measured during different well tests in this work show that it decreases with time without a corresponding (proportionate) change in the flowing rate. These trends are attributed to impairment arising from formation damage as production progresses and could be improved by stimulation. It is important to note that the PI_D may increase within the first few months of production if the well was cleaning up, but will generally follow a decline trend afterwards. The slope of the trend line is a function of the impairment experienced by the well. Steep slopes show that the well may require stimulation shortly while gentle slopes suggests stimulation in a distant future if need be; depending on the remaining reserve. Coefficient of determination was used in selecting the trend line that best-fits the data points. Therefore, trend types should be determined specifically for wells and selected by proper regression analysis. Once a correlation has been selected, the model describing the trend should be noted to determine the rate of decline for ranking candidate wells for stimulation.

- From the trend analyses, appropriate well specific correlations can be determined for every completion type. The PI decline trend is useful in ranking candidates for stimulation.
- Critical time exists when the well must be stimulated. The lower the critical time the higher the priority except for wells with high potentials at risk.
- Comparison of completion efficiency and performance efficiency helps in screening candidates for Through Tubing (TT) activities. With the help of this technique, future performance of wells can be evaluated and appropriate measures taken to ensure continued production at rates economical to the overall operation.

It is recommended that routine BHP surveys be carried out at least twice a year to aid production trend monitoring.

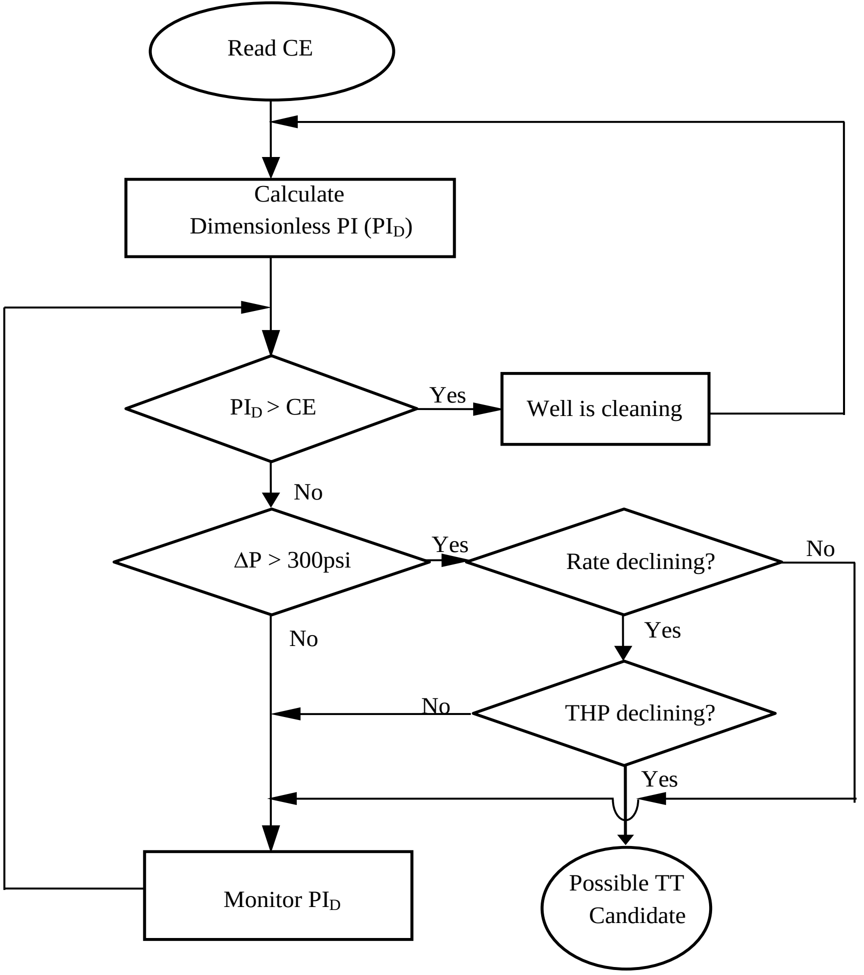

Fig. 8 Decision tree for identifying stimulation candidates

Nomenclature

BHP = bottom hole pressure (psia)
SCON = chemical sand consolidation
IGP = internal gravel pack
EGP = external gravel pack
UNTR = untreated completion
IPR = inflow performance relationship
VLP = vertical lift performance
t = time (months)
TT = Through Tubing
ΔP = pressure drop (draw down) (psia)
re = reservoir radius (ft)
re = wellbore radius (ft)
CE = completion efficiency (dimensionless)
PI_D = dimensionless productivity index (dimensionless)
PIi = ideal productivity index (STB/day/psia)
PIa = actual productivity index (STB/day/psia)
Pr = reservoir pressure (psia)
Pwf = bottomhole flowing pressure (psia)
ko = oil effective permeability (mD)
h = reservoir thickness (ft)
Bo = oil formation volume factor (rb/STB)
PE = performance efficiency (dimensionless)
St = total skin (dimensionless)
μo = oil viscosity (cp)

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