11º Congreso de Exploración y Desarrollo de Hidrocarburos
Simposio de Desarrollo de Vaca Muerta

DRAWDOWN MANAGEMENT OPTIMIZATION FROM EARLY LINEAR FLOW ANALYSIS

Agustín Terminiello[1], Pablo Crespo[2]

1: Pan American Energy SC. aterminiello@pan-energy.com

2: Pan American Energy SC. pcrespo@pan-energy.com

Keywords: Drawdown Management, Choke Management, Linear Flow Parameter, Linear Flow plot

ABSTRACT

En el desarrollo de reservorios no convencionales, las estrategias de Drawdown Management juegan un papel crítico en la vida temprana del pozo para maximizar el EUR. En el caso de generar un drawdown excesivo en el volumen de roca estimulado, la fractura hidráulica corre el riesgo de sufrir un daño y perder conductividad. Aumentar el diámetro del orificio del pozo con el objetivo de adelantar producción es económicamente tentador, pero puede causar un daño severo en la fractura hidráulica creada durante la completación del pozo.
El gráfico de Flujo Lineal exhibe una línea recta de pendiente “m” durante el período de flujo lineal que sirve como diagnóstico para evaluar el potencial de un pozo horizontal multi fracturado. Si el diámetro del orifico se aumentara de tal forma que genere un drawdown excesivo en el reservorio (y por lo tanto un daño en la fractura hidráulica) la pendiente de esta línea recta aumentaría indicando una reducción en el índice de productividad. Adicionalmente, esta pendiente “m” es inversamente proporcional al triple producto de las variables xf (media ala de fractura), Hf (altura de fractura) y a la raíz cuadrada de k (permeabilidad efectiva). El producto $xf.Hf.\sqrt{k}$ es llamado el Parámetro de Flujo Lineal y es un muy buen indicador de la productividad del pozo. Por lo tanto, si por una incorrecta estrategia de Drawdown Management se sube el diámetro del orificio del pozo de tal forma que se genere un aumento de la pendiente “m” en el gráfico de Flujo Lineal, el Parámetro de Flujo Lineal decrecerá proporcionalmente. El objetivo de este trabajo es cuantificar la pérdida de EUR del pozo que está directamente relacionada con una variación negativa del triple producto $xf.Hf.\sqrt{k}$. En otras palabras, se debe buscar una ecuación general que permita relacionar una variación de la pendiente “m” con una pérdida en la productividad del pozo.

INTRODUCTION

Drawdown Management Strategies play a key role during the early production time of an unconventional well. The Choke Management should be carefully planned in order to avoid reservoir damage. An early-time aggressive drawdown created in the reservoir can seriously reduce the size of the SRV and damage the hydraulic fracture conductivity. A correct Drawdown Management Strategy should be one that can ensure the economical production of a well, and at the same time, maximize the future performance and the estimated ultimate recovery.

As has been stated in SPE-191828-MS: "Drawdown Management Optimization from Time-Lapse Numerical Simulation": "Modern production practices have migrated from a Choke Management to a Drawdown Management Strategy to improve the control on the effective net stress over the proppant in order to prevent hydraulic fracture conductivity damage and maximize ultimate recovery".

The net stress that is exerted over the hydraulic fracture can be calculated as the difference of the minimum horizontal stress (Sh) and the bottom hole flowing pressure (BHFP). As the choke size is increased and the well is produced, the value of Sh will decrease as the reservoir is depleted. On the other hand, as a result of a bigger choke size, the BHFP decline will increase creating a higher drawdown in the reservoir. As a result of this phenomena, both Sh and BHFP will decrease with increasing choke size and the consequent reservoir depletion. Nevertheless, the value of the effective net stress will increase if the bottom hole flowing pressure decreases at a higher rate than the minimum horizontal stress. Therefore, in order to avoid hydraulic fracture damage, a correct Drawdown Management Strategy should be adopted that can allow the BHFP to decrease in such a way that prevents the effective net stress to increase significantly during reservoir depletion.

THE LINEAR FLOW PARAMETER AS A PRODUCTIVITY INDICATOR

During the early production time of a multi-fractured horizontal well the flow that dominates the system goes from the matrix to the fractures, and from the fractures to the well. This flow regime is called the Linear Flow regime and it can be detected through different diagnostic tools such as the Linear Flow plot or the log-log plot (where the data points exhibit a straight line with slope -1/2).

The solution of the Diffusivity equation for the Linear Flow regime is the following (considering negligible the skin factor in an infinite conductivity hydraulic fracture):

$$\frac{\boldsymbol{\Delta p}}{\boldsymbol{q_0}} = \frac{4.06 \cdot B_0}{x_f H_f \cdot \sqrt{k} \,.\, N} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}} \cdot \sqrt{\boldsymbol{t}}$$

As it can be observed, there is a linear relationship between the variables $\Delta P/qo$ and $\sqrt{t}$. In the Linear Flow plot the variable $\Delta P/qo$ is plotted in the y-axis against the variable $\sqrt{t}$ in the x-axis, and as a result, a straight line should be seen (as long as the Linear Flow regime dominates the system). Moreover, the slope of this straight line is inversely proportional to the triple product $xf.Hf.\sqrt{k}$ which is also called the Linear Flow Parameter (LFP).

If we call this slope "m", then:

$$\boldsymbol{m} = \frac{4.06 \cdot B_0}{\boldsymbol{x_f} . \boldsymbol{H_f} \cdot \sqrt{\boldsymbol{k}} \,.\, N} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}}$$

It should be noted that the slope "m" depends on the number of fractures "N" of the horizontal well as well as on rock and fluid properties (fluid viscosity, matrix porosity, total compressibility, and the oil formation volume factor). If a variation of the slope "m" is detected in the Linear Flow plot for a given well, then this change is directly related to a variation of the Linear Flow parameter as rock and fluid properties do not have a significant variation with small changes of pressure (especially for the case of an undersaturated reservoir where the reservoir pressure is way above the bubble point). Therefore, if the slope "m" increases (for example, due to fracture damage generated by an aggressive drawdown in the reservoir), then the Linear Flow Parameter should decrease in the same way representing a deterioration of the well´s productivity. Moreover, each slope "m" that is observed in the Linear Flow plot can be directly related to a different value of the Linear Flow Parameter (as when one variable changes so does the other one).

To clarify, Figure 1 shows the Linear Flow plot for a pair of horizontal wells of the same PAD which have been put on production on the same date. Both wells navigate the same landing zone in the reservoir, and both have the same number of fracture stages.

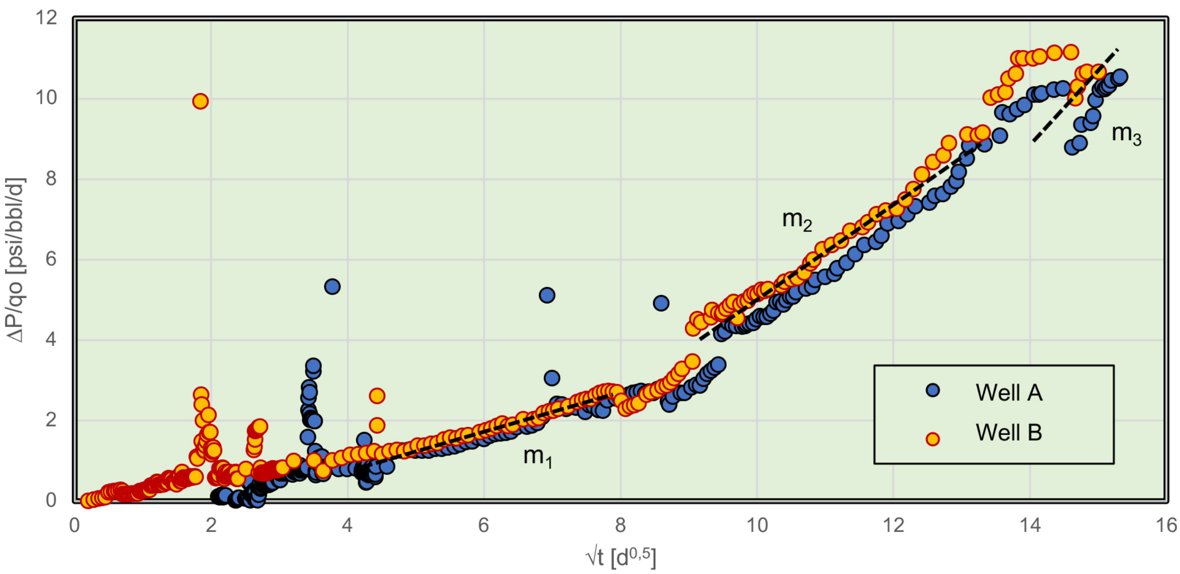

Figure 1. Linear Flow plot for a pair of horizontal wells of the same PAD.

As it can be observed, there are three different slopes for each well on the graph: m_1, m_2 and m_3. Therefore, each slope "m" can be associated to a different value of the Linear Flow Parameter:

$$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_1 \quad \text{associated to the slope } m_1$$

$$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_2 \quad \text{associated to the slope } m_2$$

$$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_3 \quad \text{associated to the slope } m_3$$

While m_2 is bigger than m_1, m_3 is bigger than m_2. In the same way, $(x_f \cdot H_f \cdot \sqrt{k})_2$ is smaller than $(x_f \cdot H_f \cdot \sqrt{k})_1$ and $(x_f \cdot H_f \cdot \sqrt{k})_3$ is smaller than $(x_f \cdot H_f \cdot \sqrt{k})_2$. This is to say that, when the slope "m" increases, the Linear Flow Parameter decreases in the same way, and consequently the well´s productivity is affected generating a negative impact on the EUR. The goal of this work is to find a mathematical equation that can relate the variation of the Linear Flow Parameter to the well´s EUR loss. Mathematically: Δm and $\Delta(xf.Hf.\sqrt{k})$ should be associated to a ΔEUR.

A question that may arise is why the variations $\Delta m_{21}=m_2-m_1$ and $\Delta m_{32}=m_3-m_2$ have been originated in the first place. This paper deals with Drawdown Management Strategies and how can an increase in the choke size to speed up production during the early life of a well can originate these sudden changes of the slope "m". For wells A and B, there has been a first choke up in the third month of the well´s life. This incident has significantly increased the bottom hole drawdown in the reservoir and has consequently generated a damage in the SRV and a reduction of the hydraulic fracture conductivity. As a result, the slope "m" in the Linear Flow plot has been doubled ($\Delta m_{21}=m_2-m_1$). Later on, in the seventh month, the choke size has been increased one more time and although it had helped to speed up oil production for some time, it can be observed that the slope "m" has once again been increased from m_2 to m_3 ($\Delta m_{32}=m_3-m_2$) representing one more time a damage in the hydraulic fracture conductivity and in the SRV size.

The Linear Flow Parameter involves three variables:

- xf (fracture half-length) and Hf (fracture height) which are related to the SRV geometry. Therefore, a deterioration of the Linear Flow Parameter can be understood as a reduction of xf and Hf, and hence, a reduction of the SRV size.
- k (effective permeability) is a variable that results from a combination of the permeability of the matrix and the permeability of the fractures of the SRV. The effective permeability is much higher than the permeability of the matrix and lower than the permeability of the fractures.

  The equation for the dimensionless conductivity of the hydraulic fracture is given by the following formula:

  $$F_{CD} = \frac{k_f \cdot w_f}{k_m \cdot x_f}$$

  The variable k_f represents the permeability of the fractures and k_m represents the permeability of the matrix. Therefore, as the effective permeability is a combination of both k_f and k_m, a reduction of k (generated by a deterioration of the Linear Flow Parameter) will inevitably result in a reduction of the fracture conductivity. This means fewer transport of fluid from the fractures to the well and therefore, a negative impact on the EUR.

A reduction of the Linear Flow Parameter cannot be attributed individually to a change of one of these three variables previously described. Hence, a reduction of the triple product $xf.Hf.\sqrt{k}$

should be understood by both a reduction of the size of the SRV (xf and Hf) and simultaneously, a deterioration of the fracture conductivity (k).

NUMERICAL SIMULATION DESIGN

As it has been stated before, when the choke size is increased during the well´s early life in such a way that it generates an aggressive bottom hole drawdown in the reservoir, both the SRV and the facture conductivity have the chance of being damaged. This phenomenon can be diagnosed by an increase of the slope "m" in the Linear Flow plot which is also associated by a reduction of the Linear Flow Parameter: $xf.Hf.\sqrt{k}$. The damage generated over the hydraulic fracture will therefore have a strong impact in the EUR of the well. This EUR loss will also be visible in a simple plot of oil rate versus time where a much higher oil rate declination will be observed after the time the fracture damage has happened. Nonetheless, this effect will not be detected immediately on a production graph and the higher rate of declination will be observed approximately twelve months later.

In order to quantify this EUR loss, a mathematical relationship should be found between the Linear Flow Parameter and the EUR so as to be able to relate a ΔEUR to a $\Delta(xf.Hf.\sqrt{k})$.

Therefore, the following function "f" should be found through numerical reservoir simulation in order to be able to relate both variables:

$$EUR = f\left(x_f \cdot Hf \cdot \sqrt{k}\right)$$

The following grid was designed for the numerical simulation:

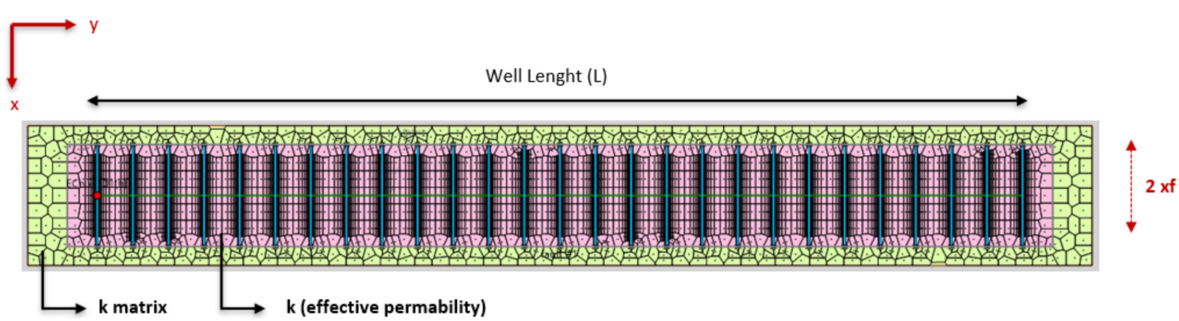

Figure 2. Grid design for the numerical simulation.

The grid consists of two different regions: the matrix (green region) and the SRV (violet region). While the SRV is limited by the length and height of the hydraulic fractures, the matrix has no limits. This is to say that there are no no-flow boundaries in the grid and no production interference with other wells.

For the Numerical Simulation, a theoretical horizontal well of lateral length “L” and “N” fracture stages was used. In particular for this work, L = 6540 ft and N = 27.

To build the fluid and reservoir model, data from the field Lindero Atravesado was used. The field is located in the Neuquina Basin in Argentina, and it comprises an area of approximately 131.000 acres. Multiple multi-fractured horizontal wells have been drilled and put on production in a development area called “El Chañar” which belongs to the northern part of the field Lindero Atravesado. All horizontal wells produce from the Vaca Muerta Formation. PVT reports as well as interpreted well logs and core analysis were used to build the reservoir and fluid model for the numerical simulation. Rate Transient Analysis were performed in all horizontal wells in “El Chañar” (with more than 12 months of production history) in order to obtain xf, Hf, k and EUR for each well.

The following table sums up the RTA results that were obtained for all five horizontal wells. The estimated ultimate recoveries obtained have been normalized:

Well Name	xf [ft]	Hf [ft]	k [md]	xf.Hf.$\sqrt{k}$ [$ft^2.md^{0.5}$]	Normalized EUR
Well #1	358	105	0,0076	3280	1,00
Well #2	282	105	0,0076	2581	0,88
Well #3	246	98	0,0075	2096	0,79
Well #4	239	98	0,0075	2040	0,70
Well #5	269	98	0,0073	2261	0,81

Table 1. RTA Results from the five oil producing wells in El Chañar (with more than 12 months of production history).

It should be stated that all five wells navigate the same landing zone in the Vaca Muerta Formation.

As it can be observed from Table 1, the range of the Linear Flow Parameter for the five wells in “El Chañar” is [3280 $ft^2.md^{0.5}$; 2040 $ft^2.md^{0.5}$]. Additionally, information from neighbor fields tells us that a range of [4332 $ft^2.md^{0.5}$; 559 $ft^2.md^{0.5}$] can also be well accepted. This range is bigger and contains the previous one and so it was used for the numerical simulation design.

As it was stated before, a function “f” that can relate the Linear Flow Parameter and the EUR should be found. In order to achieve this goal, 84 runs of the numerical simulation model were designed. Each run has a different combination of the individual values: xf, Hf and k; and for each case, an EUR is calculated. The following table shows the design of the 84 runs:

	Group I					Group II					Group III			
Run #	xf	Hf	k srv	xf.Hf.√k	Run #	xf	Hf	k srv	xf.Hf.√k	Run #	xf	Hf	k srv	xf.Hf.√k
	[ft]	[ft]	[md]	[ft^2.md^0,5]		[ft]	[ft]	[md]	[ft^2.md^0,5]		[ft]	[ft]	[md]	[ft^2.md^0,5]
1	508	98	0,0075	4332	29	585	86	0,0075	4332	57	432	116	0,0075	4332
2	492	98	0,0075	4193	30	566	86	0,0075	4193	58	418	116	0,0075	4193
3	476	98	0,0075	4053	31	547	86	0,0075	4053	59	404	116	0,0075	4053
4	459	98	0,0075	3913	32	528	86	0,0075	3913	60	390	116	0,0075	3913
5	443	98	0,0075	3773	33	509	86	0,0075	3773	61	376	116	0,0075	3773
6	426	98	0,0075	3634	34	490	86	0,0075	3634	62	362	116	0,0075	3634
7	410	98	0,0075	3494	35	472	86	0,0075	3494	63	349	116	0,0075	3494
8	394	98	0,0075	3354	36	453	86	0,0075	3354	64	335	116	0,0075	3354
9	377	98	0,0075	3214	37	434	86	0,0075	3214	65	321	116	0,0075	3214
10	361	98	0,0075	3075	38	415	86	0,0075	3075	66	307	116	0,0075	3075
11	344	98	0,0075	2935	39	396	86	0,0075	2935	67	293	116	0,0075	2935
12	328	98	0,0075	2795	40	377	86	0,0075	2795	68	279	116	0,0075	2795
13	312	98	0,0075	2655	41	358	86	0,0075	2655	69	265	116	0,0075	2655
14	295	98	0,0075	2516	42	339	86	0,0075	2516	70	251	116	0,0075	2516
15	279	98	0,0075	2376	43	321	86	0,0075	2376	71	237	116	0,0075	2376
16	262	98	0,0075	2236	44	302	86	0,0075	2236	72	223	116	0,0075	2236
17	246	98	0,0075	2096	45	283	86	0,0075	2096	73	209	116	0,0075	2096
18	230	98	0,0075	1957	46	264	86	0,0075	1957	74	195	116	0,0075	1957
19	213	98	0,0075	1817	47	245	86	0,0075	1817	75	181	116	0,0075	1817
20	197	98	0,0075	1677	48	226	86	0,0075	1677	76	167	116	0,0075	1677
21	180	98	0,0075	1537	49	207	86	0,0075	1537	77	153	116	0,0075	1537
22	164	98	0,0075	1398	50	189	86	0,0075	1398	78	139	116	0,0075	1398
23	148	98	0,0075	1258	51	170	86	0,0075	1258	79	125	116	0,0075	1258
24	131	98	0,0075	1118	52	151	86	0,0075	1118	80	112	116	0,0075	1118
25	115	98	0,0075	978	53	132	86	0,0075	978	81	98	116	0,0075	978
26	98	98	0,0075	839	54	113	86	0,0075	839	82	84	116	0,0075	839
27	82	98	0,0075	699	55	94	86	0,0075	699	83	70	116	0,0075	699
28	66	98	0,0075	559	56	75	86	0,0075	559	84	56	116	0,0075	559

Table 2. Numerical simulation design for the 84 runs of the model.

As it can be observed, there are 3 different groups of 28 runs each. All groups cover the same range of [4332 $ft^2.md^{0.5}$; 559 $ft2.md^{0.5}$] for the Linear Flow Parameter. In group 2 (runs 29 to 56), the value of xf for each run is increased in 15% versus the first 28 runs which belong to the first group. The value of k (effective permeability) is set constant to 0.0075 md and the value of Hf is "adjusted" so that the same range of the Linear Flow Parameter is obtained for each of the 28 runs of group 2 (in comparison to group 1). For group 3 (runs 57 to 84), the value of xf is decreased in 15% (versus group 1), k is kept constant at 0.0075 md and once more, the value of Hf is calculated for each run so that the same range of the Linear Flow Parameter is covered in all the 28 runs of group 3.

As a result of this design, 3 groups of 28 runs each are designed where the value of k is kept constant for all cases and the value of xf and Hf are let to vary. However, for all the 28 runs of each group, the exact same range of the Linear Flow Parameter is used.

A final comment should be made on why the value of k was decided to be kept constant for all the 84 runs. To start with, as RTA results can show, there is little variation of this variable for all five wells in "El Chañar". Also, as the value of k is "squared" inside the Linear Flow Parameter expression, the variation of k is even more insignificant when translated into a variation of the triple product $xf.Hf.\sqrt{k}$.

ANALYSIS OF RESULTS

After all 84 runs were carried out, three different curves were obtained when the Linear Flow Parameter and the Normalized EUR were plotted on the same graph:

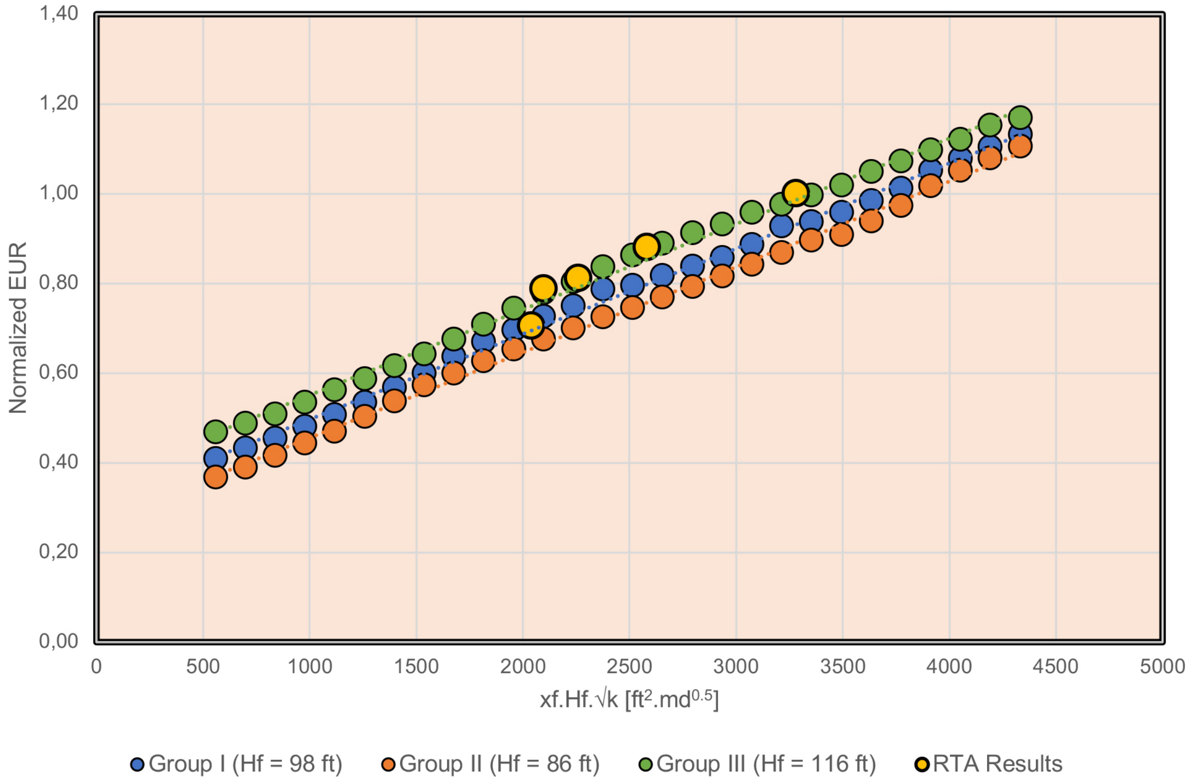

Figure 3. Linear Flow Parameter vs Normalized EUR: Numerical simulation results for the 84 runs of the model.

The following statements can be made:

- Three different curves can be observed in the graph. Each curve belongs to one of the 3 groups previously described in the Numerical Simulation design.
- There is a linear relationship between the Linear Flow Parameter and the EUR. As the value of $xf.Hf.\sqrt{k}$ is higher so is the estimated ultimate recovery of the well.
- Although all three straight-lines have different y-intercepts, they all exhibit the same slope: A_{LFP}
- There is a function "f(x)" which can be associated to all 3 straight lines: $f(x) = A_{LFP}\,x + c$, where A_{LFP} is the slope of each straight-line, and the constant "c" is the y-intercept. This constant has a different value for each straight-line.
- The RTA results for the five wells in "El Chañar" were included in the graph. It can be observed that the combinations of Linear Flow Parameters and EURs obtained for these wells lay over these three straight lines. This was made with the purpose of a QA/QC validation of the method.

EUR loss quantification

The Numerical Simulation results have shown that the function "f" which relates the Linear Flow Parameter to the EUR can be expressed as follows:

$$EUR = f\left(x_f \cdot Hf \cdot \sqrt{k}\right) = A_{LFP}\ (x_f \cdot Hf \cdot \sqrt{k}\ ) + c; where\ c\ is\ a\ constant$$

Moreover, if we differentiate the previous equation in terms of xf.Hf.√k:

$$\frac{\mathrm{d}(EUR)}{\mathrm{d}\left(xf \cdot Hf \cdot \sqrt{k}\right)} = f'\left(xf \cdot H_f \cdot \sqrt{k}\right) = \frac{\Delta(EUR)}{\Delta\left(xf \cdot Hf \cdot \sqrt{k}\right)} = A_{LFP} = constant$$

Therefore, the first derivative of "f" is constant and equal to A_{LFP} [Mbbl/ft^2.md$^{0.5}$]. Moreover, as the first derivative is constant, it does not depend on the length and fracture stages of the theoretical well that was used to build the numerical model. Additionally, it does not depend on the individual values of the variables xf, Hf and k.

Consequently, for a given fluid and reservoir model during the Linear Flow regime period, the absolute EUR loss for a well associated with a variation of the Linear Flow Parameter can be calculated as follows:

$$\Delta EUR = A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)$$

Moreover, the percentage EUR loss for a well can be expressed as:

$$\Delta\%\ EUR = \frac{\Delta EUR}{EUR\ ref} = \frac{A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)}{EUR\ ref}$$

where the EUR ref is a reference value that corresponds to the ultimate recovery of the well estimated before the variation of the Linear Flow Parameter.

It should be noted that this analysis is valid solely for the case when the well is in the Linear Flow regime period and a straight line with slope -1/2 is observed in the log-log plot: log (ΔP/qo) vs log (MBT). When a transition is observed towards the SRV flow regime and the points start to deviate from this straight line, then this analysis is no longer valid.

Going a step further, as the Linear Flow Parameter is related to the slope "m" of the Linear Flow plot, then, both absolute and percentage EUR losses can be expressed in terms of a variation of "m".

The mathematical expression of "m" which derives from the solution of the diffusivity equation for the Linear Flow regime period is:

$$m = \frac{4.06 \cdot B_0}{x_f . H_f \cdot \sqrt{k}\ . N} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}}$$

If we obtain the Linear Flow parameter in terms of "m":

$$x_f \cdot H_f \cdot \sqrt{k} = \frac{4.06 \cdot B_0}{N\ .\ m} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}}$$

Then, considering a variation of the Linear Flow Parameter as follows:

$$\Delta\left(x_f \cdot H_f \cdot \sqrt{k}\right) = \left(x_f \cdot H_f \cdot \sqrt{k}\right)_2 - \left(x_f \cdot H_f \cdot \sqrt{k}\right)_1$$

where:

$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_1$ is associated to the slope m_1, and

$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_2$ is associated to the slope m_2,

then, it is possible to express the variation of xf.Hf.$\sqrt{k}$ in terms of a variation of the slope "m":

$$\Delta(xf.\ Hf.\sqrt{k}) = \frac{4.06 \cdot B_0}{N} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}} \cdot \left(\frac{1}{m_2} - \frac{1}{m_1}\right)$$

Finally, introducing this last expression in the equation of the absolute EUR loss:

$$\Delta EUR = \frac{4.06 \cdot A_{LFP} \cdot B_0}{N} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}} \cdot \left(\frac{1}{m_2} - \frac{1}{m_1}\right)$$

Therefore, as it has been demonstrated, the absolute EUR loss of a well due to a variation of the Linear Flow Parameter can also be expressed in terms of a variation of the slope "m". The same is true for the percentage EUR loss:

$$\Delta\%\ EUR = \frac{\frac{4.06 \cdot A_{LFP} \cdot B_0}{N} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}} \cdot \left(\frac{1}{m_2} - \frac{1}{m_1}\right)}{EUR\ ref}$$

The previous equations consider negligible the variation of Bo and μ between state 1 and 2. This is especially true for the case of an undersaturated reservoir where the reservoir pressure is above the bubble point. Either way, if the engineer wants to consider this difference, the values Bo ($Pres_1$), Bo ($Pres_2$), μ ($Pres_1$) and μ ($Pres_2$) should be included in the calculation. $Pres_1$ and $Pres_2$ stand for the average reservoir pressure at states 1 and 2 respectively.

The following table resumes the four equations previously obtained to quantify the EUR loss in terms of either a variation of the Linear Flow Parameter or the slope "m". All variables are in field units.

In terms of the Linear Flow Parameter:	**In terms of the slope "m":**
Absolute EUR loss [Mbbl]: $\Delta EUR = A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)$	**Absolute EUR loss [Mbbl]:** $\Delta EUR = \frac{4.06 \cdot A_{LFP} \cdot B_0}{N} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}} \cdot \left(\frac{1}{m_2} - \frac{1}{m_1}\right)$
Percentage EUR loss [%]: $\Delta\%\ EUR = \frac{A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)}{EUR\ ref}$	**Percentage EUR loss [%]:** $\Delta\%\ EUR = \frac{\frac{4.06 \cdot A_{LFP} \cdot B_0}{N} \cdot \sqrt{\frac{\mu}{\emptyset \cdot C_t}} \cdot \left(\frac{1}{m_2} - \frac{1}{m_1}\right)}{EUR\ ref}$

Table 3. All four equations for EUR loss quantification

General Equation

All four equations for the EUR loss quantification (see Table 3) have been derived to apply in multi-fractured horizontal wells to account for the negative impact of a variation of the slope "m" in the Linear Flow plot.

The constant A_{LFP} [Mbbl/ft^2.md$^{0.5}$] is the slope of the family of straight-lines with the form: $f(x) = A_{LFP}\,x + c$ obtained in the plot of EUR vs Linear Flow Parameter. The constant A_{LFP} strongly depends on the reservoir and fluid model used in the numerical simulations that were carried out to find the family of straight lines and the function "f(x)" that relates a ΔEUR to a $\Delta(xf.Hf.\sqrt{k})$. On that account, this constant will have to be calculated for each development area and each landing zone where these equations will be applied.

So far so good. However, a final comment should be made to approach the case of a well where it is possible to observe more than two different slopes in the same Linear Flow plot.

Figure 4 shows the Linear Flow plot of a well that exhibits three different slopes. As usual, each slope "m" can be associated to a different Linear Flow Parameter. For each Δm: $m_1<m_2$ and $m_2<m_3$.

Therefore, for the case of a well that has "n+1" different slopes: $m_1<m_2<m_3<\ldots<m_n<m_{n+1}$.

In the same way, after each variation of the slope "m", the new Linear Flow Parameter will be smaller than the previous one (representing the well's productivity loss associated to reservoir and fracture damage).

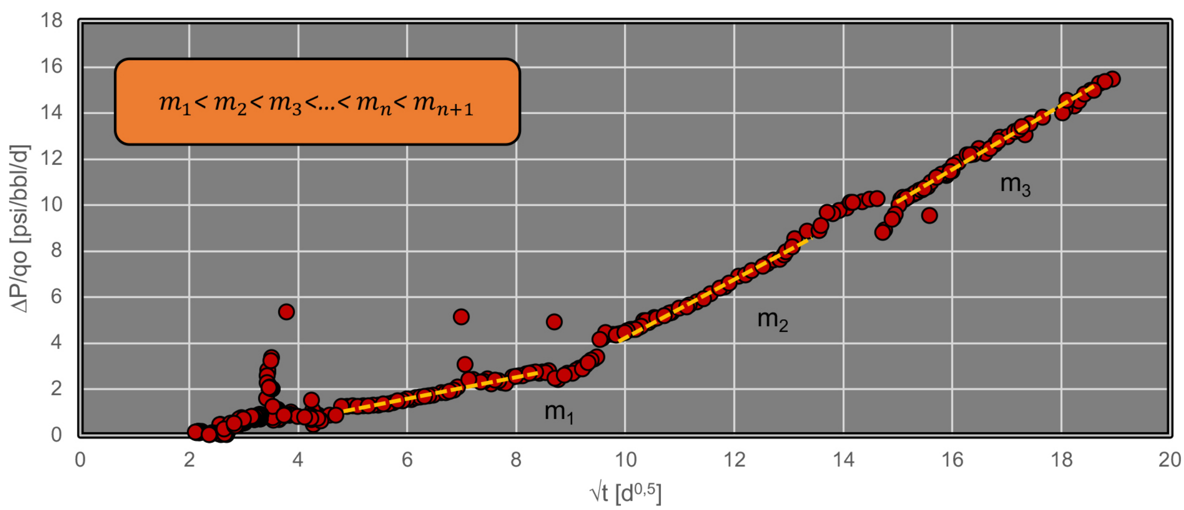

Figure 4. Linear Flow Parameter plot for the case of "n+1" different slopes.

Consequently, for the case of "n+1" different slopes, it is possible to quantify the EUR loss associated to each individual variation of the slope "m". To begin with, each slope has to be associated to a Linear Flow Parameter:

$(x_f \cdot H_f \cdot \sqrt{k})_1$ associated to the slope m_1

$(x_f \cdot H_f \cdot \sqrt{k})_2$ associated to the slope m_2

…

$(x_f \cdot H_f \cdot \sqrt{k})_n$ associated to the slope m_n

$(x_f \cdot H_f \cdot \sqrt{k})_{n+1}$ associated to the slope m_{n+1}

Then, the formula of the EUR loss quantification must be applied for each individual variation of the Linear Flow Parameter (or each individual variation of the slope "m"). Moreover, to obtain the EUR percentage loss, the EUR ref must be calculated and associated to each slope "m".

For the first variation of "m" where $\Delta m_{21}=m_2-m_1$, the EUR ref1 can be obtained from RTA, DCA, or other forecasting methods using the production data related to $(x_f \cdot H_f \cdot \sqrt{k})_1$ and the slope "m_1". Later on, for the second variation of "m" where $\Delta m_{32}=m_3-m_2$, the value of EUR ref_2 associated to slope "m_2" and $(x_f \cdot H_f \cdot \sqrt{k})_2$, has to be calculated as follows (where $\Delta EUR_{21}<0$ if $m_1<m_2$):

$$EUR_{ref_2} = EUR_{ref_1} + \Delta EUR_{21}$$

where:

$$\Delta EUR_{21} = A_{LFP} \cdot \Delta(x_f \cdot Hf \cdot \sqrt{k})_{21} = A_{LFP} \cdot [(x_f \cdot H_f \cdot \sqrt{k})_2 - (x_f \cdot H_f \cdot \sqrt{k})_1]$$

Then, the percentage EUR loss for the variation $\Delta m_{32}=m_3-m_2$ will be:

$$\Delta\%\ EUR_{32} = \frac{A_{LFP} \cdot \Delta(x_f \cdot Hf \cdot \sqrt{k})_{32}}{EUR\ ref_2}$$

Finally, for the case "n+1", the expression percentage EUR loss is:

$$\Delta\%\ EUR_{(n+1\ n)} = \frac{A_{LFP} \cdot \Delta(x_f \cdot Hf \cdot \sqrt{k})_{(n+1\ n)}}{EUR_{ref_n}}$$

where the value of EUR refn has to be calculated using the following formula:

$$EUR_{ref_n} = EUR_{ref_1} + \sum_{i=1}^{n-1} A_{LFP} \cdot \Delta(xf \cdot H_f \cdot \sqrt{k})_{(i+1\ i)}$$

This is to say that the reference EUR for the case "n" is equal to EUR ref1 plus the sum of all the EUR losses due to all the "n-1" variations of the slope "m".

We should note that this last expression is valid only for variations of the slope "m" from n+1 towards n with n≥2.

FIELD CASE STUDY

The equations previously obtained in this work were used in the following field case study to quantify the EUR loss due to variations of the Linear Flow Parameter.

In all cases, both values of A_{LFP} and EUR ref are not explicitly specified for confidentiality reasons.

The following field consists of 5 horizontal wells in production where all of them navigate the same Landing Zone in the Vaca Muerta Formation.

Well distance was set at 984 ft in order to allow for a future multilanding development where wells drilled to a second target could be placed at 492 ft of the existing wells. The following figure shows schematically the location of the five wells of the field:

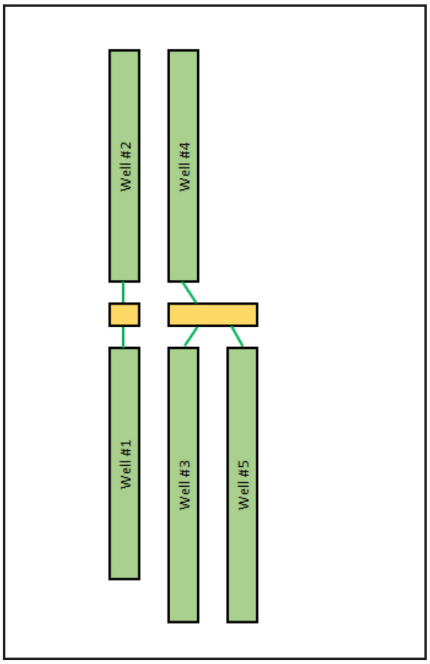

Figure 5. Field case study: Horizontal wells location.

Well #1 and Well #2 were the first two wells to be drilled and completed in the field and are considered stand-alone wells. Well #3 and Well #5 belong to the same PAD and were drilled and completed in zipper frac at one and two well distances from Well #1 respectively. These two wells can be considered Child wells and they both exhibit a higher oil declination rate trend than their Parent well (Well #1).

The following information is known for the five horizontal wells:

Well Name	Lateral Length [ft]	Number of Fracture Stages
Well #1	6560	27
Well #2	6560	27
Well #3	8200	33
Well #4	6560	27
Well #5	8200	33

Table 4. Lateral length and number of fracture stages for the 5 horizontal wells.

From the log-log plot (figure 6) it can easily be observed that all wells are in the Linear Flow regime which is accurately diagnosed by a straight-line of slope -1/2.

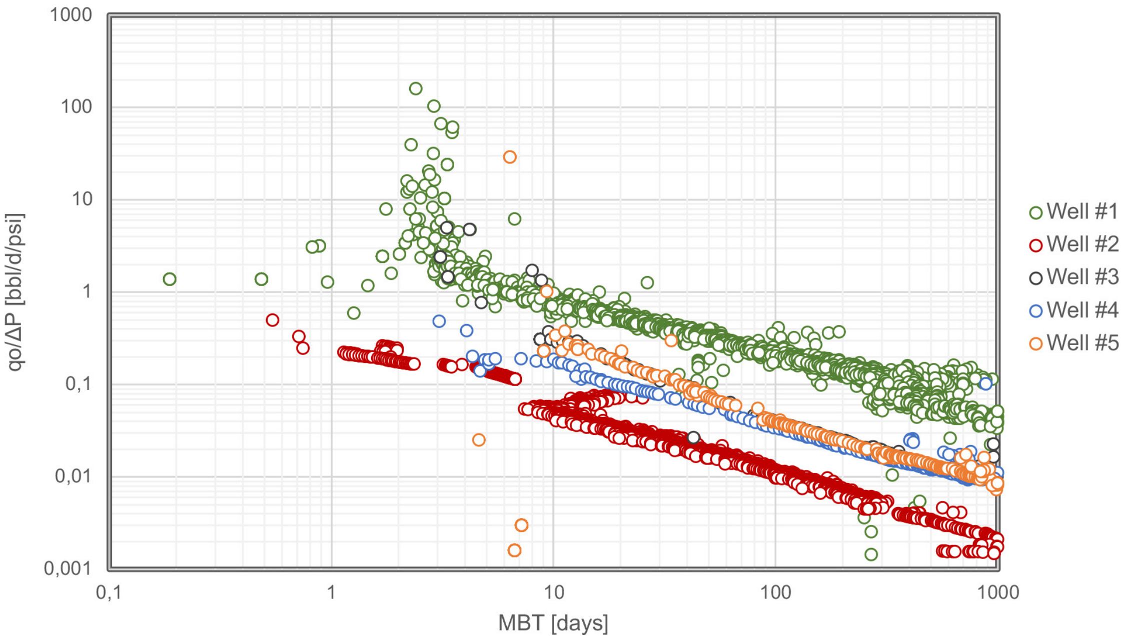

Figure 6. Log-Log plot for the five horizontal wells of the field

Therefore, a Linear Flow plot can be generated for the five horizontal wells of the field. As the wells do not have the same lateral length (L) and number of fracture stages (N), the Linear Flow plot has been normalized by N:

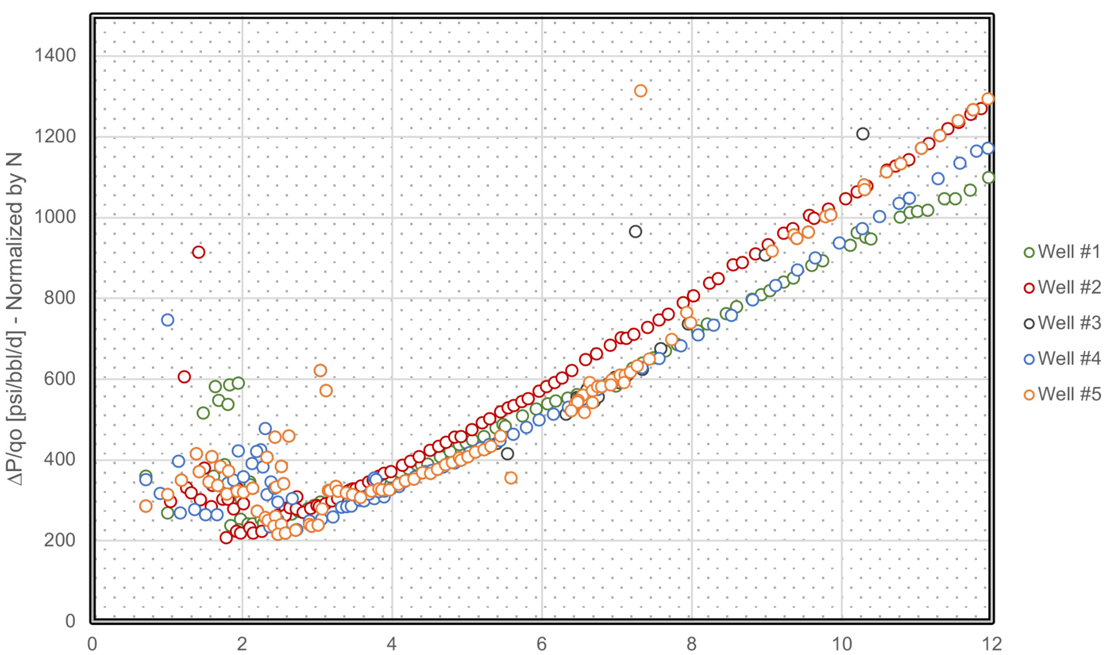

Figure 7. Linear Flow plot normalized by N (number of fracture stages) for the 5 horizontal wells of the field.

As it was predicted from the Log-Log plot, all 5 wells are in the Linear Flow regime period, and they all exhibit a straight-line when plotted in a Linear Flow plot. It has been discussed earlier that the slope "m" of these straight lines is inversely proportional to the Linear Flow Parameter which has proven to be a very good indicator of the well's productivity. Therefore, from early Linear Flow analysis it is possible to establish which wells show better potential.

The well with the lowest slope "m" (and consequently highest Linear Flow Parameter) is Well #1. This well was a stand-alone well (first to be drilled in the field) and has the highest productivity index. Well #2 has the highest slope indicating the lowest Linear Flow Parameter observed on this early production analysis which can be attributed to other field operational problems not discussed on this work.

Moreover, Well #3 and Well #5 show at first a low slope "m" (similar to Well #1) but later on, a clear deviation from these straight lines is observed and it can be seen that these slopes increase.

Let us focus first on Well #5. This horizontal well exhibits a variation of the slope "m" (from m_1 to m_2) in the Linear Flow plot after the choke size was increased from 12/64 in to 14/64 in in the third month since the well was put on production. This choke size was maintained for eighteen days before a choke back was made when the WHP declination rate as well as the bottom hole drawdown increased significantly. Figure 8 shows the variations of the slope "m": $\Delta m_{21}=m_2-m_1$ in the Linear Flow plot. Note that for this case, the plot has not been normalized by N.

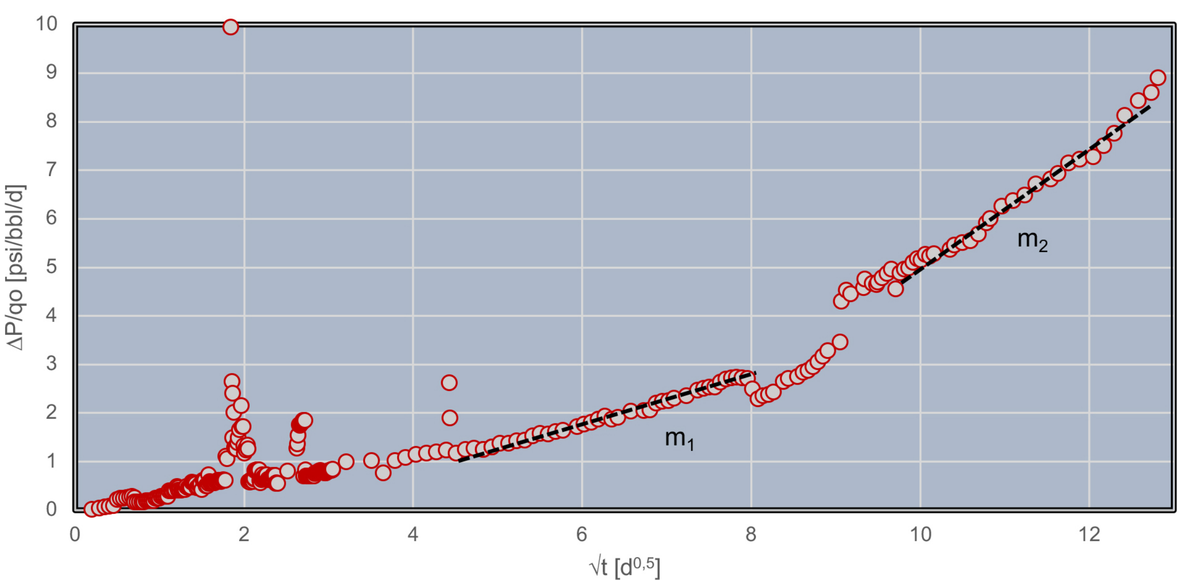

Figure 8. Linear Flow plot for Well #5.

In a production graph of oil rate versus time, this choke up can be also observed when the oil rate increased as much as 1272 bbl/d around the third month since the well was put on production.

After the choke size was corrected to 12/64 in, the oil rate goes back to the declinatory trend it had before the choke up. Nevertheless, the damage generated in the SRV and on the hydraulic fracture conductivity is irreversible and cannot be undone. The deterioration of the well´s productivity generated by this choke up is captured in the negative variation of the Linear Flow Parameter.

The negative EUR impact of the previous Drawdown Management Strategy can be calculated as follows.

Reservoir and fluid properties are known, and therefore a Linear Flow Parameter can be associated to both slopes "m_1" and "m_2":

$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_1 = 2261\ ft^2.md^{0.5}$ associated to the slope m_1

$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_2 = 1712\ ft^2.md^{0.5}$ associated to the slope m_2

An EUR ref (associated to 2261 $ft^2.md^{0.5}$) was calculated using Rate Transient Analysis and Numerical Simulation.

Therefore, the absolute EUR loss in terms of a variation of the Linear Flow Parameter can be calculates as:

$$\Delta EUR_{21} = A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{21} = A_{LFP} \cdot (1712 - 2261)$$

Then, the percentage EUR loss due to the variation of the Linear Flow Parameter is:

$$\Delta\%\ EUR_{21} = \frac{A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{21}}{EUR\ ref} = \frac{A_{LFP} \cdot (1712 - 2261)}{EUR\ ref} = -11.8\%$$

Figure 9 shows the oil production rate and the bottom hole drawdown versus time for the well. The bottom hole drawdown refers to the ΔP generated at the reservoir depth while the well is produced: ΔP = Pres – BHFP where Pres is the average reservoir pressure and BHFP is the bottom hole flowing pressure:

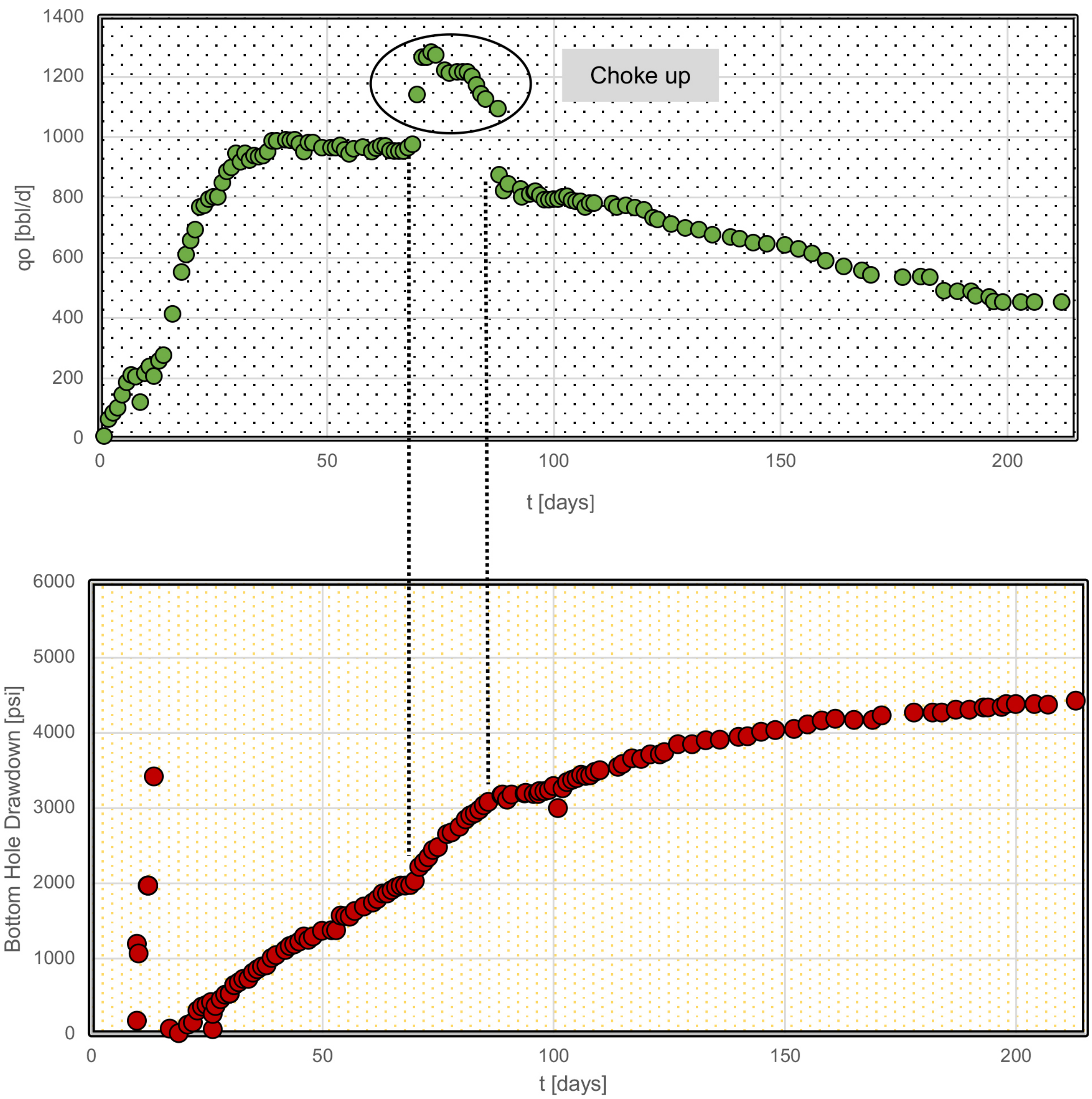

Figure 9. Oil rate and Bottom Hole Drawdown versus time for Well #5

It is consistent to see that when the choke size is increased, the bottom hole drawdown increases as well. It is important to notice that not only has the drawdown increased its magnitude but its rate of increase over time has also escalated. This is to say, the bottom hole flowing pressure is now decreasing at a higher rate than before. As it was stated at the beginning of this work, the value of the effective net stress will increase if the bottom hole flowing pressure decreases at a higher rate than the minimum horizontal stress. The result of this higher and more aggressive drawdown in the reservoir is a damage in the hydraulic fracture network which manifests itself in a variation of the slope "m" in the Linear Flow plot and a lower Linear Flow Parameter.

Well #3 and Well #5 belong to the same PAD and have been put on production on the same date.

The following analysis can be made for Well #3:

The well exhibits three different slopes (m_1, m_2 and m_3 where $m_1<m_2<m_3$) in the Linear Flow plot. The first increase of the slope "m" from m_1 to m_2 was produced after a choke up (from 12/64 in to 14/64 in) in the third month since the well was put on production (same time as Well #5 previously described). A second choke up was made in the seventh month from 12/64 in to 13/64 in generating $\Delta m_{32}=m_3-m_2$. Each choke up was followed by a choke back after detecting a high well head pressure declination rate and bottom hole drawdown.

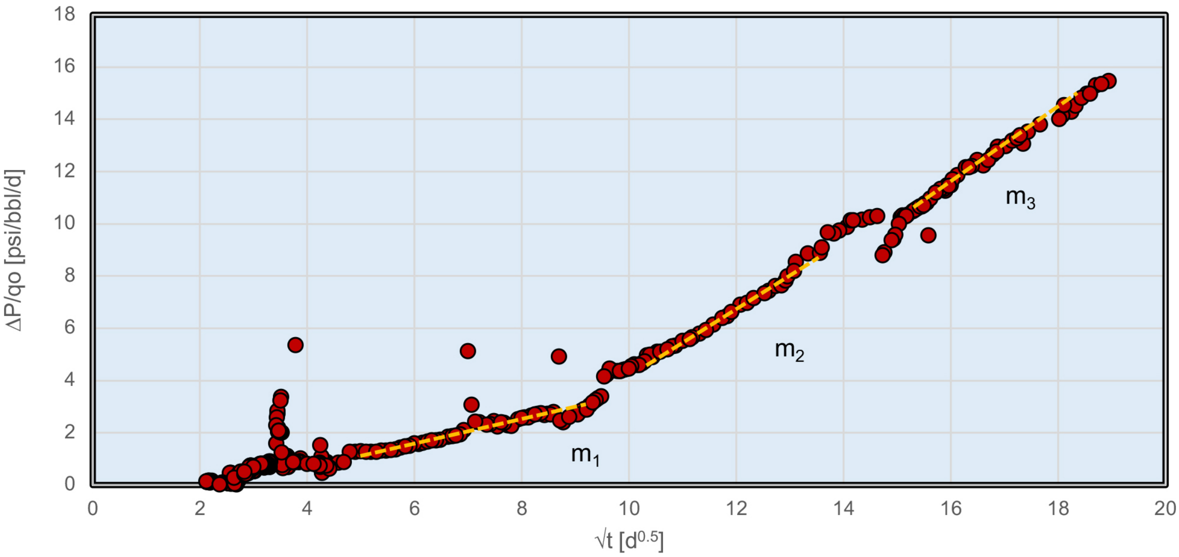

Figure 10. Linear Flow plot for the Well #3

Each slope "m" can easily be associated to a different Linear Flow Parameter as reservoir and fluid properties are known:

$(x_f \cdot H_f \cdot \sqrt{k})_1 = 2096$ ft^2.md$^{0.5}$ associated to the slope m_1

$(x_f \cdot H_f \cdot \sqrt{k})_2 = 1579$ ft^2.md$^{0.5}$ associated to the slope m_2

$(x_f \cdot H_f \cdot \sqrt{k})_3 = 1386$ ft^2.md$^{0.5}$ associated to the slope m_3

The value of EUR ref_1 (associated to 2096 ft^2.md$^{0.5}$) is known and was previously calculated with RTA and Numerical models.

Therefore, the absolute EUR loss in terms of the first variation of the Linear Flow Parameter can be calculated as follows:

$$\Delta EUR_{21} = A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{21} = A_{LFP} \cdot (1579 - 2096)$$

Then, the percentage EUR loss due to the first variation of the Linear Flow Parameter is:

$$\Delta\%\ EUR_{21} = \frac{A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{21}}{EUR\ ref_1} = -11.5\%$$

The EUR ref_2 (associated to 1579 $ft^2.md^{0.5}$) can be calculated as:

$$EUR_{ref_2} = EUR_{ref_1} + \Delta EUR_{21}$$

Then, the absolute EUR loss due to the second variation of the slope "m" is:

$$\Delta EUR_{32} = A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{32} = A_{LFP} \cdot (1386 - 1579)$$

Using the calculated EUR ref2, the percentage EUR loss is:

$$\Delta\%\ EUR_{32} = \frac{A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{32}}{EUR\ ref_2} = -4.9\%$$

Therefore, the total EUR loss due to both variations of the slope "m" is:

$$\Delta EUR_{31} = \Delta EUR_{21} + \Delta EUR_{32}$$

As it can be observed, the first choke up (from 12/64 in to 14/64 in) generated a much greater EUR loss than the second one (from 12/64 in to 13/64 in). This can be due to the fact that:

- The first choke up was made on the third month since the well was put on production, while the second one was made on the seventh month. The well is more sensitive to choke changes when they are performed in their early-time.
- The second choke up was made by adding only 1/64 in to the choke diameter while the first one was made by adding 2/64 in. The greater the increase in the choke size, the greater will be the variation of the slope "m", and consequently, the more significant the EUR loss of the well.

The next well to be analyzed on this Field Case Study is Well #4. The well exhibits two different slopes "m" in the Linear Flow plot due to a choke up that was made in the fifth month since the well was put on production. The choke size was increased from 12/64 in to 13/64 in and, after seven days, a choke back was made to 12/64 in.

What is interesting about this well is that although the time between choke up and choke back was only seven days (where an additional volume of 642 bbls of oil were produced), still, a small variation of the slope "m" can be detected in the Linear Flow plot.

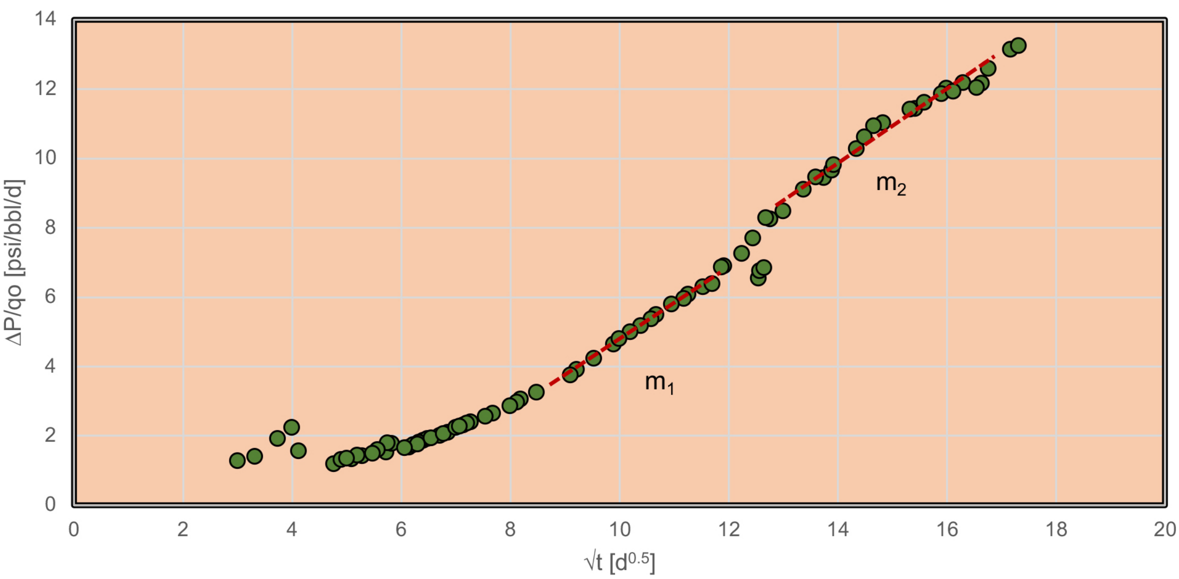

Figure 11. Linear Flow plot for the Well #4.

In order to calculate the EUR loss, the following calculations are made:

$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_1 = 2040$ ft^2.md$^{0.5}$ associated to the slope m_1
$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_2 = 1974$ ft^2.md$^{0.5}$ associated to the slope m_2

$$\Delta EUR_{21} = A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{21} = A_{LFP} \cdot (1974 - 2040)$$

$$\Delta\%\, EUR_{21} = \frac{A_{LFP} \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{21}}{EUR\, ref_1} = -1.4\%$$

It can be stated that the shorter the period between choke up and choke back, the lesser the variation of the slope "m" and the lesser the negative impact on the EUR of the well.

The last well to be analyzed belongs to a neighbor field. The following information is available:

- Reservoir: Vaca Muerta Formation
- Landing Zone: Z1 (same Landing Zone as Well #1, #2, #3, #4 and #5)
- Lateral Length: 6560 ft
- Number of fracture stages: 27

When this horizontal well was initially put on production, due to production need, the initial choke management was sped up and in less than 11 days, the well had a choke size of 12/64 in.

45 days later, a choke back was made to 10/64 in when a very high WHP declination rate was detected.

In the Linear Flow plot (Figure 12), two slopes can be observed:

- m_1: related to the period of time when the well was flowing through 12/64 in (before the choke back)
- m_2: related to the period of time when the well was flowing through 10/64 in (after the choke back)

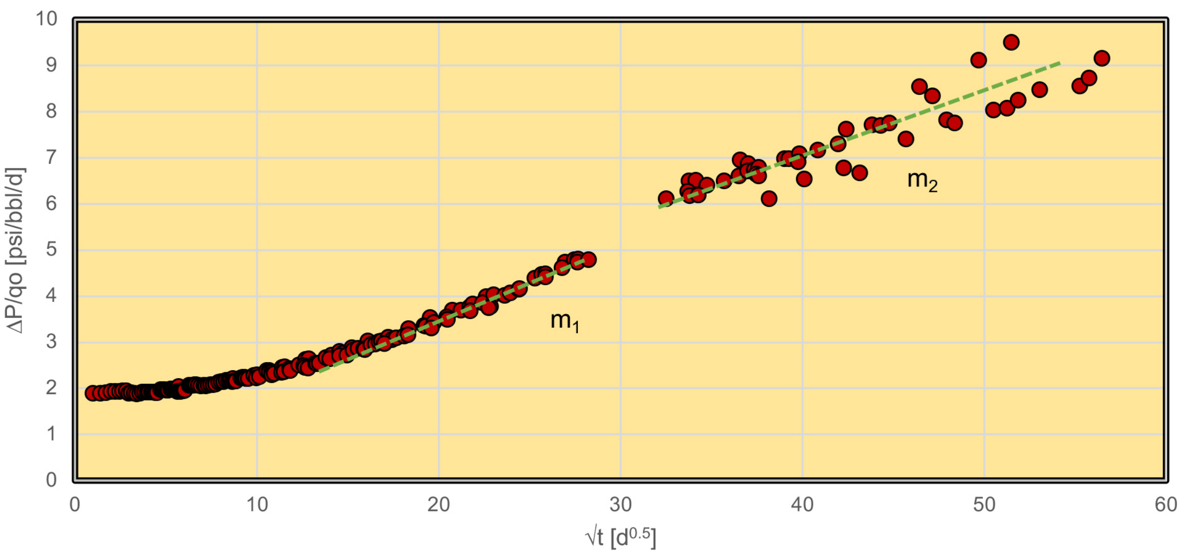

Figure 12. Linear Flow plot for the well.

It can be observed that m2<m1, so therefore, on this case, the Linear Flow Parameter increased after the choke back was made. This is to say that, after reducing the choke diameter and consequently the bottom hole drawdown in the reservoir, the slope "m" in the Linear Flow plot stabilized at a lower value and so, avoiding the reservoir damage to be even more serious.

In this case, the variation of the Linear Flow Parameter shows a positive difference as the well´s productivity recovered.

Therefore, a Linear Flow Parameter was associated to each slope "m". Notice that for this case, the second one is higher than the first one.

$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_1$ = 1881 ft^2.md$^{0.5}$ associated to the slope m_1

$\left(x_f \cdot H_f \cdot \sqrt{k}\right)_2$ = 2245 ft^2.md$^{0.5}$ associated to the slope m_2

The positive difference in the EUR can be calculates as follows:

$$\Delta EUR_{21} = 0.1734 \cdot \Delta\left(x_f \cdot Hf \cdot \sqrt{k}\right)_{21} = A_{LFP} \cdot (2245 - 1881)$$

FURTHER DISCUSSION

The Field Case Study previously described shows how the EUR loss equations can be applied in real cases where a variation of the slope “m” is observed in the Linear Flow plot.

Increasing the choke size during the early life of a multi-fractured horizontal well can cause serious damage on the SRV and hydraulic fracture conductivity, which later on is translated into a higher bottom hole flowing pressure declination rate and consequently, a lower estimated ultimate recovery.

The critical period of time in which Drawdown Management Strategies play a key role in the future performance of the well is approximately 12 months since the well is put on production. During this period of time, the well is more sensitive to choke size changes or any other event that can increase the drawdown generated in the reservoir. After the first year of production, the well has each time a lesser response to choke size changes.

One final comment should be made on how to apply these EUR loss equations. If the engineer can predict how much EUR will be lost for increasing the choke size and speeding up production, he will be able to answer two fundamental questions:

- Is it economically convenient to speed up production on a particular well?
- Will the additional production income generated by the increase in the choke size pay the estimated ultimate recovery loss?

Depending on the answer to these two fundamental questions, the engineer should design the Drawdown Management Strategy for the field that can best enhance the economic value of the project.

CONCLUSIONS

- The Linear Flow Parameter is a strong indicator of the well´s productivity. The higher the Linear Flow Parameter, the higher the Estimated Ultimate Recovery of the well.
- There is a function “f” of the form: $f(x) = A_{LFP}\ x + c$ that relates the EUR and the Linear Flow Parameter. The first derivative of this function “f” can be used to relate a variation of the Linear Flow Parameter (and consequently a variation of the slope “m” in the Linear Flow plot) with an EUR loss.

  The constant “ALFP” has to be calculated with Numerical Simulation for each landing zone and development area where the EUR loss equations will be applied.

- A Field Case Study has shown that multi-fractured horizontal wells are very sensitive to choke size changes during their early production time (approximately during the first 12 months of production history). An increase in the choke size generates a negative variation of the Linear Flow Parameter which later on can be translated into an EUR loss. This phenomenon can be diagnosed by an increase of the slope "m" in the Linear Flow plot.
- The Field Case Study has proven that the greater the increase in the choke size, the more significant will be the EUR loss of the well.
- EUR loss equations should be used to design future Drawdown Management Strategies and account for the economic impact of speeding up production during the early production time of the well.

NOMENCLATURE

- Xf [ft]: Hydraulic fracture half-length
- Hf [ft]: Hydraulic fracture height
- K [md]: Effective permeability
- B_o [bbl/bbl]: Oil volumetric formation factor
- μ [cp]: Oil viscosity
- Ct [1/psia]: Total compressibility
- Ø [fraction]: Porosity
- L [ft]: Lateral length
- N: Number of fracture stages
- $xf.Hf.\sqrt{k}$ [$ft^2.md^{0.5}$]: Linear Flow Parameter
- EUR [Mbbl]: Estimated ultimate recovery
- A_{LFP} [$Mbbl/ft^2.md^{0.5}$]: Slope of the straight-lines observed in the graph of EUR vs Linear Flow Parameter
- F_{cd} [dimensionless]: Hydraulic fracture dimensionless conductivity
- w_f [ft]: Hydraulic fracture width
- k_f md]: Permeability of the fractures
- k_m [md]: Permeability of the matrix

ACKNOWLEDGEMENTS

The authors would like to thank Pan American Energy for the authorization to share this interdisciplinary and integrated work to evaluate the impact of drawdown management strategies on well performance and ultimate recovery estimation.

REFERENCES

Sharma, A., & Lee, W. J. (2016, August 1). Improved Workflow for EUR Prediction in Unconventional Reservoirs. Unconventional Resources Technology Conference. doi:10.15530/URTEC-2016-2444280.

Crespo, Pablo Agustin, and Sergio Cuervo. "Drawdown Management Optimization from Time-Lapse Numerical Simulation." Paper presented at the SPE Argentina Exploration and Production of Unconventional Resources Symposium, Neuquén, Argentina, August 2018. doi: https://doi.org/10.2118/191828-MS