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Well Spacing for Horizontal Wells

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Abstract: In the developing phase of a hydrocarbon reservoir and planning for drilling the production wells, it is necessary to drill the wells in an appropriate spacing to achieve maximum economic revenues during the reservoir life span. Well spacing which is the real location and interrelationship between producing oil or gas wells in an oil field is an important parameter. It is determined for the maximum ultimate production of a given reservoir and should be taken in consideration during well planning to avoid drilling of unnecessary wells. This study presents the concept of drainage area on horizontal well and horizontal productivity indices with different equations and their applications. A user friendly Excel Spreadsheet program was developed to calculate the productivity values of horizontal wells using three major available productivity equations. Also, the developed spreadsheet program was used to evaluate the effect of well spacing on the productivities of horizontal wells using productivity index approach and drainage area concept. It also helps to review the comparison between vertical and horizontal wells spacing based on drainage area concept. This program was validated, and then was used to study the effect of horizontal well length on the ratio of horizontal well productivity to vertical well productivity. The results show that higher ratio of horizontal well productivity to vertical well productivity values are obtained with increase length of the horizontal well. It is a very useful tool for making decision about the application of well spacing for horizontal wells.

Key words: Drilling, horizontal, planning, productivity, vertical, well spacing

INTRODUCTION

With the continuing progress in drilling techniques, the use of horizontal wells has been increasing very rapidly throughout the oil industry. The major purpose of a horizontal well is to enhance reservoir contact and thereby enhance well productivity. In general, a horizontal well is drilled to the reservoir bedding plane. Some published articles (El-Sayed *et al*., 1996) show that horizontal wells are used so far primarily to solve specific production problems. These include low permeability formations, specially fractured formations, low permeability gas reservoirs, unusual gas sources, gas or water conning, thin formations, and viscous oil. Horizontal wells seem very appropriate for offshore and hostile environment applications where a substantial upfront saving can be obtained by drilling long horizontal wells. This is because a large area can be drained by using a reduced number of wells. This reduces the number of slots that are required on offshore platforms, and thereby significantly reduces the cost of these platforms. Well spacing which is the real location and interrelationship between producing oil or gas wells in an oil field is an important parameter. It is determined for the maximum ultimate production of a given reservoir and should be taken in consideration during well planning to avoid drilling of unnecessary wells.

At the beginning of a hydrocarbon field development plan, when the field's geometry and the amount of proven, probable and possible reserves have been delineated, among the most important variables to be considered for proper development are optimum number of wells and spacing. Well spacing is generally defined as the maximum area of the resource reservoir that can be efficiently and economically drained by one well. The purposes of well spacing are to prevent waste, avoid the drilling of unnecessary wells, and protect the rights of reserves owners. The well spacing problem can be discussed from two points of view which are the physical ultimate recovery and the economic ultimate recovery (Tabatabaei, 2007). From the physical standpoint, there are a minimum number of wells required to achieve maximum extraction. Increasing the number of wells beyond this number would not increase the ultimate primary extraction. From the economic ultimate recovery standpoint, giving no time limit for a reservoir development project's life, it can be stated, pure theoretically that at one extreme a few wells can drain the

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whole reservoir, and at the other extreme, an unnecessary high number of wells could effectively drain the reservoir more rapidly, but at a high cost. In either case, the project's economic return would be negatively affected.

Objectives of the study:
The objectives of this study are:

- To develop an Excel spreadsheet to calculate the productivity values of horizontal wells using three major available productivity equations.
- To use the developed Excel spreadsheet to evaluate the effect of well spacing on the productivities of horizontal wells using productivity index approach and drainage area concept
- Review the comparison between vertical wells and horizontal wells spacing based on drainage area concept.

MATERIALS AND METHODS

An excel spreadsheet program was developed to compute the productivity index employing the methods of Joshi (1991) Borisov, (Joshi, 1991) Elgagah/Osisanya and Tiab (Osisanya, 2009). With knowledge of the optimal productivity index from the three methods employed, an optimal drainage architecture program was developed for effective well spacing.

Well productivities for vertical wells and horizontal wells using drainage area based for well spacing: The actual production mechanism and reservoir flow regimes around the horizontal well are considered more complicated than those for the vertical well, especially if the horizontal section of the well is of a considerable length. Some combination of both linear and radial flow actually exists, and the well may behave in a manner similar to that of a well that has been extensively fractured. Several authors (Tarek, 2006) reported that the shape of measured IPRs for horizontal wells is similar to those predicted by the Vogel or Fetkovich methods. The authors pointed out that the productivity gain from drilling 1,500-ft-long horizontal wells is two to four times that of vertical wells (Tarek, 2006).

There are several methods that are designed to predict the productivity index from the fluid and reservoir properties. For the purpose of this study, the following methods would be used to develop the excel spreadsheet:

- Borisov's Method
- Joshi's Method
- Elgagah-Osisanya-Tiab Method

Borisov's method: Borisov proposed the following expression for predicting the productivity index of a horizontal well in an isotropic reservoir, that is, $k_v = k_h$ (Joshi, 1991):

$$J_h = \frac{\left(0.007078hk_h\right)}{\left(\mu_o * B_o * \left(\ln\frac{\left(4r_{eh}\right)}{L} + \left(\frac{h}{L}\right) * \ln\frac{h}{\left(2\pi r_w\right)}\right)\right)} \quad (1)$$

Joshi's method: Joshi (1991) again presented the following expression for estimating the productivity index of a horizontal well in isotropic reservoirs:

$$J_h = \frac{\left(0.007078hk_h\right)}{\left(\mu_o * B_o * \left(\ln(R) + \left(\frac{h}{L}\right) * \ln\frac{h}{\left(2\pi r_w\right)}\right)\right)} \quad (2)$$

where;

$$R = \frac{\left(a + \sqrt{\left(a^2 - \left(\frac{L}{2}\right)^2\right)}\right)}{\left(\frac{L}{2}\right)}$$

with "a" being half the major axis of drainage ellipse and given by:

$$a = \left(\frac{L}{2}\right)\left[0.5 + \sqrt{\left(0.25 + \left(\frac{2r_{eh}}{L}\right)^4\right)}\right]^{0.5} \quad (3)$$

Elgagah-Osisanya-Tiab method: Elgagah presented the following expression for estimating the productivity index of a horizontal well in isotropic reservoirs:

$$J_h = \frac{\left(0.007078hk_h\right)}{\left[\mu_o * B_o * \left[\ln\frac{\left(\frac{h}{2r_w}\right)}{\left(\frac{L}{h}\right)} + \left(0.25 + \frac{C}{L}\right) * \left(\frac{1}{r_w} - \frac{2}{h}\right)\right]\right]} \quad (4)$$

where C=470-0.2L

where, C is a constant in ft and L is the well length in ft. Elgagah-Osisanya-Tiab developed a constant for C for specific range of horizontal lengths as shown in Table 1.

Table 1: A developed value of the constant, C by Elgagah-Osisanya-Tiab is as followed

Horizontal Well Length (L), ft	Values of constant (C) or equivalent to be used to calculated the constant
$0 < L \le 1000$	C = 270 ft
$1000 < L \le 3000$	C = 470 – 0.20*L

Since, the constant C in Elgagah's method was determined by regression analysis, C will be zero or negative for $L \ge 2350$-ft. For the purpose of this study, we have restricted our analysis to L= 2000-ft.

Effective wellbore radius of a horizontal well: The effective wellbore radius of a horizontal well can be obtained by converting productivity of a horizontal well into that of an equivalent vertical well (Joshi, 1991). The effective wellbore radius is defined by:

$$r'_w = r_w \exp(-s) \tag{5}$$

Assuming isotropy, equal drainage volumes ($r_{eh} = r_{ev}$), and equal productivity indices for horizontal and vertical wells $(q/\Delta P)_h = (q/\Delta P)_v$, the vertical wellbore diameter to produce oil at the same rate as that of a horizontal well is given by the following equation:

$$r_w' = \frac{\left(r_{eh}(L/2)\right)}{\left(a\left[1+\sqrt{\left(1-\left(1-\left(L/(2a)\right)^2\right)\right)}\right]*\left[h/(2r_w)\right]^{(h/L)}\right)} \tag{6}$$

If the reservoir is anisotropic, equation 3.18 is modified by introducing the parameter or factor β to give the following equation:

$$r_w' = \frac{\left(r_{eh}(L/2)\right)}{\left(a\left[1+\sqrt{\left(1-\left(L/(2a)\right)^2\right)}\right]*\left[\beta h/(2r_w)\right]^{(\beta h/L)}\right)} \tag{7}$$

Skin factor for horizontal well: Joshi (1991) presented the following expression for estimating the skin factor (s) of a horizontal well in isotropic reservoirs as:

$$\frac{J_h}{J_v} = \frac{\left[\ln\left(\frac{r_{eh}}{r_w}\right) + s\right]}{\left[\ln\left(\frac{r_{ev}}{r_w}\right) + s\right]}, \quad \text{where} \quad s = -\ln - \ln\left(\frac{r_w'}{r_w}\right) \tag{8}$$

Thus, concepts of skin factor, effective wellbore radius, and productivity index are used to present well productivity (Joshi, 1991).

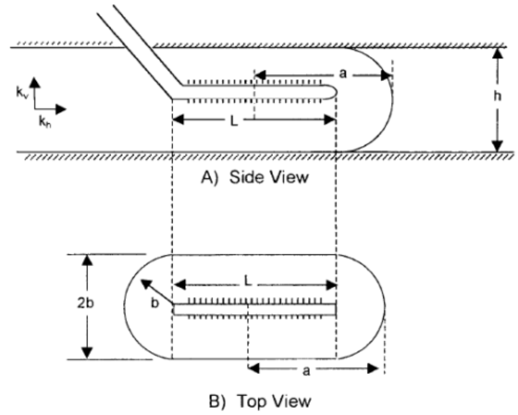

Fig. 1: Horizontal well drainage area

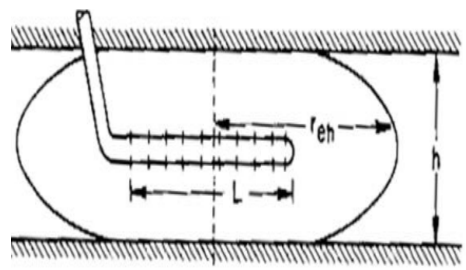

Fig. 2: Ellipsoidal horizontal well drainage area

Application of the concept of drainage area to horizontal well: Horizontal well drainage area for an isotropic reservoir is calculated using the two different methods.

Method 1: In the first method, the drainage area is represented as two half circles of radius $r_{ev} = b$ at the end and a rectangle, of dimensions $L*2r_{ev}$, in the centre as shown in Fig. 1. The drainage area A, of the horizontal well is:

$$A_h = \frac{\left(L(2*b) + \pi*b^2\right)}{43{,}560} \text{ and } r_{ev} = b = \sqrt{\left(\frac{A_v*43{,}560}{\pi}\right)}$$

Method 2: This method assumes that a horizontal well drains an ellipse with major axis "a" and minor axis "b" as shown in Fig. 2.

$$A_h = \frac{(\pi*ab)}{43{,}560} \text{ With, a =L/2+b, and } r_{eh} = \sqrt{\left(\frac{(43{,}560*A)}{\pi}\right)}$$

For the purpose of this study, Method I and Method II will be used to calculate the drainage area and the possible number of horizontal wells that will drain the lease effectively.

RESULTS AND DISCUSSION

Application of Borisov's, Joshi's and Elgagah's methods on productivity index of horizontal wells: Assuming a steady-state and a homogeneous reservoir for a horizontal well, Borisov, Joshi and Elgagah/Osisanya/Tiab equations would be employed to determine the horizontal productivity indexes for a 40 and 80 acres drain areas using methods 1 and 2. Assuming that a single vertical well effectively drains 40 acres and 80 acres, the possible number of horizontal wells that would drain the same lease effectively would be determined from a field of 400-acre developed using 10 vertical wells. The field would be redesigned proposing a 500, 1000, 1500 and a 2000-ft long horizontal wells spaces.
With the following Reservoir properties.

$k_v = k_h = 75$ *md*, $\mu_o = 0.62$ *cp*, $h = 160$ *ft*, $B_o = 1.34$ *res.bbl/stb*, $\Phi = 3.8\%$, $r_w = 0.365$ *ft*

Table A1 to A2 in Appendix A, show the results for the drainage areas for the different proposed lengths for the three authors; Borisov's, Joshi's and Elgagah/Osisanya/Tiab, using methods 1 and 2 approaches. Table A3 shows the average of the horizontal well drainage area and number of horizontal wells for using methods 1 and 2 for a 40 and 80 acres spacing. Table B1 and B2 in Appendix B shows the results on the effect of horizontal well length on Horizontal Productivity Index. From Appendix C, Table C1 to C8 show the results of the productivity ratios and areal productivity index for the different lengths and acres using methods 1 and 2 to determine the outputs for the three authors; Borisov's, Joshi's and Elgagah/Osisanya/Tiab Appendix D show the summary results of the effect of horizontal well length on Productivity Ratio (j_h/j_v) for Methods I and II for both 40 and 80 acres spacing. The plots in Fig. 3 to 6 are the results from Appendix D.

Comparison: From Fig. 3 to 6, Elgagah and Borisov's methods could be recommended when applying Method 1 for 40 acres well spacing. Borisov's Method should be recommended when applying Method 2 for 40 acres well spacing. Elgagah's Method should therefore be recommended when applying Method I for 80 acres well spacing. Elgagah's Method can therefore be recommended as the best method when applying Method 2 for 80 acres well spacing. It is important to note that as the well spacing increases (when the horizontal well length

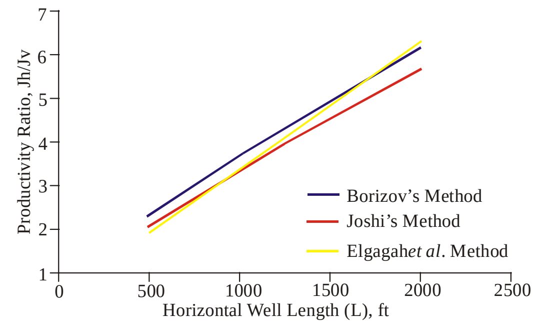

Fig. 3: Productivity ratio versus horizontal well length of method 1 using 40 acres spacing

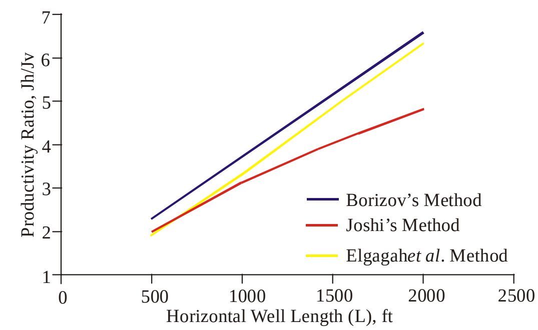

Fig. 4: Productivity ratio versus horizontal well length of method 2 using 40 acres spacing

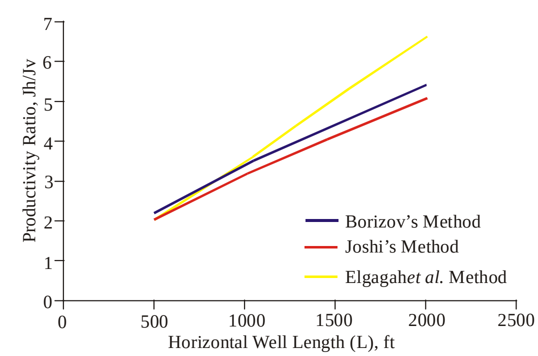

Fig. 5: Productivity ratio versus horizontal well length of method 1 using 80 acres spacing

increases), Joshi records the least productivity ratio (J_h/J_v) in both 40 and 80-acres spacing for methods notable in methods 2 whiles for the same conditions, the productivity ratio of the Elgagah conserve the same values in both methods 1 and 2 for 40-acres spacing. Also, the values obtained in methods 1 and 2 remain the same for 80-acres spacing.

Summary: The effective and efficient spacing of oil wells is a problem of vital importance to the oil industry. Conservation demands a maximum recovery, while

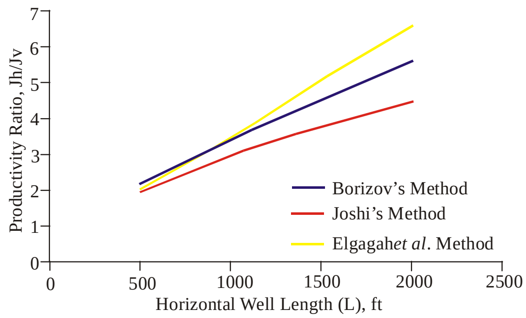

Fig. 6: Productivity ratio versus horizontal well length of method 2 using 80 acres spacing

economic considerations attach primary importance to profitable extraction of the hydrocarbon. A user friendly Excel Spreadsheet program has been developed to calculate the productivity values of horizontal wells using three major available productivity equations. Also, the developed spreadsheet program had been used to evaluate the effect of well spacing on the productivities of horizontal wells using productivity index approach and drainage area concept. It also helps to review the comparison between vertical and horizontal wells spacing based on drainage area concept. The important advantage of the programme is that it is a very useful tool for decision making for horizontal well spacing and very user-friendly as well.

CONCLUSION

- An Excel spreadsheet program was developed that incorporated the drainage area concept for the computation of the optimum number of horizontal wells and the productivity indices based on different acres spacing of vertical wells.
- Productivity values using the three available equations obtained are in good agreement with each other.
- Higher productivity ratios (J_h/J_v) values are obtainable with increasing horizontal well length.
- For the same horizontal length, the number of horizontal wells needed to develop a field decrease with increase in acreage and vice-versa.
- The productivity values obtained using the ellipse drainage area showed some deviations with high increase in horizontal length.

RECOMMENDATION

It is recommended that more research should be done as a follow up on the economic benefits of efficient well spacing using the three authors.

NOMENCLATURE

a = Parameter of Joshi's equation, ft

$$a = \left(\frac{L}{2}\right)\left[0.5 + \sqrt{\left(0.25 + \left(\frac{2r_{eh}}{L}\right)\right)^4}\right]$$

A_h = Drainage area of the horizontal well, acres
L = Length of the horizontal well, ft
b = Half minor axis of an ellipse, ft
A_v = Drainage Area of the Vertical Well, acres
a = Half major axis of an ellipse,ft
r_{eh} = Drainage radius of the horizontal well, ft
h = Reservoir thickness, ft
r_{ev} = Drainage radius of the vertical well, ft
r_w = Wellbore radius, ft
J_v = Vertical well productivity index, STB/day/psi
μ_o = Crude oil viscosity, cp
B_o = Oil formation volume factor, rbbl/STB
Q_{oh} = Horizontal well flowrate, STB/day
Δp = Pressure drop from the drainage boundary to wellbore, psi
J_h = Productivity index of the horizontal well, STB/day/psi
k_h = Horizontal permeability, md
k_v = Vertical permeability, md
L = Length of the horizontal well, ft
R = Parameter of Joshi's equation, ft
β = Parameter of Joshi's equation
r_{eh} = Drainage radius of the horizontal well, ft
J_h = Horizontal well productivity index, STB/day/psi
C = Constant, ft
J_h/J_v = Productivity Ratio

ACKNOWLEDGMENT

We would like to express our sincere gratitude to Dr. Samuel O. Osisanya and Dr. Godwin Chukwu for their advice, support, assistance and guidance. Without them, this work would not have been success.

Appendix A:

Table A1: Computation of the drainage radius of vertical well and the drainage area of the horizontal well and the number of horizontal wells with methods 1 and 2 using 40- acres spacing

Method for 40-acres	I				II			
Horizontal Well Length (L), ft	500	1000	1500	2000	500	1000	1500	2000
Vertical Well Drainage radius (rev=b)	745	745	745	745	745	745	745	745
Horizontal Well Drainage Area (A), Acres	57	74	91	108	53	67	80	94
Number of Horizontal Wells (n) for 400-acres field	7	5	4	4	7	6	5	4

Table A2: Computation of the drainage radius of vertical well and the drainage area of the horizontal well and the number of horizontal wells with methods 1 and 2 using 80- acres spacing.

Method for 80-acres	Using 40-acres				Using 80-acres			
Horizontal Well Length (L), ft	500	1000	1500	2000	500	1000	1500	2000
Vertical Well Drainage radius(rev=b)	1053	1053	1053	1053	1053	1053	1053	1053
Horizontal Well Drainage Area(A), Acres	104	128	153	177	99	118	137	156
Number of Horizontal Wells (n) for 400-acres field	4	3	3	2	4	3	3	3

Table A3: Average of the horizontal well drainage area and number of horizontal wells of method 1 and 2 using 40 and 80 acres spacing

Average Drainage Area of Method I & II	Using 40-acres				Using 80-acres			
Horizontal Well Length (L), ft	500	1000	1500	2000	500	1000	1500	2000
Average of Horizontal Well Drainage Area (A)	55	71	86	101	102	123	145	166
Number of Horizontal Wells (n) for 400-acres field	7	6	5	4	4	3	3	2

Appendix B:

Table B1: Effect of horizontal well length on the horizontal productivity index for method 1 using 40- acres spacing

Effect of Horizontal Well length on the Horizontal Productivity Index using 80-acres								
Method I and II	I				II			
Horizontal Well Length (L), ft	500	1000	1500	2000	500	1000	1500	2000
Horizontal Productivity Index, (Jh), STB/(day-psi)								
Borisov's Method	28.23	43.43	56.54	69.04	28.43	44.23	58.27	72.08
Joshi's Method	25.63	40.29	52.9	64.81	25.18	38.4	48.71	57.49
Elgagah-Osisanya-Tiab Method	26.35	44.83	65.29	84.6	26.35	44.83	65.29	84.6

Table B2: Effect of horizontal well length on the horizontal productivity index for methods 1 and 2 using 80- acres spacing

Effect of Horizontal Well length on the Horizontal Productivity Index using 40-acres								
Method I and II	I				II			
Horizontal Well Length (L), ft	500	1000	1500	2000	500	1000	1500	2000
Horizontal Productivity Index, (Jh), STB/(day-psi)								
Borisov's Method	30.78	49.16	65.89	82.68	31.09	50.42	68.74	87.85
Joshi's Method	27.72	45.14	60.87	76.22	27.03	42.17	54.15	64.45
Elgagah-Osisanya-Tiab Method	26.35	44.83	65.29	84.6	26.35	44.83	65.29	84.6

Appendix C:

Table C1: Computation of the productivity ratios and areal productivity index for a 57 and 53 (respectively) acres spacing horizontal well by different methods for horizontal well length of 500 ft for methods 1 and 2 using 40-acres spacing vertical well

J_h/J_v by Different Methods for Horizontal Well length of 500 ft using 40-acres								
	Horizontal Productivity Index (J_h), STB/(day-psi)	Vertical Productivity Index (J_v), STB/(day-psi)	J_h/J_v	Areal Productivity Index= J_h/acres, STB/(day-psi-acres) STB/(day-psi)	Horizontal Productivity Index (J_h), STB/(day-psi)	Vertical productivity Index (J_v),	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres)
Methods	I				II			
Borisov	30.78	13.41	2.3	0.54	31.09	13.41	2.32	0.58
Joshi	27.72	13.41	2.07	0.49	27.03	13.41	2.02	0.51
Elgagah *et al*	26.35	13.41	1.96	0.46	26.35	13.41	1.96	0.49

Table C2: Computation of the productivity ratios and areal productivity index for a 74 and 67 (respectively) acres spacing horizontal well by different methods for horizontal well length of 1000 ft for Methods 1 and 2 using 40-acres spacing vertical well

J_h/J_v by Different Methods for Horizontal Well length of 1000 ft using 40-acres

Methods	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v), STB/(day-psi)	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres) STB/(day-psi)	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity Index (J_v),	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres)
	I				II			
Borisov	49.16	13.41	3.67	0.66	50.42	13.41	3.76	0.75
Joshi	45.14	13.41	3.37	0.61	42.17	13.41	3.14	0.63
Elgagah *et al*	44.83	13.41	3.34	0.6	4.83	13.41	3.34	0.67

Table C3: Computation of the productivity ratios and areal productivity index for a 91 and 80 (respectively) acres spacing horizontal well by different methods for horizontal well length of 1500 ft for methods 1 and 2 using 40-acres spacing vertical well

J_h/J_v by Different Methods for Horizontal Well length of 1500 ft using 40-acres

Methods	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v), STB/(day-psi)	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres) STB/(day-psi)	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v),	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres)
	I				II			
Borisov	65.89	13.41	4.91	0.72	68.74	13.41	5.13	0.86
Joshi	60.87	13.41	4.54	0.67	54.15	13.41	4.04	0.67
Elgagah *et al*	65.29	13.41	4.87	0.72	65.29	13.41	4.87	0.81

Table C4: Computation of the productivity ratios and areal productivity index for a 94 and 108 (respectively) acres spacing horizontal well by different methods for horizontal well length of 2000 ft for methods 1 and 2 using 40-acres spacing vertical well

J_h/J_v by Different Methods for Horizontal Well length of 2000 ft using 40-acres

Methods	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v), STB/(day-psi)	J_h/J_v	Areal productivity Index= J_h/acres, STB/(day-psi-acres) STB/(day-psi)	Horizontal Productivity Index (J_h), STB/(day-psi)	Vertical productivity index (J_v),	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres)
	I				II			
Borisov	82.68	13.41	6.17	0.76	87.85	13.41	6.55	0.94
Joshi	76.22	13.41	5.68	0.70	64.45	13.41	4.81	0.69
Elgagah *et al*	84.6	13.41	6.31	0.78	84.6	13.41	6.31	0.90

Table C5: Computation of the productivity ratios and areal productivity index for a 104 and 99 (respectively) acres spacing horizontal well by different methods for horizontal well length of 500 ft for methods 1 and 2 using 80-acres spacing vertical well

J_h/J_v by Different Methods for Horizontal Well length of 500 ft using 80-acres

Methods	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v), STB/(day-psi)	J_h/J_v	Areal productivity Index = J_h/acres, STB/ (day-psi-acres) STB/ (day-psi)	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v),	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres)
	I				II			
Borisov	28.23	12.83	2.20	0.27	28.43	12.83	2.22	0.29
Joshi	25.63	12.83	2.00	0.25	25.18	12.83	1.96	0.25
Elgagah *et al*	26.35	12.83	2.05	0.25	26.35	12.83	2.05	0.27

Table C6: Computation of the productivity ratios and areal productivity index for a 128 and 118 (respectively) acres spacing horizontal well by different methods for horizontal well length of 1000 ft for methods 1 and 2 using 80-acres spacing vertical well

J_h/J_v by Different Methods for Horizontal Well length of 1000 ft using 80-acres

Methods	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v), STB/(day-psi)	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres) STB/(day-psi)	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v),	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres)
	I				II			
Borisov	43.43	12.83	3.39	0.34	44.23	12.83	3.45	0.37
Joshi	40.29	12.83	3.14	0.31	38.4	12.83	2.99	0.33
Elgagah *et al*	44.83	12.83	3.49	0.35	44.83	12.83	3.49	0.38

Table C7: Computation of the productivity ratios and areal productivity index for a 153 and 137 (respectively) acres spacing horizontal well by different methods for horizontal well length of 1500 ft for methods 1 and 2 using 80-acres spacing vertical well

J_h/J_v by Different Methods for Horizontal Well length of 1500 ft using 80-acres

Methods	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v), STB/(day-psi)	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres) STB/(day-psi)	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v),	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres)
	I				II			
Borisov	56.54	12.83	4.41	0.37	58.27	12.83	4.54	0.43
Joshi	52.9	12.83	4.12	0.35	48.71	12.83	3.8	0.36
Elgagah *et al*	65.29	12.83	5.09	0.43	65.29	12.83	5.09	0.48

Table C8: Computation of the productivity ratios and areal productivity index for a 177 and 156 (respectively) acres spacing horizontal well by different methods for horizontal well length of 2000 ft for method 1 using 80-acres spacing vertical well

J_h/J_v by Different Methods for Horizontal Well length of 1500 ft using 80-acres

Methods	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v), STB/(day-psi)	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres) STB/(day-psi)	Horizontal productivity index (J_h), STB/(day-psi)	Vertical productivity index (J_v),	J_h/J_v	Areal productivity Index = J_h/acres, STB/(day-psi-acres)
	I				II			
Borisov	69.04	12.83	5.38	0.39	72.08	12.83	5.62	0.46
Joshi	64.81	12.83	5.05	0.37	57.49	12.83	4.48	0.37
Elgagah *et al*	84.6	12.83	6.59	0.48	84.60	12.83	6.59	0.54

Appendix D:

Table D1: Summary results of the effect of horizontal well length on productivity ratio (j_h/j_v) for methods 1 and 2 using 40 acres spacing

40-Acres	Method I			Method II		
Horizontal Well Length (L), ft	Borizov J_h/J_v	Joshi J_h/J_v	Elgagah's *et al* J_h/J_v	Borizov J_h/J_v	Joshi J_h/J_v	Elgagah's *et al* J_h/J_v
500	2.3	2.07	1.96	2.32	2.02	1.96
1000	3.67	3.37	3.34	3.76	3.14	3.34
1500	4.91	4.54	4.87	5.13	4.04	4.87
2000	6.17	5.68	6.31	6.55	4.81	6.31

Table D2: Summary results of the effect of horizontal well length on productivity ratio (j_h/j_v) for methods 1 and 2 using 80 acres spacing

40-Acres	Method I			Method II		
Horizontal Well Length (L), ft	Borizov J_h/J_v	Joshi J_h/J_v	Elgagah's *et al* J_h/J_v	Borizov J_h/J_v	Joshi J_h/J_v	Elgagah's *et al* J_h/J_v
500	2.20	2	2.05	2.22	1.96	2.05
1000	3.39	3.14	3.49	3.45	2.99	3.49
1500	4.41	4.12	5.09	4.54	3.8	5.09
2000	5.38	5.05	6.59	5.62	4.48	6.59

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