STUDY ON PRODUCTIVITY IMPROVEMENT OF LOW PERMEABILITY GAS RESERVOIR BY HYDRAULIC FRACTURING

By: **Usman[1)]**, **Darsono Marino[2)]**, and **Marzuki Soelistijono**
Researcher[1)], Earth Investigator at "LEMIGAS" R & D Centre for Oil and Gas Technology
Jl. Ciledug Raya Kav. 109, Cipulir, Kebayoran Lama, Jakarta Selatan 12230, Indonesia
Tromol Pos: 6022/KBYB-Jakarta 12120, Telephone: 62-21-7394422, Faxsimile: 62-21-7246150
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ABSTRACT

The C5 well completed in the LZ tight gas limestone reservoir of C field is considered very good candidate for stimulation by hydraulic fracturing for the following reasons. The reservoir gross thickness of 127 ft is thick enough. Long fractures can be created. Penetrated zone is far from lowest known gas. The permeability of 0.2973 mD and the absolute open flow potential of 2.3 MMscf are low. Estimated proven gas accumulation of 24.5 Bscf is significant.

Crosslinked Gel + Hi Temp Stabilizer is used as fracturing fluid due to high temperature reservoir of 334^{o}F. High-strength of Sintered Bauxite proppant with 20/40 mesh sand is selected for this high stress formation of reservoir rock. The desired propped fracture width is 0.1004 inch. The fracture height is approximately 62.5 ft based on the half height from the centre depth of reservoir upward and downward. The propped fracture half-lengths are predicted by Perkins-Kern-Nordgren model.

Prediction shows that to have the propped fracture half-lengths of 1335, 1587, 1850, 2114, 2356, 2576 and 2640 ft for the propped fracture width of 0.1004 inch and the fracture height of 62.5 ft, the required proppant weight in one fracture wing are 139, 167, 195, 221, 246, 271 and 278 Mlbs respectively. With the obtained propped fracture half-lengths, the productivities improvement (J/Jo) are 13.8, 16.4, 19.2, 21.9, 24.4, 26.7 and 27.3.

Key Words: *Productivity improvement, low permeability, hydraulic fracturing, propped fracture geometry*

I. INTRODUCTION

Hydraulic fracturing is very popular and one of the primary engineering tools for improving well productivity associated with low permeability reservoirs. The low permeable of rock causes fluid flow difficulties. Hydraulic fracturing is intended to remedy or even improve the natural connection of the wellbore with the reservoir by creating high permeability canal deep into a formation and by increasing the formation flow area. The degree of productivity improvement depends on fracture length, formation permeability, and fracture conductivity. Improvement of well productivity from low permeability-high pressure reservoirs has been studied by several authors (Elbel, 1986, Holditch, S. A., 1991, and Darsono Marino, *et al.*, 1994, G. Coghlan and B. Holland, 2009). Massive hydraulic fracturing is recently possible to make thousands feet of fracture length.

The rock fractures owing to the action of the hydraulic fluid pressure and its growth strongly controlled by stress underground (Economides, et al., 1989). As most wells are vertical and the smallest stress is the minimum horizontal stress, the initial breakdown results in a vertical direction. The breakdown and early fracture growth expose new formation area to the injected fluid, and causing the rate of fluid leaking off into the formation stars to increase. However, if the pumping rate is maintained at a rate higher than the fluid-loss rate, then the newly created fracture must continue to propagate and grow. Hydraulic fluid to be transported into the fracture involves a propping agent. The propping agent remains in place to keep the fracture open and maintain the conductive flow path once pumping stops.

Well stimulation by hydraulic fracturing is aimed at tight reservoirs. The LZ reservoir in C field has been chosen as a reservoir candidate in this study because this reservoir is a tight limestone formation and is estimated to have significant gas accumulation. The reservoir intersected by the C5 well. This paper addresses evaluation of reservoir is candidates, hydraulic fracturing design, and prediction of productivity improvement after hydraulic fracturing treatment.

Candidate evaluation comprises the studies of geology, geophysics, and reservoir engineering. The results of candidate evaluation will be used in designing the hydraulic fracturing and predicting the productivity improvement after hydraulic fracturing treatment. Hydraulic fracturing design consists of fracturing fluid, proppant, and fracture model selections, fracture height and propped fracture width determinations, and propped fracture half-length and post fracture productivity index improvement predictions.

II. CANDIDATE EVALUATION

The main structure in the C field developed and formed the horst and graben structures with a NNW-SSE trending where the hydrocarbons trapped at the horst structures. From the results of subsurface mapping, the closure structure can be found on the limestone highs that they were controlled by tensional faults with a NNW-SSE trending (Figure 1). With this tensional direction, the fracture propagation will be in the same direction and allows us to design relatively long fracture length as in Figure 2.

The potential reservoir of C field derived from UZ, LZ, and JU formations which comprise of patch

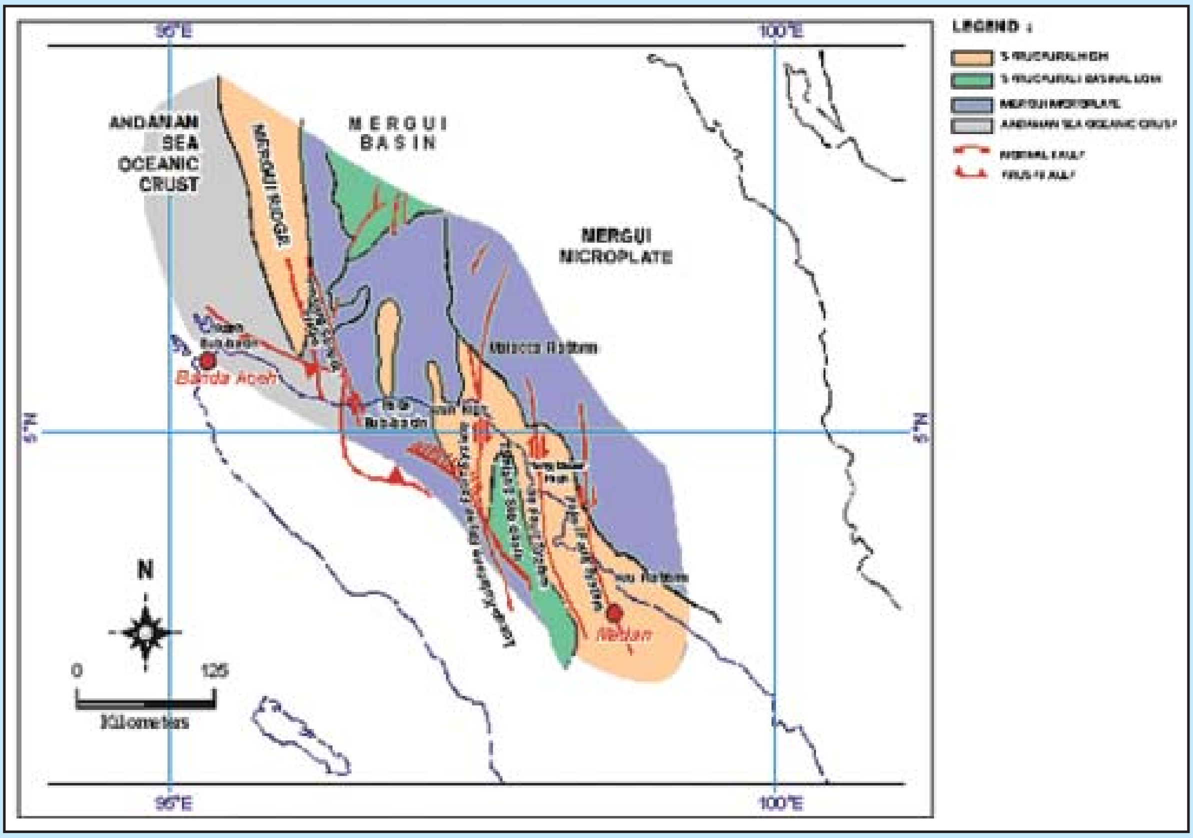

Figure 1
Regional tectonic element of the C field

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reef carbonates deposited in a moderate to high energy back-reef to reef-flat environment. The formations intersected by C2 and C5 wells. The C2 well penetrated UZ and JU formations while the C5 well found UZ and LZ formations. Original gas in-place for the UZ, LZ, and JU reservoirs are 1.0, 24.5, and 26.1 Bscf respectively. The Lowest known gas (LKG) of xx205 ft-ss derived from interval test that has been used instead of gas water contact to control the lower proven limit. LKG is found in JU reservoir of C2 well but not in C5 well. All interval of LZ reservoir in C5 well is gas zone.

Well test analysis indicates that effective gas permeabilities are 0.3610 mD and 0.2973 mD for JU and LZ reservoirs respectively. The magnitude of absolute open flow (AOF) potential of C2 well is 23.97 MMscf/day while the C5 well is 2.29 MMscf/day. The reservoir pressure and temperature at datum are 6767 psi and 334 ^{o}F.

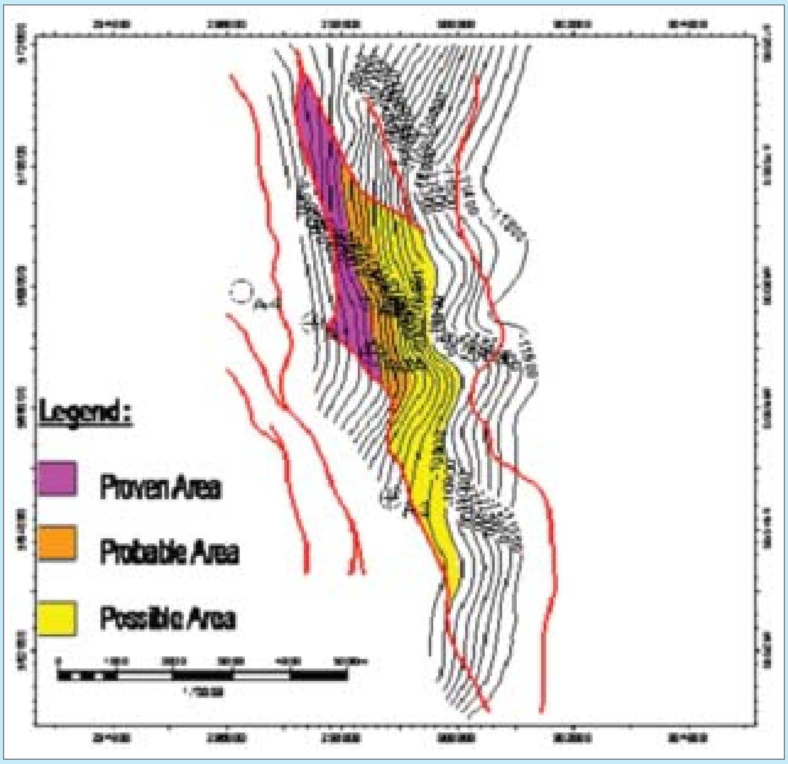

Figure 2
Depth structure map of LZ reservoir

With those above facts, the C5 well perforated in LZ reservoir is selected as hydraulic fracturing candidate in this study. Result of log analysis for this reservoir is depicted in Figure 3. Tight zone is also indicated by high resistivity due to the presence of high water saturation. The rock mechanic parameters for this formation interval of x908.7 – xx034.1 ft-ss are then evaluated based on the sonic log reading. These parameters are given in Table 1. The Poisson’s ratio of 0.3039 which is higher than one of the adjacent shale of 0.2797 indicates that the height of fracture can not be created as height as whole formation interval. This high Poisson’s ration is also indicating a tight zone.

Reservoir	LZ
Well	C5
KB, ft	35
Top reservoir, ft-ss	x908.7
Bottom reservoir, ft-ss	xx034.1
Gross reservoir, ft	125.4
Middle reservoir, ft-ss	x971.4
Top fracture, ft-ss	x940.2
Bottom fracture, ft-ss	xx002.7
Fracture height, ft	**62.5**
Avg. Poisson’s ratio, fraction	0.3039
Avg. shear modulus, psi/rad	2256984.6
Avg. Young’s modulus, lb/in2	5885000.0
Avg. bulk modulus, psi	4998579.5
Avg. compressibility, psi-1	2,001E-7
Avg. reservoir pressure, psi	6485.5
Reservoir temperature, oF	334
Overburden gradient, psi/ft	10357
Biot poro elastic constant, fraction	0.7
Avg. effective vertical stress, psi	5785.9
Avg. effective horizontal stress, psi	2527.1
Remarks	**Vertical fracture will be created**

Table 1
Rock mechanics properties and fracture height determination

III. HYDRAULIC FRACTURING DESIGN

A. Fracturing Fluid Selection

The fracturing fluid is a critical component of the hydraulic fracturing treatment. Its main functions are to open the fracture and to transport propping agent

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along the length of fracture. Fracturing fluid is selected by considering its influence to fracture geometry and to formation damage. Fracture geometry will depend on the ability of fluid to transport proppant, settling, its ability to pump, friction, leakoff, and degradation. Meanwhile, formation damage may be created by blocking, swelling, compatibility with the formation and reservoir fluid, and ability to flow back.

Due to high temperature reservoir of 334°F, crosslinked Gel + Hi Temp Stabilizer has been selected as fracturing fluid in this study. The properties of Crosslinked Gel + Hi Temp Stabilizer are listed in Table 2 (Allen, Thomas O., and Roberts, Alan P., 1989). The Crosslinked Gel + Hi Temp Stabilizer is the power law fluid. Its rheological properties to be related by:

$$\mu = \frac{47880 K'}{\gamma^{1-n'}} \qquad (1)$$

Refer to Nomenclature for explanation on notation.

Table 2
Properties of the selected fracturing fluid

Fluids System Dowell	Crosslinked Gel + Hi-Temp Stabilizer
Trade Name	Widefrac YF²400²
Chemical Code	J347 + J353
Polymer	Guar
Polymer Concentration, lb/bbl	2
Kind	Water Base Fracturing Fluid
Bottom-Hole Temp. Range, °F	200 – 350
Power Law Fluid Parameters:	
n' @300 °F	0.71300
K'@300 °F	0.00430
n' @350 °F	0.72700
K'@350 °F	0.00290
n' @334 °F	0.72252
K'@334 °F	0.00335
S_g	1.03
Fluid Loss Spurt Volume, ft³	0
Fluid Loss Coefficient, ft/min	0.003

B. Proppant Selection

Proppants are used to hold the walls of the fracture apart to create a conductive path to the wellbore after pumping has stopped and the fracturing fluid has leaked off. Placing the appropriate concentration and type of proppant in the fracture is critical to the success of a hydraulic fracturing treatment. Factors that should be considered in the proppant selection are easy to transport, embedgement, conductivity, and influence of closure pressure to conductivity. High stress of the reservoir rock needs high stress proppant. Sintered bauxite of 20/40 mesh size with properties given in Table 3 (Allen, Thomas O., and Roberts, Alan P., 1989) is selected to meet this requirement.

C. Fracture Geometry Estimation

Fracture geometry comprises propped width, propped fracture half-length, and fracture height. For a reservoir candidate with very low rock permeability, the productivity improve-

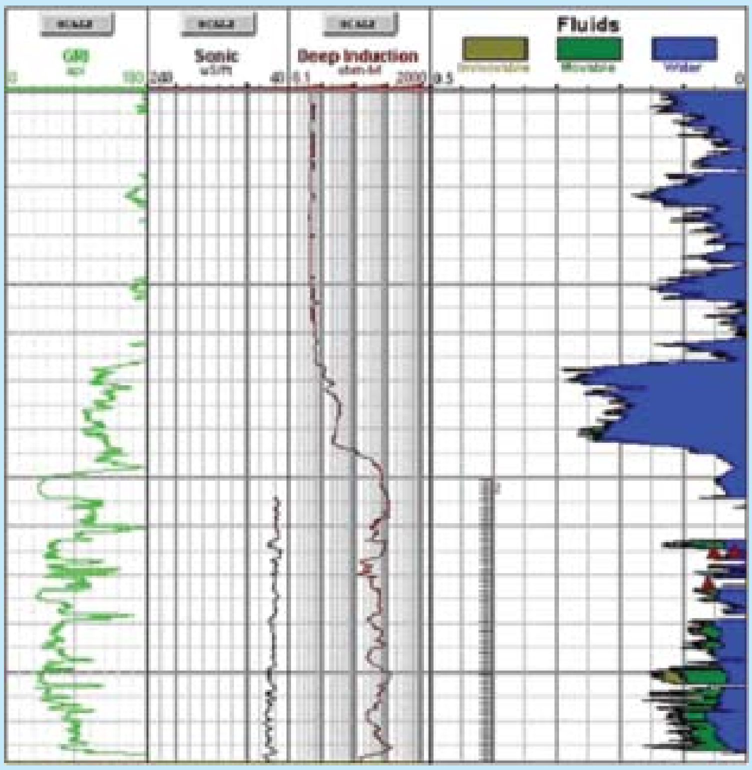

Figure 3
Log analysis of LZ reservoir

ment is mainly desired from the propped fracture half-length.

Perkins-Kern-Nodgren (PKN) model that allows us to predict the relatively large total length compared to the height is used through this study. A numeric of this model called Frac Dim was developed for the purpose of this study. Geersma-de Klerk (GDK) model which is more appropriate when the fracture length is smaller than the height is also included in the numeric model. Fracture configuration for the PKN model is illustrated in Figure 4 (Economides, et al., 1989).

1. Perkins-Kern-Nodgren (PKN) Model

PKN Model is based the following equations. The fracture length and the fracture width at well bore are given by

$$L = aL_D \quad (2)$$

$$w_{wb} = ew_D \quad (3)$$

where the Nordgren length and width constants and dimensionless geometries are defined respectively

$$a = 7.468\,x10^{-2}\left[\frac{(1-v)\mu_e q_i^5}{652\,C^8 h_g^4 G}\left(\frac{h_g}{h_n}\right)^s\right]^{1/3} \quad (4)$$

$$e = 55.0872x10^{-2}\left[\frac{16(1-v)\mu_e q_i^2}{C^2 h_g G}\left(\frac{h_g}{h_n}\right)^n\right]^{1/2} \quad (5)$$

$$L_D = 0.5809 t_D^{0.6295} \quad (6)$$

$$w_D = 0.5809 t_D^{0.1645} \quad (7)$$

The dimensionless job time is

$$t_D = \frac{t}{B} \quad (8)$$

where the Nordgren time constant is

$$B = 1.7737x10^{-4}\left(\frac{(1-v)\mu_e q_i^2 h_g^5}{32C^2 h_g G h_n}\right)^{\frac{1}{2}} \quad (9)$$

The effective non-Newtonion fracture fluid viscosity, expressed as

$$\mu_e = 47{,}880K\left(\frac{80.842 q_i}{h_g \overline{w}^2}\right)^{K-1} \quad (10)$$

Table 3
Properties of the selected proppant

Name	Sintered Bauxite
API Size, mesh	20/40
Avg. Proppant Diameter, inch	0.0248
Max. Proppant Diameter, inch	0.0335
Min. Proppant Diameter, inch	0.0167
Proppant Concentration, lbm/ft^3	0.4 – 4.0
Avg. Initial Closure Stress, psi	2,527.1
Permeability, mD	430
Density, gr/cc	3.70
Porosity, fraction	0.42
Remarks	**Permeability and size are good**

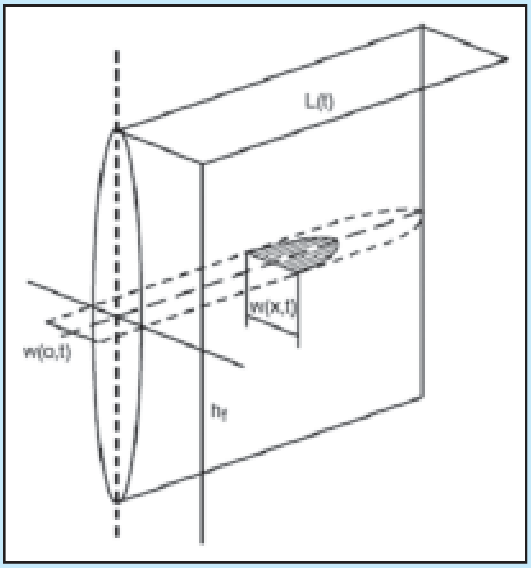

Figure 4
Fracture configuration – PKN model

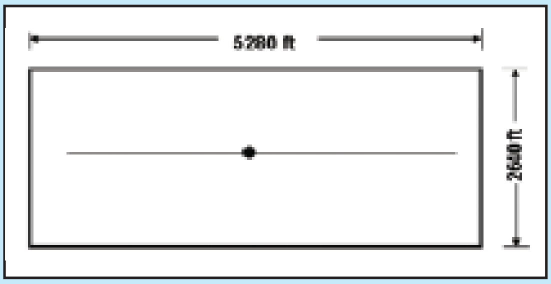

Figure 5
Plane view of fractured well for 320 acres spacing

where the volumetric average fracture width may depend only on the fracture width at well bore through a relation of the form

$$\overline{w} = \left(\frac{\pi}{4}\right)^2 w_{wb} \qquad (11)$$

Then, the volume of one wing fracture is given by

$$V = \overline{w} h_g L \qquad (12)$$

and the propped fracture length can be obtained as

$$Lp = \frac{12(V_{EOJ} - V_{pad})}{h_g \overline{w}} \qquad (13)$$

where the average propped fracture width at the end of pumping and at the end of pad volume are related to the propped fracture width as follow

$$w_p = \frac{12 m_p}{\rho_p h_g L_p} \qquad (14)$$

$$w_p = \left(\frac{\pi}{4}\right)^2 \overline{w}_{EOJ} \qquad (15)$$

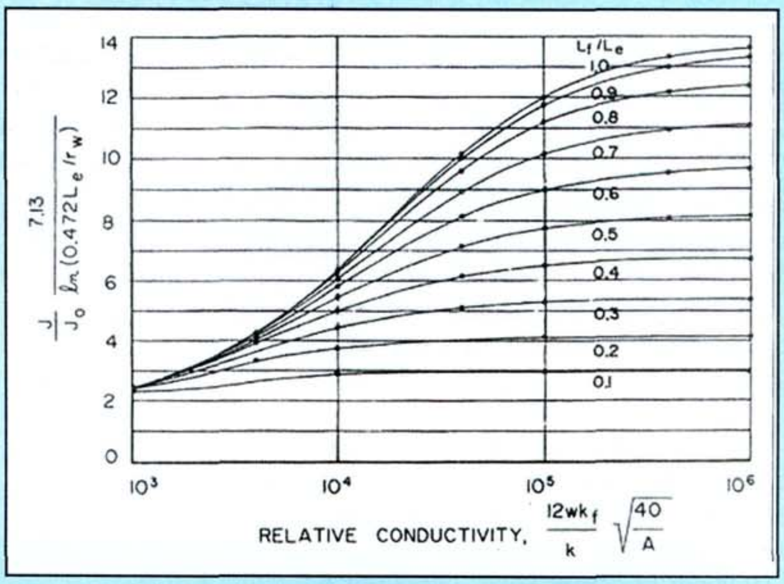

Figure 6
Holditch curve for Productivity Index (J/Jo) ratio

2. Propped Fracture Width and Fracture Height

The propped fracture width is determined about three times of maximum proppant diameter (Allen, Thomas O., and Roberts, Alan P., 1989) given in Table 2, which has been calculated to be 0.1004 inch (3×0.03346 inch). Meanwhile the fracture height is designed half the height from the center depth of reservoir upward and downward because the Poisson's ratio of carbonate reservoir rock is larger than adjacent bed of shale or cap rocks. The desired fracture top, bottom, and height are xx384.0 ft-KB (x940.2 ft-ss), xx451.5 ft-KB (xx002.7 ft-ss), and 62.5 ft respectively.

Table 4
Fixed input data for fracture geometries calculation

Formation permeability, mD	0.2973
q_i, bpm	15
h_g, ft	125.4
h_n, ft	62.5
S_g, dimensionless	1.03
C, ft/min$^{0.5}$	0.003
Fluid loss spurt volume, ft^3	0
n', dimensionless	0.72252
K', dimensionless	0.00335
t, minute	10
ρ_p, lbs/ft^3	3.70
Avg. proppand diameter, inch	0.0248
v, dimensionless	0.3039
Avg. Young's modulus, psi	5,885,000
Avg. Shear modulus, psi/rad	225,6984.6

3. Propped Fracture Half-Length

Given the drainage area spacing of 320 acres (52802640) ft)^2 leads to the maximum fracture half-length is 2640 ft (Figure 5). The propped fracture half-lengths for propped fracture width of 0.1004 are estimated using Frac Dim. The fracturing fluid injection rate is set to 15 barrel per minute (bpm) for this estimation. The proppant weight in one wing and the total time to injection (10 minutes pad injection) are varied. Table 4 exhibits the fixed input data. The variable input data are the total time to injection in min

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utes and the proppant weight in one fracture wing in Mlb.

To find propped fracture half-lengths in order to obtain 0.1004 inch propped fracture width, Frac Dim is run for each total injection time of 160, 200, 250, 300, 350, 400 and 425 minutes with different proppant weight in one fracture wing. Prediction shows that to have the propped fracture half-lengths of 1335, 1587, 1850, 2114, 2356, 2576 and 2640 ft, the required proppant weight in one fracture wing are 139, 167, 195, 221, 246, 271 and 278 Mlbs respectively.

4. Post Fracture Evaluation

Productivity Index (PI) improvement (J/Jo) after and before hydraulic fracturing is predicted using Holditch method revealed in Figure 6 (Gidley, Jhon L., 1989). The abscies and ordinate of the Holditch J/J_o Chart are 12 $w\, k_f/k$ (40/A) 0.5 and (J/J_o) [7.13/ln(0.472 L_e/r_w)] for various ratio of propped fracture length (L_f) to drainage radius (L_e). The Holditch J/J_o Chart is resulted from the fracture well simulation with modern finite difference reservoir simulator with Mc Guire-Sikora Chart modification. The assumptions for the Holditch J/J_o Chart are pseudo-steady state flow (constant rate production with no flow across the boundary), square drainage area, compressible fluids flow, and a fracture propped throughout the entire productive interval. A numeric Holditch J/J_o Chart model was developed for this study denoted as Post Frac.

The PI ratio of after and before hydraulic fracturing for various propped fracture half-length with propped fracture width of 0.10004 are evaluated by the developed Pos Frac. The fixed input data of Post Frac are listed in Table 5. With the obtained propped fracture half-lengths, the productivities improvement (J/Jo) are 13.8, 16.4, 19.2, 21.9, 24.4, 26.7 and 27.3. Table 6 summarizes the estimated fracture geometries and the PI ratios for the reservoir studied here.

IV. CONCLUSIONS

Following are the important conclusions drawn from this study:

1. The LZ tight gas limestone reservoir penetrated by C5 well is very good candidate for stimulation

Table 5
Fixed input data for PI prediction

Width times fracture permeability, mD-inch	44176
Reservoir effective permeability, mD	0.2973
Drainage area, acres	320
Half-width of drainage area, ft	167.3
Well radius, ft	0.354
Net pay, ft	107.6
Fracture height to net pay, ft	0.497607
Reservoir porosity, fraction	0.1001
Gas viscosity, cp	0.03439
Total compressibility, psi^{-1}	2,001E-07

Table 6
Summary of propped fracture half-length and PI for a 15 bpm injection rate

Injection Time (minute)	Proppant Weight (lbs)	Propped Fracture Half-Length (ft)	Propped Fracture Width (ft)	Fracture Permeability (mD)	Fracture Conductivity (mD-ft)	J/Jo
160	139	1335	0.1004	440000	3681	13.8
200	167	1587	0.1004	440000	3681	16.4
250	195	1850	0.1004	440000	3681	19.2
300	221	2114	0.1004	440000	3681	21.9
350	246	2356	0.1004	440000	3681	24.4
400	271	2576	0.1004	440000	3681	26.7
415	278	2640	0.1004	440000	3681	27.3

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by hydraulic fracturing. The reasons are the reservoir gross thickness of 127 ft is thick, long fractures can be created, penetrated zone far from lowest known gas, low permeability of 0.2973 mD, low absolute open flow potential of 2.3 MMscf, and significant proven gas accumulation of 24.5 Bscf.

2. Crosslinked Gel + Hi Temp Stabilizer fracturing fluid is selected to use because of the formation has high temperature of 300 ^oF. High-strength sintered bauxite proppant of 20/40 mesh size is recommended as the reservoir rock has high stress formation.
3. The propped fracture width is determined about three times of maximum proppant diameter, which is been calculated to be 0.1004 inch. Meanwhile the obtained fracture height is 62.5 ft designed from half height from the center depth of reservoir upward and downward interval of xx384.0 - xx451.5 ft-KB. The drainage area spacing is 320 acres (52802640) ft)^2 leads to the maximum fracture half-length of 2640 ft.
4. Prediction shows that to have the propped fracture half-lengths of 1335, 1587, 1850, 2114, 2356, 2576 and 2640 ft for the propped fracture width of 0.1004 inch and the fracture height of 62.5 ft, the required proppant weight in one fracture wing are 139, 167, 195, 221, 246, 271 and 278 Mlbs respectively. The corresponding productivity improvement (J/Jo) are 13.8, 16.4, 19.2, 21.9, 24.4, 26.7 and 27.3.

NOMENCLATURE

a = Nordgren length constant, ft
B = Nordgren time constant, minute
C = fluid loss coefficient, ft/min$^{0.5}$
e = Nordgren width constant, ft
G = shear modulus, psi
h_g = gross fracture height, ft
h_n = net fracture height, ft
K = power law constant, lbf-sec/ft^2
K' = power law consistency index, lbf-sec/ft^2
L = fracture length, ft
L_D = dimensionless fracture length
L_p = propped fracture length, ft
m_p = proppant weight in one fracture wing, lbs
n' = power law exponent, dimensionless
q_i = flow rate into one fracture wing, bpm
S_g = specific gravity of fracturing fluid, dimensionless
t = pumping time, minute
t_D = dimensionless job time
V = volume of one wing fracture, ft^3
V_{EOJ} = volume of one wing fracture at the end of pumping, ft^3
V_{pad} = volume of one wing fracture at the end of pad volume, ft^3
v = dimensionless poisson's ratio
$\overline{w}$ = volumetric average fracture width, inch
$\overline{w}_{BOJ}$ = average propped fracture width at the end of pumping, inch
w_D = dimensionless fracture width
w_p = propped fracture width, inch
w_{wb} = fracture width at well bore, inch
γ = shear rate, sec^{-1}
μ = viscosity, cp
μ_e = effective non-newtonian fracture-fluid viscosity, cp
ρ_p = proppant bulk density, lbs/ ft^3

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