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Current Use of Limited-Entry Hydraulic Fracturing in the Codell/Niobrara Formations—DJ Basin

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This paper was prepared for presentation at the 1995 SPE Rocky Mountain Meeting, Denver, March 20-22.

Abstract

In the last several years, limited-entry perforating has been used for hydraulically fracturing the Codell and Niobrara formations in the Denver-Julesburg (DJ) Basin. Limited-entry perforating reduces stimulation costs with no apparent effect on production.

Several papers have presented guidelines for designing a limited-entry treatment. A primary concern for treating multiple intervals is to ensure that both zones receive the necessary treatment. Currently, some operators simply ratio the number of perforations in each interval to the volume of treatment required for each interval. To ensure that both zones are being treated, a minimum pressure drop of 700 to 1,000 psi is usually used for limited-entry design. Changes in the perforation discharge coefficient and diameter during the treatment, combined with changes in the net treating pressure, affect the perforation pressure drop calculation. To determine the actual pressure drop across the perforations, designers use a real-time spreadsheet calculation.

This paper reviews limited-entry treatments pumped in 34 wells that verify spreadsheet calculations. Changes in the perforation discharge coefficient and diameter will be presented, as well as the effect of proppant concentration and velocity through the perforation. The current spreadsheet calculation used on location to calculate the pressure drop across the perforations is also discussed.

Introduction

The Niobrara and Codell formations are the two primary production intervals for most of the wells being completed in the DJ Basin. The Niobrara is a micritic limestone[1] consisting of three benches. At a depth of approximately 6,800 ft, the overall interval is generally between 150 and 250 ft thick. The Ft. Hays formation, the lower member of the Niobrara group, separates the Niobrara and Codell. There is a transition at the top of the Codell from a carbonate to a calcareous sandstone to a fine-grained sandstone with a high clay content.[2] At a depth of approximately 7,000 ft, the Codell is typically 8 to 14 ft thick. Both the Codell and Niobrara are overpressured gas reservoirs with a low permeability ranging from 0.01 to 0.1 md.

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In the past, the Codell and Niobrara intervals were fractured separately. The Codell was fractured first with treatments ranging from 150,000 to 350,000 lb of sand.[3] Next, all three benches of the Niobrara were fractured in a single treatment. As operators started moving into marginal acreage, the economics of fracture treatments had to be improved. In addition to optimizing fracture treatment sizes, other methods of reducing costs had to be found. One way of reducing cost while improving fracture treatments was to complete both intervals at once.

Limited-Entry Technique

Limited-entry perforating is one method for completing multiple intervals with a single treatment. During a limited-entry treatment, operators maintain a pressure drop across the perforations (P_{perf}) greater than the stress differential between the intervals. A pressure drop across the perforations is created by forcing the treating fluid through a limited number of perforations of a known diameter. The size and number of perforations placed opposite each interval are determined based on the percentage of the total treatment planned for each interval, and the total number of perforations required to produce the necessary pressure drop.[4]

During a limited-entry fracture treatment, P_{perf} should be monitored to ensure that all perforations are open and that the necessary pressure drop is maintained. With the advent of more advanced on-site computer systems, improved fluid friction correlations,[5-7] and better quality control programs, predictions of P_{perf} are becoming more accurate.

Calculations

The standard equation for calculating the bottomhole treating pressure during a fracturing treatment is shown below:

$$BHTP = WHTP + P_{hyd} - P_{frict} - P_{frac} \quad \text{.......... (1)}$$

Fracture-entry pressure (P_{frac}) has several components, including perforation friction, near-wellbore tortuosity, and fracture friction. When the rate per perforation is low (< 0.2 bbl/min/perf), P_{perf} is generally considered to be zero. In limited-entry jobs, however, this assumption is not the case, and determining the true bottomhole treating pressure (BHTP) becomes more difficult. Although near-wellbore tortuosity can be significant, for the purposes of this paper, near-wellbore tortuosity and fracture friction will be set to zero. As a result, P_{perf} will be the sole component of P_{frac} in Eq. 1.

During a fracturing treatment, the wellhead treating pressure (WHTP), pump rate, and proppant concentrations are constantly changing. Computer-based data acquisition systems (DAS) are used to record these three variables. Additional programs are then used to calculate hydrostatic pressure (P_{hyd}) and tubular friction pressure (P_{frict}).

During a typical fracture treatment, the pump rate is stopped after the first half of the pad fluid is pumped to determine the instantaneous shut-in pressure (ISIP). When the rate is zero, P_{perf} and P_{frict} are also zero, and the BHTP can be expressed as shown below:

$$BHTP = ISIP_s + P_{hyd} \quad \text{................................ (2)}$$

where

$ISIP_s$ = surface instantaneous shut-in pressure

When pumping is resumed, this BHTP value can be used in Eq. 1 to estimate P_{perf}. However, for most cases, BHTP either increases or decreases during the treatment, depending on the fracture geometry.[8,9] The effect this change in BHTP has on the calculation of P_{perf} can be significant and should be considered whenever possible during P_{perf} calculations.

P_{perf} can also be calculated from the following equation:

$$P_{perf} = 0.2369\rho\left[\frac{Q}{ND_p^2C_d}\right]^2 \quad \text{.................... (3)}$$

where

ρ = density of fluid (lb/gal)

Q = total pump rate (bbl/min)

N = number of perforations

When abrasive fluids, such as those containing sand, are pumped, the diameter of the perforation (D_p) and the coefficient of discharge(C_d) will change with respect to P_{perf} and sand concentration during the treatment. Several attempts have been made to quantify changes in D_p and C_d. Crump and Conway[10] demonstrated that C_d can increase by 15%. Willingham, et al., showed that the values for C_d can range from 0.62 to 0.95,[11] depending on whether abrasive fluid has been pumped through the perforations. Cramer[12] presented a hydraulic perforation erosion constant of 0.00418 in./1,000 lb of 20/40 mesh sand pumped. This constant is used to calculate the diameter increase of a 0.375-in. perforation, based on proppant volume pumped through a perforation. Changes in D_p and C_d will also be evaluated in this paper.

Well Information

In 1994, over 300 limited-entry treatments were pumped within the Wattenberg field. For this paper, limited-entry treatments in 34 wells were evaluated. All treatments are in the Codell/Niobrara intervals.

Of the 34 wells evaluated, 27 were completed with 4 1/2-in., 11.6-lb/ft, I-70 casing cemented in a 7 7/8-in. hole. Each well was perforated with six shots in the Niobrara and 12 shots in the Codell.

The remaining seven wells were completed with 2 7/8-in., 6.40-lb/ft, N-80 casing cemented in a 7 7/8-in. hole. Each of these wells was perforated with four shots in the Niobrara and seven shots in the Codell.

Both well types were perforated with jets. In the 27 wells having 4 1/2-in. casing, 3 1/8-in. OD carrier guns with 10-g charges were used. For the seven wells having 2 7/8-in. casing, 2 1/16-in. OD carrier guns with 8-g charges were used. Both gun types had a 0.31-in. perforation diameter.[13]

During a standard treatment, 412,000 lb of sand and 104,000 gal of fluid were placed into both intervals. The perforation placement was designed to place one-third of the treatment into the Niobrara and the remaining two-thirds of the treatment into the Codell. **Table 1** shows the various stages of a typical Codell/Niobrara treatment.

When treated individually, the initial BHTP in the Niobrara is typically 450 to 700 psi higher than in the Codell. (To help break down the Niobrara perforations, HCl is pumped ahead of the treatment.) Based on this stress differential, the proper ratio of perforations is 7 in the Niobrara and 11 in the Codell. However, a typical net pressure increase in the Niobrara is between 0 to 200 psi, while typical increases in the Codell are 400 to 600 psi. As a result, the BHTP is essentially the same for both intervals at the end of the treatments. The 6-to-12 ratio of perforations is based on these BHTP conditions. Final results from multiple tracers run in early treatments indicate that all intervals were taking fluid throughout the entire treatment. **Fig. 1** (Page 4) shows the results of one of the tracer surveys. Production results from limited-entry treatments are comparable to wells treated individually, further validating that the proper proportion of the treatment is being placed in each interval.

Table 1: Typical Codell/Niobrara Treatment Schedule

Stage	Clean Volume	Fluid Description	Sand Concentration
1	1,000	HCl	—
2	20,000	35 lb CMHPG*	—
3	40,000	35 lb CMHPG*	2 - 4.7
4	20,000	30 lb CMHPG*	4.7 - 6
5	20,000	30 lb CMHPG*	6 - 8
6	4,000	30 lb CMHPG*	8
7	4,000	Water	—

*Per 1,000 gal

Data Acquisition

All treatments were recorded on the same data acquisition system. In addition to recording the standard pressure, rate, and density variables, this system also records all real-time calculated values. All the treatments used for this paper were recalculated using the same program.

The software program calculates BHTP at time t ($BHTP_{calc}$) based on the following equation:

$$BHTP_{calc} = WHTP + P_{hyd} - P_{frict} \quad \text{................. (4)}$$

To calculate P_{hyd} and P_{frict}, the program breaks the wellbore into 15 segments and then tracks each segment as it moves down the wellbore. The software also has several options available for calculating pipe friction.

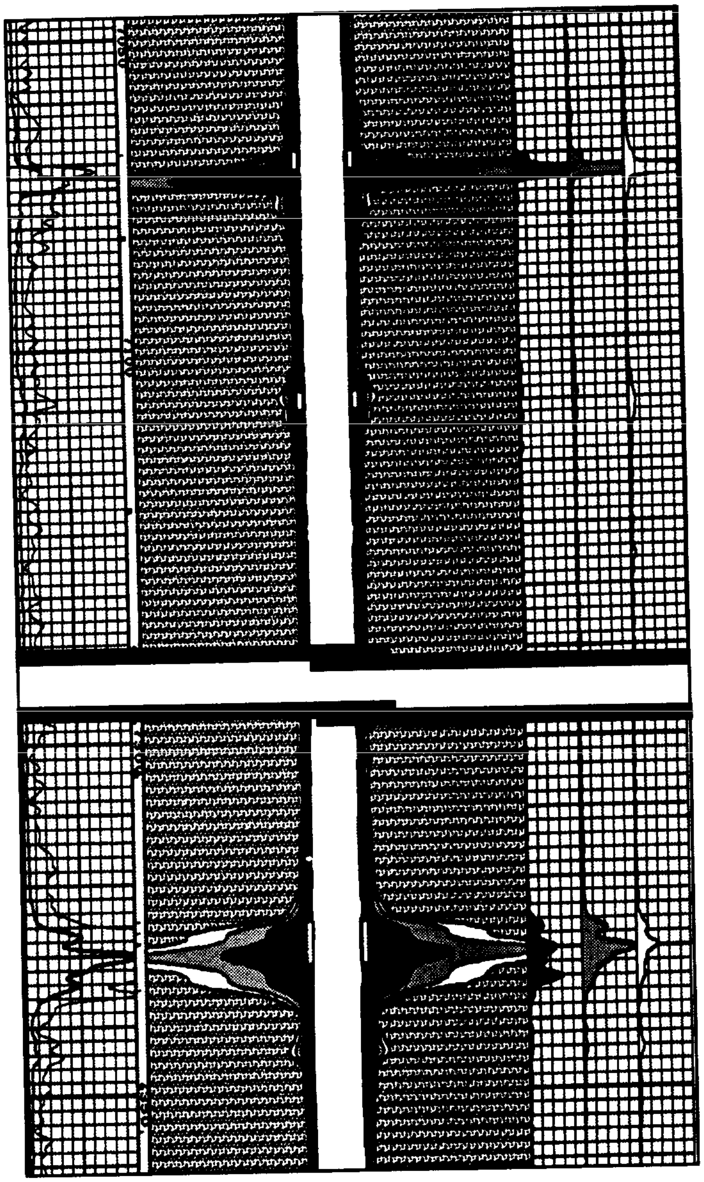

Fig. 1—Multiple tracer log of a limited-entry treatment.

Evaluation of P_{perf}

To evaluate P_{perf} and its associated variables C_d and D_p, the program compares the P_{perf} calculated from Eq. 1 to the P_{perf} calculated from Eq. 3. Independent variables are used by each equation to calculate P_{perf}. This method was also used in early versions of the real-time perforation friction spreadsheet to verify the number of open perforations as well as P_{perf}.

WHTP is a direct measurement; with the accuracy of today's transducers, WHTP will be very consistent. Calculating the hydrostatic pressure of the wellbore computer systems. Calculating pipe friction and changes in the BHTP are not as accurate, however.

When Eq. 1 is used to calculate P_{perf}, the value for BHTP is generally calculated from Eq. 2, and an ISIP is taken during pad. This BHTP value is then used for the remainder of the treatment. In Codell/Niobrara treatments, the net pressure can increase from 50 to 500 psi during pumping. If the increase in net pressure is ignored, P_{perf} will be overcalculated by the net pressure value, as the following equation shows.

$$P_{perf_t} = BHTP_{calc} - \left(BHISIP_{pad} + \Delta Net_t\right) \quad \text{.......................................} \quad (5)$$

Fig. 2 shows the effect that the change in net pressure has in calculation P_{perf} for one well. In this paper, ΔNet is the difference between the ISIP taken during the pad and the final ISIP at the end of the treatment. For the final ISIP, the DAS-calculated value for BHTP was used, which is a more accurate calculation of the final P_{hyd}. The ΔNet was then divided by the number of data points and applied linearly throughout the treatment.

For real-time calculation of P_{perf}, an accurate prediction of the ΔNet is required. Net pressure can be determined based on other treatment results on wells in the area, or 3-D models can be used to predict ΔNet throughout the treatment.

Pipe friction is dependent on the tubular configuration, fluid rheology, sand concentration, and treatment rate. Because of varying sand concentrations and fluid

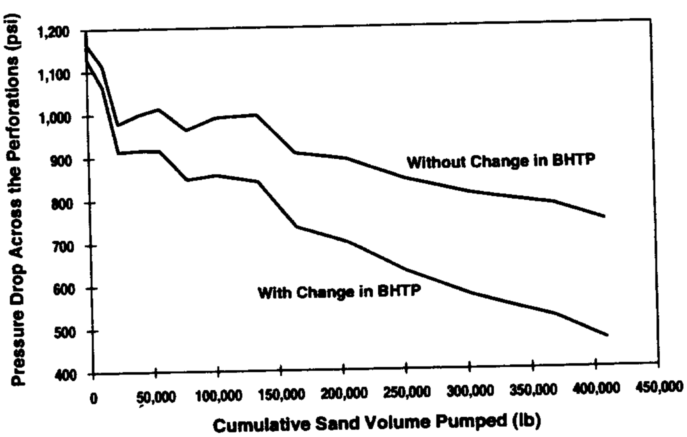

Fig. 2—P_{perf} calculated with and without the change in BHTP.

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