CONSIDERATIONS IN HORIZONTAL WELL COMPLETIONS

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ABSTRACT

Fracturing has become a viable and important option for completing horizontal wells, especially in the case of tight-gas formations. There are many fracturing processes and methods to consider for placement of these fractures. Optimization of the completion process, including the number and size of fractures, is still a challenging consideration.

Fracturing horizontal wells has unique aspects that require special attention to secure successful treatment. Differences between horizontal and vertical wells exist in areas of rock mechanics, reservoir engineering, and operations. All of these aspects affect the optimization process for successful treatment placement and optimum asset performance.

This paper presents various factors crucial to successful completion of a fractured horizontal well. We will discuss these factors in relation to both longitudinal and transverse fracture applications. Success factors include the optimum perforation process, overcoming fluid flow convergence toward the wellbore in case of a transverse fracture, and the fluid flow and stress interference among multiple fractures.

The paper presents field cases and laboratory and numerical experimentations illustrating the impact of the various factors on the completion of the horizontal wells, and the optimization of the fracturing process. Unique aspects that may be encountered during fracturing a horizontal well in tight-gas formations are noted.

INTRODUCTION

Fracturing is no longer restricted to vertical wells drilled in hard formations with low permeability. High permeability, soft formation wells, and horizontal wells are now routinely fractured. This trend has contributed to the importance of examining all reservoir aspects to reach a better understanding of efficient fracture design and eventually the optimization of the well completion. This examination should include the theoretical and operational parameters influencing the completion of a well. Fluid flow and geomechanical aspects of fracturing a well cannot be ignored when multiple fractures are created. This is especially true in the case of fracturing horizontal wells.

Although unstimulated horizontal wells have been very successful in naturally fractured reservoirs and in reservoirs with gas- or water-coning problems, there are many situations where fracturing a horizontal well to improve production capability is a viable or necessary option. The orientation of a hydraulic fracture, with respect to the wellbore, is directly related to the wellbore azimuth with respect to the in-situ stress field. Therefore, the possibility of fracturing a horizontal well must be considered before the well is drilled. The appropriate contingency plans should be made to anticipate the possibility of low productivity from an unstimulated well.

It should also be remembered that fracturing a horizontal well may dictate which direction the well should be drilled and how it should be completed. Fracturing a horizontal well does not necessarily mean that the well has to be cased and cemented. There are many cases of fracturing horizontal wells in openhole or uncemented liners. The field example within this paper discusses one of these cases. Fracturing a horizontal well may be considered when one of the following situations is apparent.

- Restricted vertical flow caused by low vertical permeability or lamination.
- Low formation productivity because of low formation permeability.
- Low-stress contrast between the pay zone and the surrounding layers. In this case, a large fracturing treatment of a vertical well would not be an acceptable option because the fracture would grow in height as well as length.

Although fundamentally similar to fracturing vertical wells, fracturing horizontal wells has unique aspects that require special attention if the most successful treatment is to be secured. Differences between horizontal and vertical wells exist in the areas of fluid flow, rock mechanics, perforation strategy, and operational procedures. It has already been well established that the two extreme fracture orientation cases are transverse and longitudinal fractures. The strategy may also be affected by the formation permeability. Tight-gas formations may require a somewhat different treatment than a higher-permeability, oil-bearing formation.

FLUID FLOW ASPECTS OF FRACTURED HORIZONTAL WELLS

A horizontal well may be fractured to create either a series of transverse or longitudinal fractures. The pattern of flow and the areal coverage of the reservoir vary, depending on which scheme is used. Based on which completion type is chosen direction of drilling, perforation, etc. will have to be planned accordingly. Many authors have presented papers on the subject.[1-9]

FLOW REGIMES IN A FRACTURED HORIZONTAL WELL—TRANSVERSE FRACTURE

The early-time flow regime around a transverse fracture is different from the flow regime that occurred in the case of a fractured vertical well. Because the wellbore intersects the fracture in the center, the flow regime may initially be approximated by radial flow, followed by linear-radial flow.[3] The linear radial flow period corresponds to the bi-linear flow regime observed when fracturing a vertical well. Because multiple fractures are usually created, this linear-radial flow period ends when interference from the surrounding fractures is observed.

The radial convergence of the fluid toward the wellbore results in an additional pressure drop as compared the bilinear flow regime. This effect will cause a single transverse fracture to be less effective than a fracture intersecting a vertical well. The difference between the two declines as the fracture conductivity increases. The two flow regimes are identical for infinite conductivity fractures. The problem with this convergence of fluid may be exacerbated if a non-Darcy effect becomes significant.

Because high pressure drop is expected because of the fluid-flow convergence that occurs around the entry to the transverse fracture, tailing in the pumping stages of a hydraulic fracturing operation with a high conductivity “tail-in” proppant is recommended. Hydrajetting the wellbore before fracturing and packing the fracture during the later stages of fracturing with a larger and/or stronger proppant is highly recommended.

Because the radial-linear solution is valid only at early time, several authors[10-15] have expanded their investigations to study the flow regimes in the reservoir at a later time. Roberts, et al.[10] presented a description of the expected flow regimes linear-radial, formation-linear, compound linear, and finally, pseudo-radial flow regimes. These flow regimes are illustrated in **Fig. 1**. A transition period is expected between the various flow regimes. Some of these flow regimes may not be apparent, depending on reservoir extent, continuity, and geometry.

When the wellbore is allowed to contribute to production, by either fracturing openhole or by performing perforating operations, there will be some impact on the well productivity and on the flow regimes. It is apparent that the overall magnitude of this production effect will depend on the reservoir and fluid properties; however, as **Figs. 2a–2c** demonstrate, the contribution of the wellbore will decline fairly quickly with time. It should be noted however, that there will be an expected deviation from the ideal flow regime as described in Fig. 1.

Vertical permeability has a very strong effect on the contribution of the unfractured part of the horizontal well. In tighter formations with low vertical permeability, almost all production will be flowing to the well via the fractures.

Fig. 1 corresponds to fracturing a horizontal well that has been cased and cemented prior to fracturing, while Fig. 2 is equivalent to creating hydraulic fractures in an open hole using techniques such as hydrajet-assisted fracturing. **Fig. 2** represents flow in a formation of moderately high permeability.

FLOW REGIMES IN A FRACTURED HORIZONTAL WELL—LONGITUDINAL FRACTURE

The performance of longitudinal fractures may be compared to that of fractured vertical wells and transverse fractures. This comparison depends on dimensionless fracture conductivity, vertical permeability of the formation, and the fracture aspect ratio. Aspect ratio of the fracture is defined as the ratio of fracture length (tip to tip) to height.

When the fracture conductivity is infinite or almost infinite, the fluid flow in the reservoir towards the longitudinal fracture will be in the horizontal plane only. In other words, the vertical permeability would not have any effect on the flow regime. In this case, the flow regime would be directly comparable to the flow regimes for a vertical well intersecting an infinitely conductive vertical fracture.

However, if the dimensionless fracture conductivity is low, the fluid may tend to move a greater distance in the formation towards the wellbore. In such a case, the vertical permeability would directly affect the fluid flow. Therefore, in this case, the behavior for a horizontal well intersecting a longitudinal fracture would be different from a vertical well intersecting a vertical fracture. In addition, it is intuitive that the distance the fluid moves within the longitudinal fracture is somewhat less than in a vertical well intersecting a fracture with similar dimensions.

PRODUCTION COMPARISON FROM DIFFERENT WELL TYPES

Experimentations with a numerical simulator for transverse, longitudinal, and fractured vertical wells have been performed and the results are presented in **Fig. 3**. In this case the total fracture area (height-length product of the fracture) is the same for each fracturing scheme. The aspect ratio for the longitudinal and fractured vertical well is 3.3. The figure shows the clear superiority of a longitudinal fracture over a fractured vertical well when the fracture conductivity becomes low. At high dimensionless-fracture conductivity the two scenarios are comparable. This means that in case of a tight, thick formation where the aspect ratio is not much larger than 1 and achieving a high dimensionless conductivity is relatively easy, a longitudinal or fractured vertical well with the same fracture dimensions would be competitive. However, in the case where formation permeability is mid-range, 1-5 md, where the dimensionless conductivity would be relatively low, it would be preferable to create a longitudinal fracture. Similarly, if the formation is fairly thin, potentially leading to a large aspect ratio, a longitudinal fracture would also outperform a fractured vertical well. Operationally, creating longitudinal fractures using several stages is more achievable than creating a long fracture in a vertical located in a thin formation.

The performance of transverse fractures is, however, considerably superior to the performance of either longitudinal or fractured vertical well in the case of high dimensionless conductivity fractures. This is illustrated in **Fig. 4**. When the fracture dimensionless conductivity is low, the performance of a longitudinal fracture would be comparable to that of transverse fractures. However, transverse fractures can provide potential advantages vs. longitudinal fractures even at low dimensionless conductivities, in late-time performance. This advantage is related to the convergence of fluid within the fractures as the fluid approaches the wellbore. As has been discussed earlier the effect of convergence becomes more severe as the dimensionless fracture conductivity declines.

To address this convergence phenomenon, it is suggested to maintain high fracture conductivity near the mouth of the fracture. This may be achieved by tailing in the fracturing treatment with larger and or stronger proppant. Additional methods to enhance fracture/wellbore communication include initiating the fracture by jetting the wellbore or designing a tip screenout and packing the frac to increase the frac width at the wellbore.

Fig. 4 also includes a case that demonstrates the influence of achieving a high dimensionless fracture conductivity for just a 10-ft radius from the wellbore. The observed tremendous increase in well productivity/deliverability leaves no doubt regarding the importance in achieving and maintaining conductivity in the near-wellbore regions when designing these treatments.

APPLICATION TO TIGHT-GAS FORMATIONS

With the recent significant increase in gas and oil prices coupled with the realization of reduced reserve of conventional gas, interest and activity in unconventional gas reservoirs has increased significantly. Unconventional gas reservoirs include tight-gas formations, coalbed methane (CBM) formations, and fractured gas shale. Of particular intersest are tight-gas formations.

In this section we investigate productivity from tight-gas formations. Because of the low formation permeability, reaching very high dimensionless fracture conductivity is definitely within reach, meaning that essentially infinite fracture conductivity is achievable. From our previous discussion it would be expected that the performance of a set of transverse fractures would be superior a longitudinal fracture with the same area. A comparison of different completion types was, however, conducted.

In the base runs we assumed that the formation is 400 ft thick, and having permeability of 0.005 md. The effect of height and permeability was also considered. The investigated properties are given below

- Pressure 4,000 psi.
- Fracture Parameters.
  - half length 400 ft, Conductivity, 1750 md-ft
- MLT - 6 arms 550 ft each plus the vertical well.
- Horizontal well
  - 1320 ft.
  - Four fractures, each equal to the one described above.

Fig.5 shows a comparison of production for a tight-gas formation with formation permeability of 0.005 md. **Fig. 6** shows the same simulation with a formation permeability of 0.05 md. The figures show the performance superiority of of transverse fractures over other completion. They also show that as permeability gets higher, the gap between the transverse fracture completion and other completions narrows.

GEOMECHANICS CONSIDERATION OF FRACTURING HORIZONTAL WELLS

Three different aspects of fracturing in horizontal wells are discussed in this section: breakdown pressure, depletion effects, and stress interference of multiple transverse or longitudinal fractures.

Fracturing Breakdown—Transverse Fractures

The Hubert and Willis[19] failure criterion is commonly used to predict the breakdown pressure of a vertical well. In vertical wells, fractures are usually axial, and consequently, the failure criterion occurs when the tangential pressure is less than zero. In other words, the tensile breakdown pressure for a vertical well under this failure criterion is given by the following equation.

$$p_b = 3\sigma_h - \sigma_H \text{ ....(3)}$$

This failure criterion may be used in case of longitudinal fractures to determine the breakdown pressure. However, it has been observed in the laboratory[20,21] and in the field[21] that the Hubert and Willis failure criterion may significantly underestimate the breakdown pressure for a transverse fracture. This is essentially because this failure criterion assumes the creation of an axial fracture. Weijers, et al.[22] could not correlate the fracture initiation pressure and the tensile failure solution. The hubert and Willis failure criterion is valid for a vertical well or a horizontal well where the fracture is longitudinal, however it does not fit a situation in which the fracture is transverse.

The Hoek and Brown[23,24] failure criterion was applied to fracturing a horizontal well[25] (creating a transverse fracture). The breakdown pressure under this failure criterion is given in the following equation:

$$p_b = \frac{3}{2}\sigma_l - \sigma_L - \sigma_c \text{ ....(4)}$$

where σ_L is the largest of $\sigma_v \; and \; \sigma_H$ and σ_l is the smaller of the two.

σ_c is the compressive strength of the rock.

This failure criterion was applied to laboratory experiments for fractured horizontal wells with a reasonable success. **Table 1** gives a comparison of observed versus calculated breakdown pressure for a transverse fracture. Please note that each row of the table represents several experiments.

Table 1 clearly demonstrates that the Hoek and Brown failure criterion gives a significantly better estimate of the breakdown pressure necessary to create a transverse fracture than the Hubert and Willis failure criterion. The Hubert and Willis failure criterion calculation is an indication of the breakdown pressure necessary to create an axial fracture. Table 1 indicates that under the same stress field, it is easier to create an axial fracture than a transverse fracture.

Owens, et al.[26] presented another approach for calculating the breakdown pressure of an arbitrarily oriented horizontal well. In their approach, Owens, et al. applied the equations developed by Daneshy[27] to calculate fracture initiation pressure. Their calculated values compared favorably to observed field data from a North Sea field.

One technique that has been successfully applied in cemented and cased horizontal wells requires drilling the well in the direction of minimum stress, and then perforating very short intervals. This interval should not be more than four times the openhole diameter of the wellbore. **Fig. 7,**[20] which demonstrates that if the perforated interval is short, a planar fracture is created that is transverse to the well. If the perforated is longer than four times the diameter of the well, then we would expect to see a complex, non-planar fracture, such as in **Fig. 8.**[28]

Another technique that has been developed for particular application in open hole relies on the use of hydrajetting. Hydrajetting the borehole wall creates a clean, fairly large, and continuous path into the formation.[29-32] Additionally, hydrajetting creates a clean path away from the wellbore, thus reducing the breakdown pressure necessary to initiate the transverse fracture. In an experiment to study the effect of notching, which is similar but not identical to hydrajetting, on the creation of a longitudinal fracture, it was found that a notched well could be fractured at a lower pressure than either an openhole or perforated formation. **Fig. 9** shows the setup of the experiments. Once the fracture is initiated, the hydrajetting process uses basic fluid mechanics principles to cause the fluid being injected, through both the annulus and tubing, to move into the fracture plane. This is essentially the basic principle behind the jet pump. Also, the mixing of high-velocity fluid coming from the jet, with the low-velocity fluid coming from the annulus, causes the pressure inside the hydrajetted tunnel to increase. The basic fluid mechanics equation for this principle is known as Bernoulli’s equation.

Fracturing Breakdown—Longitudinal Fractures

To create longitudinal (axial) fractures, the well has to be drilled perpendicular to the minimum horizontal stress. The most commonplace completion technique chosen is to conventionally case and cement the well, then perforate short sections in the vertical plane. Subsequently, sections of the well are isolated and fractured in the same way. The length of the perforated sections depends on the mechanical and physical homogeneity of the formation and on the degree of control that one may want to exercise over creating the longitudinal fractures. Since longer fracture require higher injection rates, injection rate may be one of the controlling factors. Creating elongated slots or hydrajetting in the upper and/or lower sides of the well could very well replace the perforation process, and would lead to lower breakdown pressure.

The shorter the isolated area, the more control one has over the created fracture. However, if the formation is fairly homogeneous, a longer section may be fractured without compromising this control. The extreme case is to fracture the total length of the horizontal well in one stage under openhole completion conditions. Such a scenario was implemented in several wells successfully.[33]

PRESSURE DEPLETION EFFECTS

As the pressure inside the reservoir and fracture declines, the reservoir permeability, porosity, and the fracture conductivity may decline. This process is generally not reversible, although undergoing hysteresis. The nature of the hysteresis depends on the particular formation rock properties. To study the effect of the change of the reservoir permeability as a function of stress, we applied the approach developed by Settari[34] into the simulator used in this study.

Fig. 10 shows the change in pressure as function of the total production for two cases. All the reservoir parameters are the same except for considering the effect of changing permeability as reservoir pressure declines. The figure clearly indicates that ignoring the effect of geomechanics will have an effect on the long-term production. **Fig. 10** shows that the difference in cumulative production is only 6%, however this translates, with current oil prices of $70/bbl, to over-estimation of revenue by more than $3,000,000.

The effect could become more significant if the hysteresis effect on reduction of permeability and porosity is considered and the well had gone through several cycles of production and shut-in.

STRESS INTERFERENCE BETWEEN FRACTURES

The creation of a hydraulic fracture can readily alter the stress field within its immediate vicinity[35-36] and thus potentially affect the orientation of other hydraulic fractures created from nearby wells. Sneddon’s solution for a semi-infinite fracture[38] was used by Warpinski and Branagan[37] to study the alteration of stress around a fracture. The effect may be more significant if multiple fractures are created from a single well. Soliman[38] studied this effect using Sneddon’s solution for both a semi-infinite[35] and penny-shaped[36] fractures. The presence of cased hole versus openhole completion could also make a difference.

In fracturing horizontal wells with multiple transverse fractures, it is important to understand the effect that stress interference may have on fracture behavior. Because of the creation of multiple propped fractures, it is expected that the stress interference will increase as the number of fractures increases.

Fig. 11 indicates that if the distances between the transverse fractures are equal to the fracture diameter, and dimensionless distance between fractures is equal to 1, then while creating the fourth fracture it would be expected that the net pressure would increase by 21% above the net pressure encountered during the creation of the first fracture. The net pressure is defined as the fracturing pressure above closure pressure. This increase in pressure may not be alarming. However, if the distance between the fractures is one-half that of the diameter of the fractures, then the net pressure expected during the creation of the fourth fracture is almost twice that encountered during the creation of the first fracture. The net pressure significantly increases in later stages as shown in **Fig. 11.**

The interference between fractures causes all stresses to change, and the minimum horizontal stress (perpendicular to the fracture) increases by a larger degree than the other two. Actually the stresses parallel to the fracture will slightly decline at a distance larger than 0.4 of the fracture diameter. This will cause the stress contrast to change (decline) as more fractures are created. If at any point the stress changes by a value larger than the original contrast, it would be expected that the preferred fracturing orientation near the wellbore may also change. If not accounted for, this could be problematic. The situation is even more critical when openhole fracturing such as hydrajet-assisted fracturing[29-31] is practiced. **Fig. 12** shows the potential change in stress contrast caused by creation of multiple fractures. This figure indicates that if the distances between the transverse fractures are equal and equal to the fracture diameter, then while creating the fourth fracture it would expected that the change of stress contrast would be about 24% of the net pressure encountered during the creation of the first fracture. If the distance between the fractures is half that of the diameter of the fractures then the change in the stress contrast expected during the creating the third fracture is a little more than the net pressure encountered during the creation of the first fracture. In other words the stress contrast has changed by an amount about twice the net pressure encountered during the creation of the first fracture.

Change in stress orientation near the wellbore does not mean change away from the wellbore. This indicates that the change in the stress field near the wellbore may be reversed causing the creation of a longitudinal instead of a transverse fracture. However away from the wellbore the stress field may revert back to its original condition. This would cause the fracture to reorient itself again in space. This again may cause severe tortousity and potentially sanding out of the fracture.

Fig. 13 is a Barnett Shale horizontal well with uncemented casing that was treated with 12 hydrajet waterfrac treatments in one day. The graph clearly demonstrates increasing stress interference between the fractures from the first frac through the 12th frac. Based on this evidence, it would appear that highly-fractured formations have the capacity to absorb stresses created by the growth of hydraulically induced fractures while reservoirs with little natural fracturing would have substantial treating pressure issues when creating multiple fractures using the hydrajet-fracturing process. In Fig. 13 the change in ISIP represent a change in the closure pressure or in other words change in the minimum stress.

EFFECT OF DIFFERENT TYPES OF COMPLETION OF HORIZONTAL WELLS ON STRESS INTERFERENCE

Regardless of the type of completion, the effect of stress interference will exist. However, in openhole fracturing, as in hydrajet-assisted fracturing, the effect may be more pronounced. This is because of two factors. The first is the capability of fluid to enter the fractures previously opened thereby raising the pressure in the fracture to a new level. The second factor is that if the change in stress contrast is great enough, longitudinal and/or non-planar fractures may initiate, which may cause an early and unplanned sand-out.

OPTIMIZATION OF THE NUMBER OF TRANSVERSE FRACTURES

To optimize the number of fractures intersecting a horizontal well, the fluid flow and geomechanics aspects that have been discussed need to be applied. As we have seen, increasing the number of fractures intersecting a well will increase the total production from the fractured well; however the rate per fracture will decline because of their interference.

Stress interference between the fractures and its potential effect on the stress values and even the orientation of the intended fracture may dictate the distances between fractures to minimize or eliminate potential operational problems. However, the number of fractures would be determined based primarily on an economic analysis that considers the economic parameters for a specific set of conditions. This parameter may include net present value (NPV), ROI, ROE, etc. The risk factor involved in creating multiple fractures may be incorporated into the system by using an optimization parameter such as benefit-cost ratio.[5]

OPERATIONAL ASPECTS OF FRACTURING HORIZONTAL WELLS

The most important factor in ensuring that a single fracture is initiated in a horizontal well is to apply focused energy during the initiation process. There are a number of different ways in which this can be achieved, and these are discussed for various completion types within this section.

OPENHOLE COMPLETIONS

When working in an openhole scenario, the principal requirement is to initiate and propagate the fracture in the desired location to ensure optimum productivity. The stresses along the wellbore and friction of the fluid being pumped down the wellbore will affect where the fracture initiates and may or may not give us a desirable outcome.

Methods that can be used to help ensure success include:

- Hydraulically perforating or notching the openhole formation with a hydrajetting tool.
- Using a propellant or perforating to initiate a fracture in the open hole.
- Mechanically isolating a short section of open hole and treating only this interval.

Of these techniques, the most consistently successful approach has been the hydrajetting of the formation for perforating and fracture initiation. Mechanical isolation of the formation has also been widely applied with perforating, sliding-sleeves, and acid-soluble ports; however, retained isolation has proven evasive as shown by micro-seismic mapping and gauge data.

OPEN HOLE WITH SLOTTED LINER

In an openhole scenario there are more potential candidates, with few delivering the consistent results that are expected. One of the first applications was the use of preperforated liner and high rate, commonly referred to as a sprinkler system. The thought was to use the perforations as a way to evenly distribute the treatment as seen in the top picture. Monitoring of the fracturing process indicated that the fractures concentrated near the heel and toe of the horizontal well. Results were at best marginal and inconsistent.

In wells perforated with conventional methods, acid-soluble ports, or a sliding sleeve (mechanical or ball-operated) have been used. However, these techniques have shown a low success rate of isolation, as has been demonstrated by pressure gauges and microsiesmic mapping. Even if successful isolation occurs, the fracturing energy is spread out across the entire openhole section, leading to difficult fracture generation, and no predictability in placement, leading to higher failure rates in placing proppant.

Another option to leaving the open hole fully exposed is hydrajetting the holes in the pipe and initiating a fracture with the hydrajet tool. This has a chance of providing the focused energy needed to initiate a fracture where you are cutting.

The last option for this scenario is the use of a chemical packer for isolation of the annulus, perforating conventionally using acid-soluble ports or a sliding sleeve (mechanical or ball-operated). The high extrusion pressure will allow effective energy focus, once the hole is in the pipe, to allow the focused fracture generation. If required to perform an openhole cased completion, one of these last two options or combination of them would be preferred.

The cased and cemented option can include two options, cementing with conventional cement or acid-soluble cement **(Fig. 14).** When cementing with conventional cement, it is well known that a high net pressure is required to maintain the fracture generation as documented by Garces, et al.[39] and acid-soluble cement has clearly demonstrated success in minimizing entry friction and improving completion success.[40-41]

If conventional cement is run, hydrajet perforating is recommended to prevent the near-wellbore entry problems. If acid-soluble cement is run, conventional perforating, sliding sleeves (mechanical and ball-operated), or hydrajetting are all acceptable ways of achieving holes in the pipe. In each case any fracture treatment should be preceded with a volume of acid to remove the acid-soluble cement from around the perforations. When using this type of cementing process, the results have consistently demonstrated predictable and focused fracture generation. This has allowed consistent focused energy to effectively fracture treat the reservoir.

In summary, the decision to drill a horizontal well is a completion technique, not a drilling process. The decision of what type of completion technique to apply should include the completion engineer at the beginning of the planning process. To be successful the completion engineer must select the stimulation process that delivers energy focused to initiate the fracture. Energy dispersed over a large interval when trying to create a fracture will lead to inconsistent fracture geometry and less than optimum results. The thought process must be centered on focused energy to initiate a single fracture.

HORIZONTAL WELL FRACTURING—FIELD CASE

The following data summarizes the application of multiple fracturing in a horizontal well (Well A) as a remedial completion technique within a poorly performing existing completion; the completion type was not chosen to assist the multiple fracturing scenario.

Fracture design was investigated for the well and three transverse fractures were planned with roughly equal spacing along the horizontal section. The well had been originally completed with an uncemented slotted liner. Because this could not be altered, it was decided to apply the hydrajetting technique to maximize the efficiency of the fracture-to-wellbore communication.

For each of the fracturing treatments the following stages were performed.

1. Circulation and hydrajet perforating or notching of the liner at measured depth.
2. Performing a minifrac (closure pressure and fluid efficiency).
3. Perform a hydrajet-assisted fracturing treatment at the desired measured depth.

A schematic of the treated well is provided in **Fig. 15**.

CIRCULATION AND JETTING

During the first stage the well was circulated using 35-lb linear gel at 0.8 m^3/min with a total of 36 m^3 fluid, this stage confirmed that all three jets were open. After the perforations had been jetted for 7 min, the annulus valve was closed to achieve a breakdown of the formation. The annulus pressure increased rapidly from 18 to 94 bar, and annulus pumping was then initiated to achieve a fracturing rate and preparations was made to perform the minifrac.

MINIFRAC OPERATIONS

Fig. 16 shows the rate and pressure that were observed during the minifrac test and **Fig. 17** shows the diagnostic plot of the minifrac data indicating that the fracture encountered some height recession, which is attributable to penetration into a higher-stress formation.

The minifrac analysis indicated that the surface ISIP was 95 bar. Taking into account the hydrostatic column, the bottomhole ISIP was estimated to be 376 bar. From the minifrac analysis the bottomhole closure pressure was calculated at 289 bar, yielding a closure gradient of 0.126 bar/m. Fluid efficiency was calculated to be 47% while the reservoir pressure was estimated to be 231 bar.

MAIN FRAC OPERATIONS

During the early stages of the main fracturing treatment, a steady net pressure increase was observed at surface. This is reflected in the annulus pressure, which increased from 108 to 128 bar over this period.

Midway into the treatment a sudden pressure spike from 306 to 462 bar on the tubing side was observed, however there was no change on the annulus pressure. This was readily interpretable as one of the jets becoming blocked. This was confirmed when the jetting tool was recovered and metal debris was found lodged in one jet.

To continue, the tubing pump rate was reduced such that the maximum pressure limits were not exceeded. The post-frac ISIP was 120 bar, which indicated a permanent net pressure increase of 25 bar. **Fig. 18** is a summary of the pumping operations for the first treatment; subsequent treatments were uneventful.

From the above field case, it can be concluded that:

- The frac treatment was pumped and displaced completely, indicating that this technology can be applied as a remedial technique for fracturing horizontal wells in this field.
- No significant annulus response was encountered during the cutting stages of the operations and the formation was efficiently broken down without problems.

SUMMARY

As the experience, efficiency, and applicability of multifractured horizontal wells increases within the industry, there will be a drive to ensure application in appropriate situations. It is not difficult to appreciate that in either offshore or sensitive environments, the minimization of surface facilities/footprint will provide a niche opportunity for multifractured horizontal wells.

TECHNOLOGY APPLICATION

Fracturing of horizontal wells, as a primary completion technique, is becoming more and more desirable, for a variety of reasons, and a strong understanding and capability within the industry to efficiently and economically deliver this approach is an absolute necessity.

As discussed in the previous sections, it is imperative that fracturing requirements are considered as part of the well planning process. This is something of a 'sea-change' in normal practice but will be essential to ensure successful application.

Operators are generally interested in three principal areas when applying variations of this technique; new developments, remedial operations, and water-flood management.

REMEDIAL OPERATIONS

During the 1980s and 1990s the industry "stampeded" toward completing and developing entire oil and gas fields with horizontal wells; in some cases appropriately and in others for no more good reason than it was the fashion at the time. These wells/fields have produced continued analysis indicating that many of these completions fail to perform or deliver as expected and that remedial actions are required to improve the well or field deliverability. As we have seen in previous discussion, it is essential (during the well planning phase) that some consideration for hydraulic fracturing be made, however this was not the case for many of these wells drilled during this period.

From the field case in the previous section, we can see that hydrajetting has proved to be an extremely effective method of remedially treating, with multiple fractures, a very unfavorable completion type (slotted liner in open hole). It is expected that the industry will continue to develop these approaches such that more opportunities become available by improving the useable toolbox.

WATER-INJECTION WELLS

It is commonly understood that, in most practical cases, water-injectors are thermally fractured sometime after startup. In many cases this may not be problematic, however where poor frac-height control exists, it can lead to excessive fracture geometry, inefficient sweep and water disposal rather than water injection.

The technique of multiple fracture initiation (no proppant) in a horizontal well, as a means of providing a solution to better water-injector conformance; has been applied very successfully on previous occasions.[42]

Although the use of propped hydraulic fractures is generally not recommended (because of potential fracture plugging), better management of water quality and injection pressures could provide an opportunity for multiple fractured horizontal wells. This is particularly true when it is planned to pre-produce the injector for a period of time, where significant value may be achieved during the pre-production period.

REFRACTURING

Fracturing a tight-gas formation, especially fracturing horizontal wells, is probably the best way to produce from these formations. However it has been noticed that fracture performance often declines with time. This raises a few questions:

- What are reasons for performance degradation?
- How to diagnose reasons for the performance degradation?
- What happens during the re-fracturing process?

Reasons for performance degradation include:

- Loss of fracture conductivity near the wellbore due imbedment.
- Degradation of proppant with time and stress.
- Loss of fracture height with time.
- Loss of fracture length due degradation of proppant.
- Loss of fracture conductivity due to fine migration
- Loss of formation permeability near the fracture forming a barrier.
- Entrapment of liquid around the fracture face by capillary force. This effect may be aggravated by fluid loss during drilling and fracturing and by later movement of fines. This may be of special importance in tight-gas formations where high capillary pressures may be expected in cases having a water phase.

Diagnostic techniques include:

- Well test analysis. Determining the fracture dimensions under low permeability conditions is in many times a difficult goal even for a uniform fracture. The problem becomes even more difficult when factors such as the ones discussed above are included.
- MiniFrac analysis. Specialized MiniFrac techniques have been developed to analyze to determine fracture and reservoir properties from MiniFrac tests. Some of these tests analyze the pre-closure[7] data while others concentrated on the analysis of the post closure[8-9] data.

Suggestions have been made about the refracturing process, including reopening the original frac to make it longer or to increase conductivity. Another suggestion was to create a new fracture. This area is outside the scope of this paper and should be addressed in a separate publication.

CONCLUSIONS

This paper presented a discussion of the various parameters it is necessary to consider to optimize the fracturing of a horizontal well. These parameters included the fluid flow, geomechanics, perforations, and operational aspects. The paper also presented field cases in which these parameters have been considered in the design process.

The flow regimes and productivities for the cases of transverse, longitudinal, horizontal, and fractured vertical wells have been compared and their relative applications presented and discussed.

The magnitude and assessment of breakdown pressure has been presented along with the importance of the fracture initiation process. Efficient techniques to initiate fractures for various completion types were also presented.

Evidence has been presented that hydrajetting, for fracture initiation, can provide one of the most versatile and successful means of remediating existing horizontal well completions.

The importance of the consideration of stress interference among subsequent fractures in horizontal wells was also presented, along with field evidence for increasing stress levels.

Finally, a successful field case was described indicating the efficient fracture initiation and placement for one of the most difficult completion case scenarios (remedial treatment of a slotted-liner completion in an open hole).

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Table 1—Comparison of Breakdown Pressure Calculation to Observed Laboratory Data

Experiment Group[21]	Observed Pressure,[21] psi	Calculated Pressure Using H&W Criterion, psi	Calculated Pressure Using H&B Criterion, psi
HZ-1	2,850–3,850	1,750	3,275
HX-2	3,400–4,250	1,750	3,600

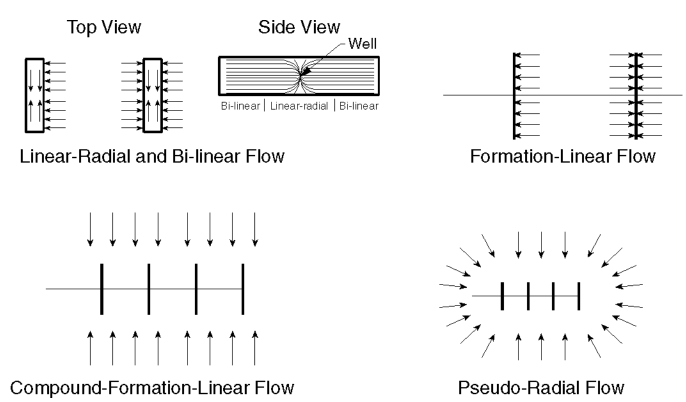

Figure 1—Potential flow regime in a fractured horizontal well.[10]

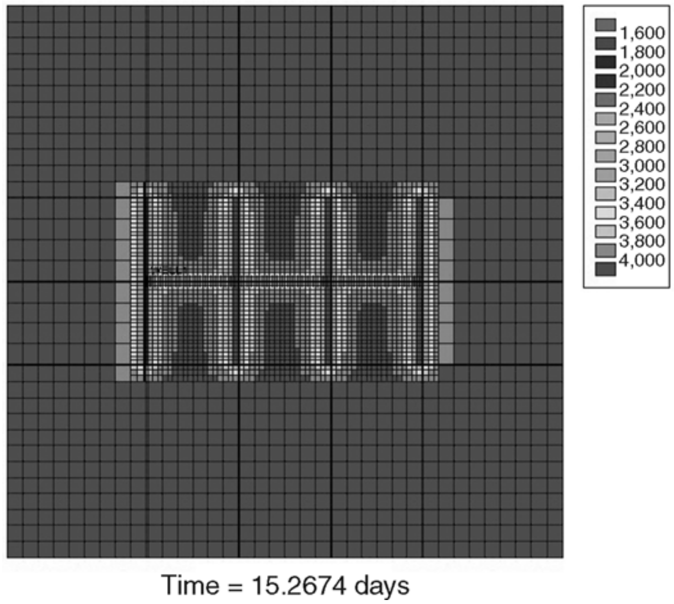

Figure 2a—Simulated pressure distribution around individual fracs in early-time.

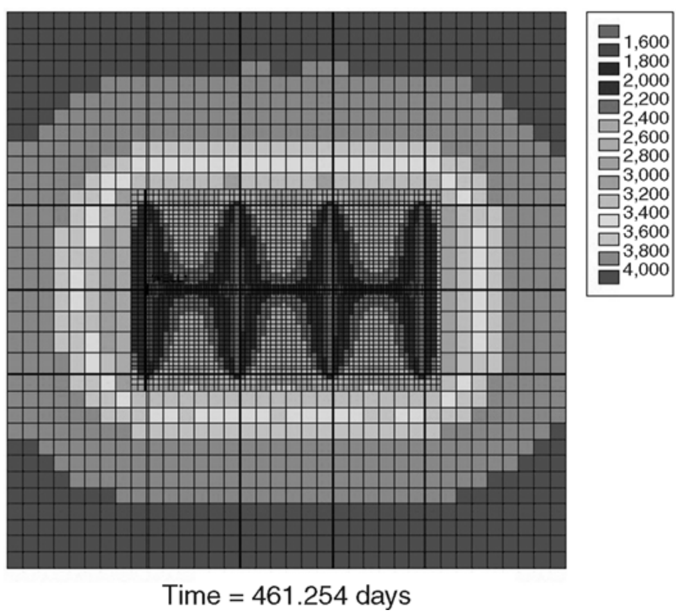

Figure 2b—Simulated pressure distribution after 461 days of production.

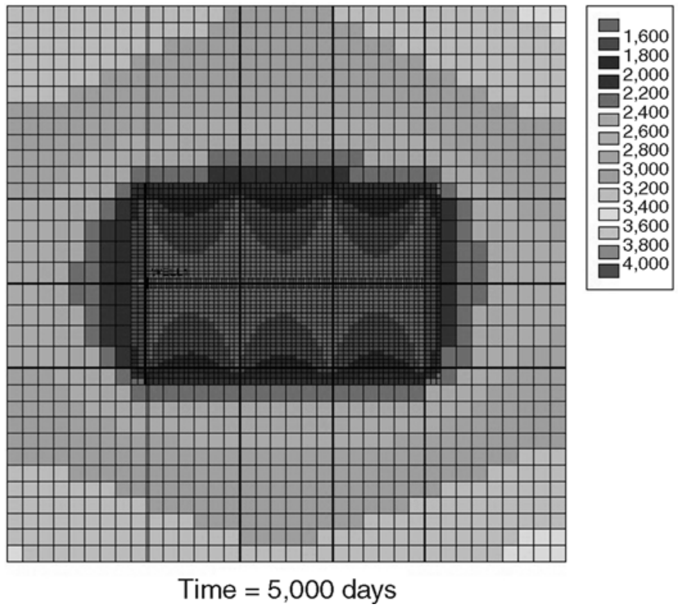

Figure 2c—Simulated pressure distribution after 5,000 days of production.

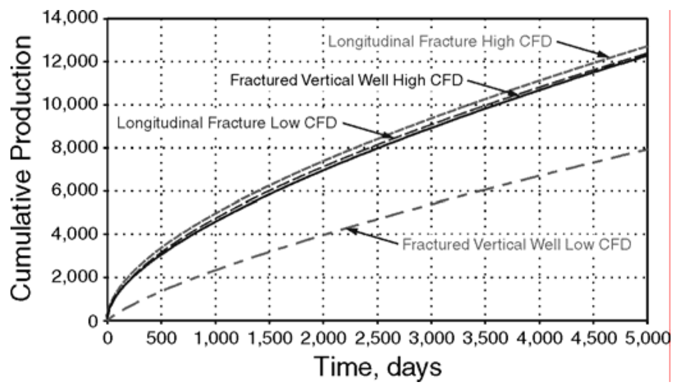

Figure 3—Comparison of longitudinal fracture vs. fractured vertical well.

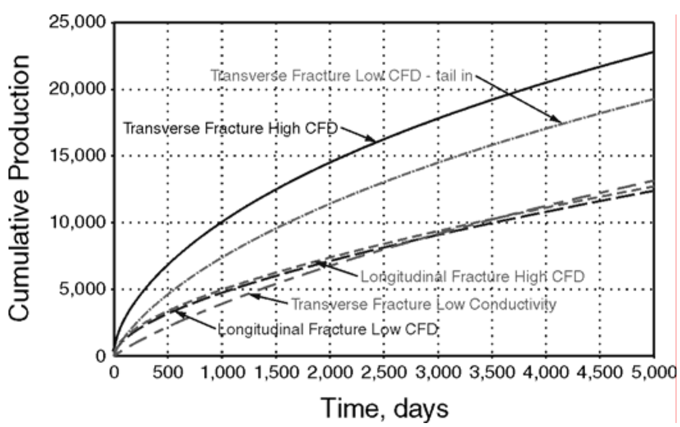

Figure 4—Comparison of longitudinal fracture vs. transverse-fractured horizontal well.

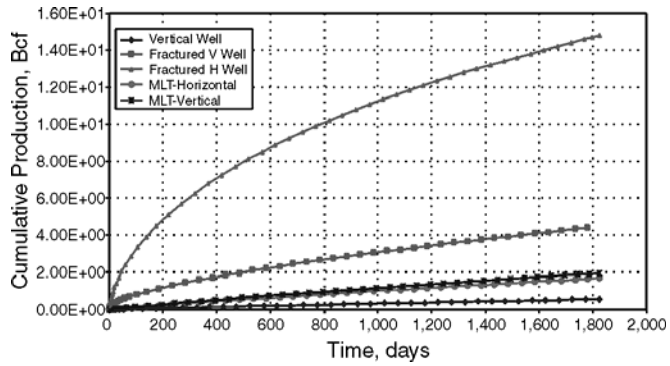

Figure 5 – production comparison of various well completion scenarios

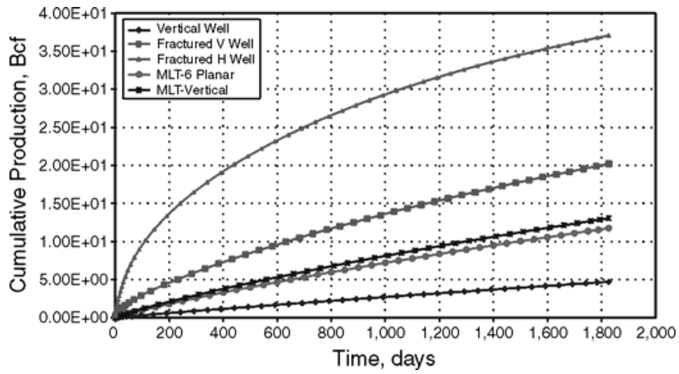

Figure 6 – Production comparison of various well completions, formation permeability =0.05 md

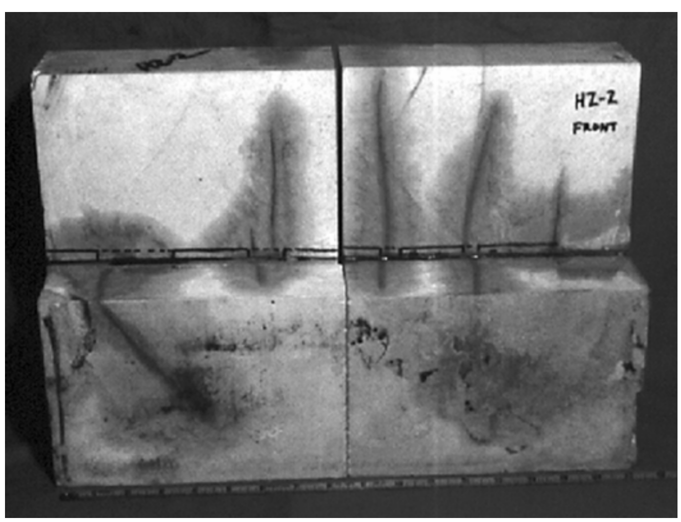

Figure 7—Effect of length of perforated interval on the creation of a transverse fracture.

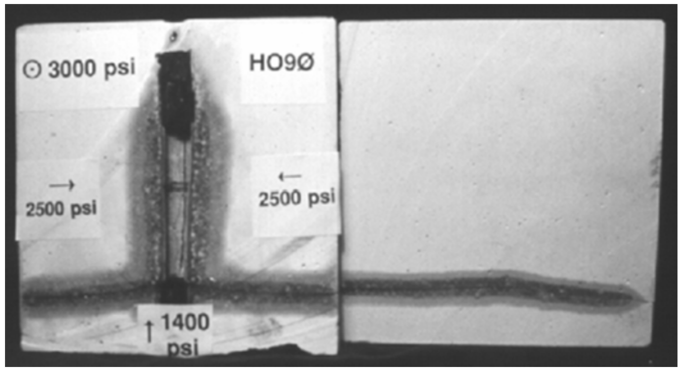

Figure 8—Fractured block sample showing inverted T-shaped fracture.

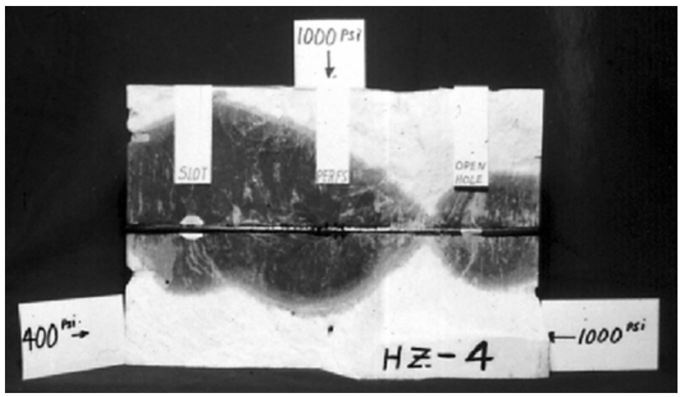

Figure 9—Effect of completion type on creating a longitudinal fracture.

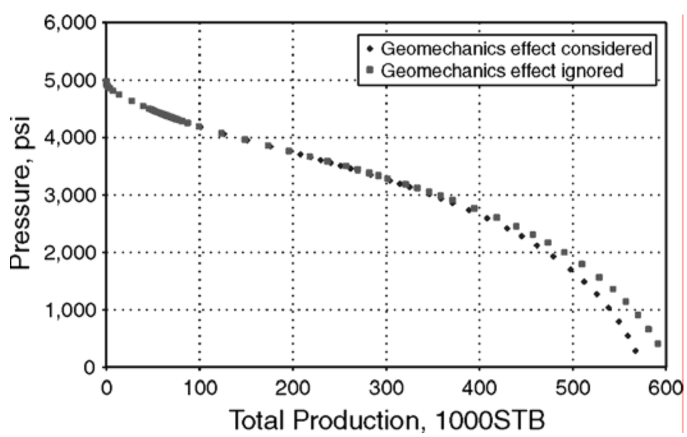

Figure 10—Effect of stress sensitive formation on well productivity.

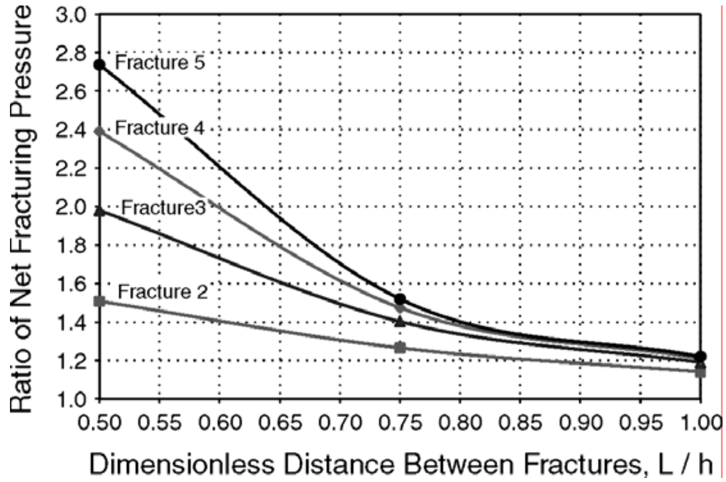

Figure 11—Change of fracturing net pressure as a function of number of transverse fractures and distance between them.

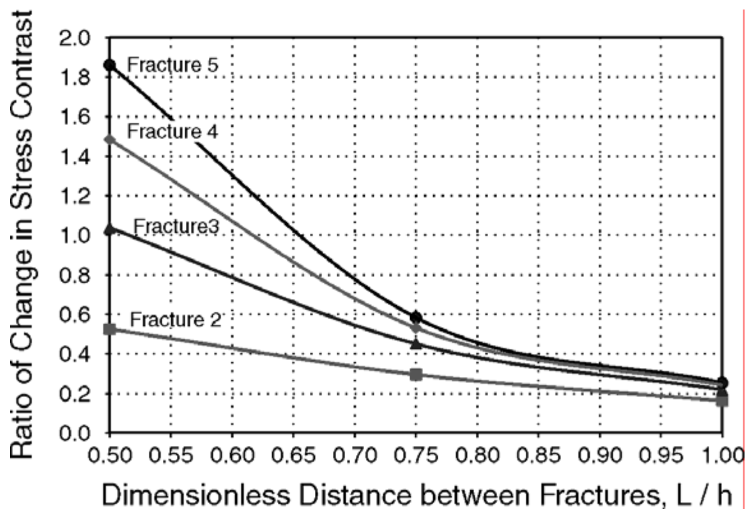

Figure 12—Change of stress contrast as a function of number of transverse fractures and distance.

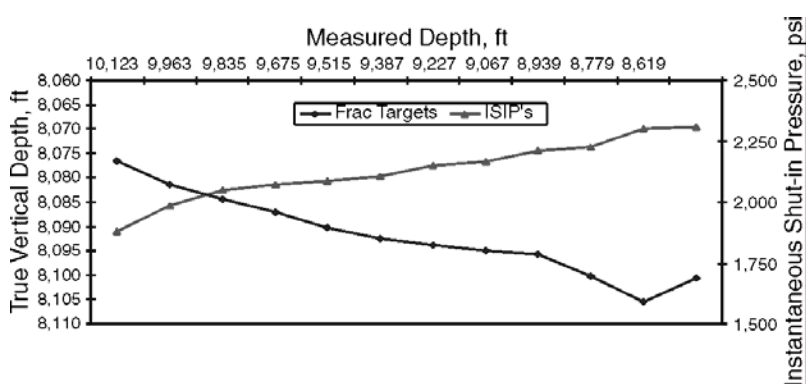

Figure 13—ISIPs for 12 consecutive Barnett shale hydrajet water fracs placed in a horizontal well in one day.

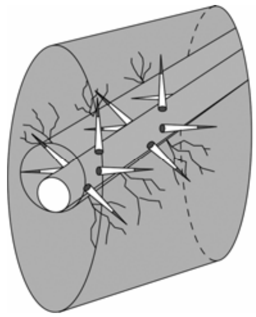

Figure 14a—Conventional cement leads to high entry friction.

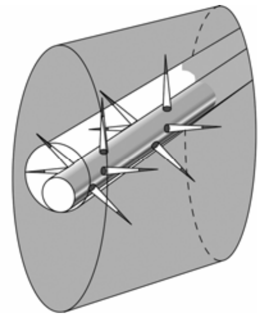

Figure 14b—Acid-soluble cement is washed away by acid from removing the tortuous path.

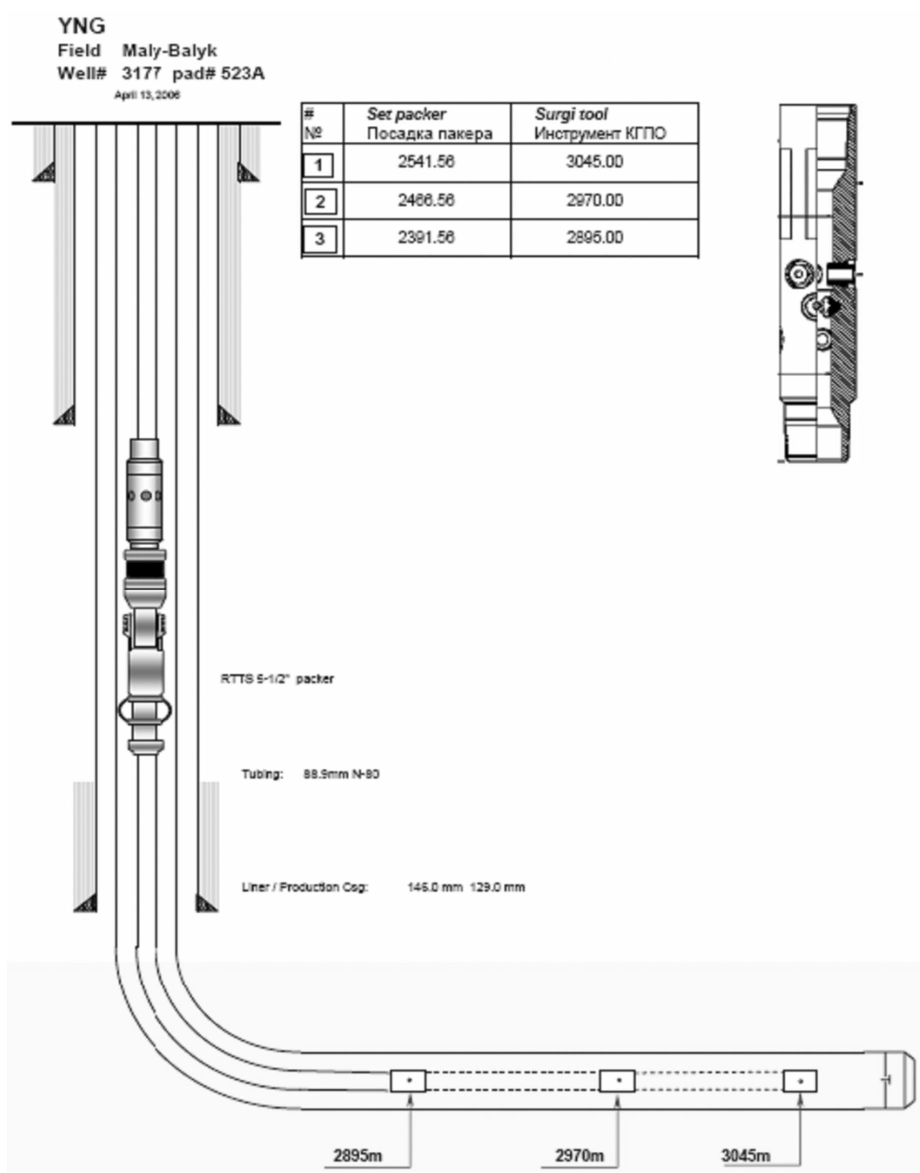

Figure 15—Well A1 schematic of the wellbore indicating individual frac locations.

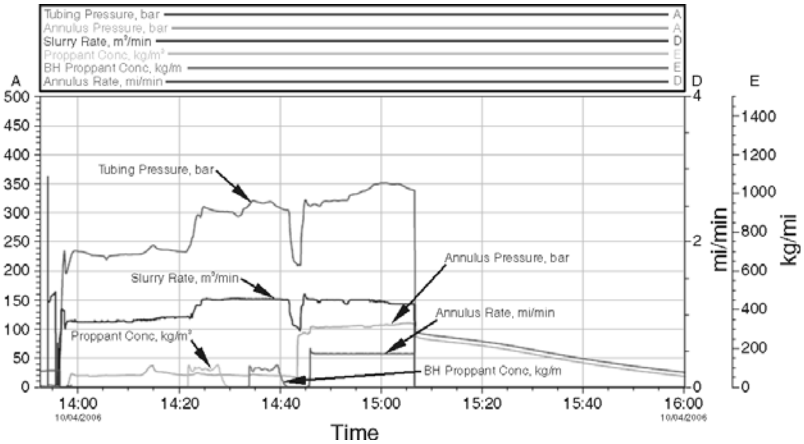

Figure 16—Minifrac test rate and pressure plot.

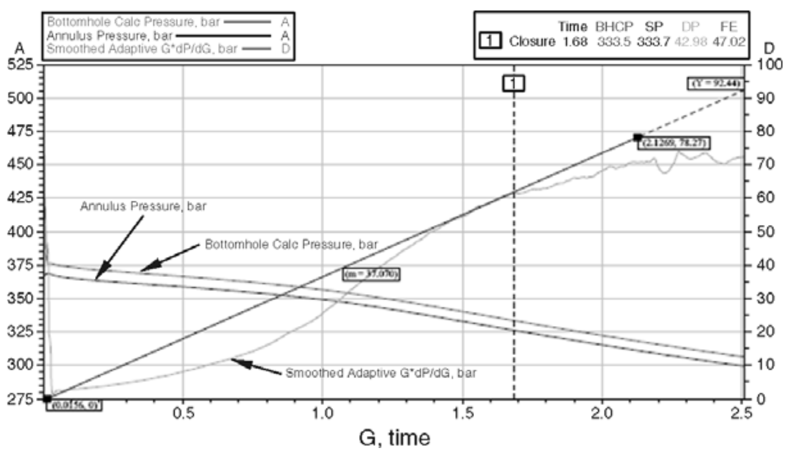

Figure 17—Minifrac analysis diagnostic summary.

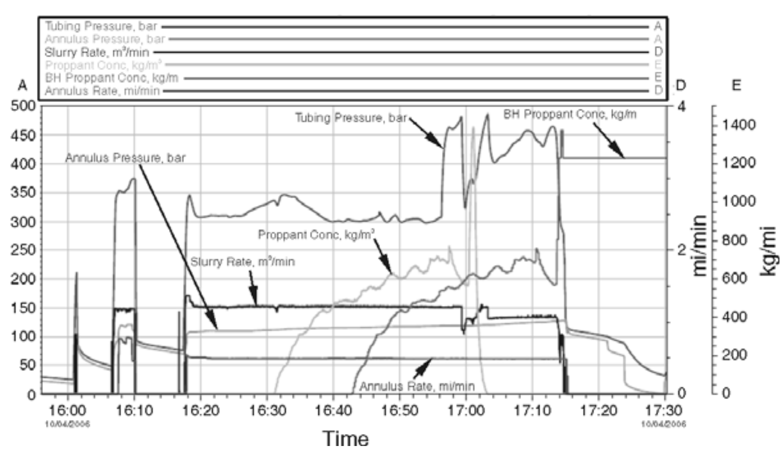

Figure 18—First fracturing treatment rate and pressure plot.