Horizontal-Well Fracturing: Why Is it So Different?

Ali Daneshy, SPE, Daneshy Consultants International

Advances in drilling and fracturing horizontal wells have been two of the main contributors to economic production from very-low-permeability oil and gas reservoirs. In spite of much attention to the subject, several critical questions regarding horizontal-well fracturing remain unanswered. Among these are higher fracturing pressures, large pressure fluctuations, and more frequent screenouts, which has prompted use of much finer proppant at very low concentrations. This article answers some of these questions.

Fracture Initiation From Horizontal Wells

The state of stress in a borehole gives it a natural tendency for longitudinal (axial) fracture initiation **(Fig. 1a).** This is a geometrical effect and independent of the in-situ stress orientations (Daneshy 1973). It can occur even when the least in-situ principal stress is parallel with borehole axis. Since the fracture is not perpendicular to the least in-situ principal stress, it takes higher pressure to extend it. As the axial fracture grows, it will eventually reorient itself to become perpendicular to the least in-situ principal stress and the fluid pressure gradually decreases with it. The location of fracture reorientation depends on location and orientation of planes of weakness in the formation. This leaves open the possibility that the fracture may reorient itself more than once, and depending on the orientation and size of the plane of weakness, may temporarily grow in directions other than perpendicular to the least in-situ principal stress.

Initiation of a transverse fracture (perpendicular to borehole axis) requires axial forces and stresses (parallel with borehole axis), which is shown in Fig. 1b. In open holes, such stresses can be induced inside open natural fractures, at the packer seats, or at the bottom of the well (if exposed to fluid), each with its own characteristics. This is shown in **Fig. 2.**

Natural fractures are randomly located and distributed along the well. Initiation from natural fractures results in random location, orientation, and spacing between fractures. One way for partial location control is to reduce the spacing between the packers, thus reducing the length of the pressurized interval.

The next likely sites for transverse fracture initiation are at the packers or bottom of the hole, assisted by stresses induced by axial forces. This also is shown in Fig. 2.

The two main difficulties in initiating fractures in open horizontal wells are control of fracture type and its location. In the absence of a trigger mechanism for transverse fracturing, the fracture is likely to initiate and extend axially at least for some time. There is ample field data supporting presence of extensive axial fracturing, such as the case presented in **Fig. 3,** where axial fracturing has occurred along at least 4,000 ft of open hole. In the tracer log shown here, a transverse fracture is expected to have very high intensity signal, but cover a very short interval (less than a few feet). In this example, although the radioactive tracer has high intensity along some intervals (e.g., 11,000–11,500 ft), the lateral extent of the high-intensity signal still indicates presence of non-transverse fracturing. A side complication of axial fracture extension is the possibility of the fracture crossing over the openhole packers (Fig. 3). This can substantially jeopardize execution of a fracturing plan and interfere with optimum well production.

The second issue with fracturing horizontal open holes is controlling the location of the fracture. Optimum production and reservoir drainage often require a specified spacing between fractures. Random fracture distribution disrupts a long-term structured flow pattern and controlled reservoir drainage. Fractures will soon overlap each other's drainage area. The effect is higher short-term production at the expense of long-term drainage.

Creation of axial fractures also reduces the depth of fracture penetration into the reservoir. In the example shown in Fig. 3, the axial fracture

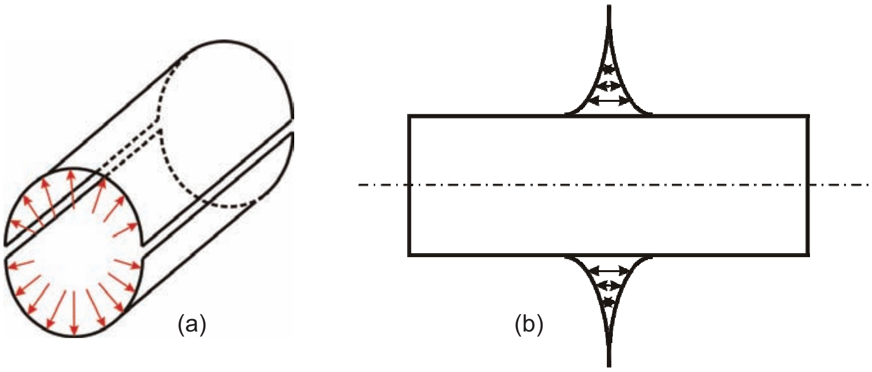

Fig. 1—(a) Natural well tendency to fracturing. (b) Stresses required for transverse fracture initiation.

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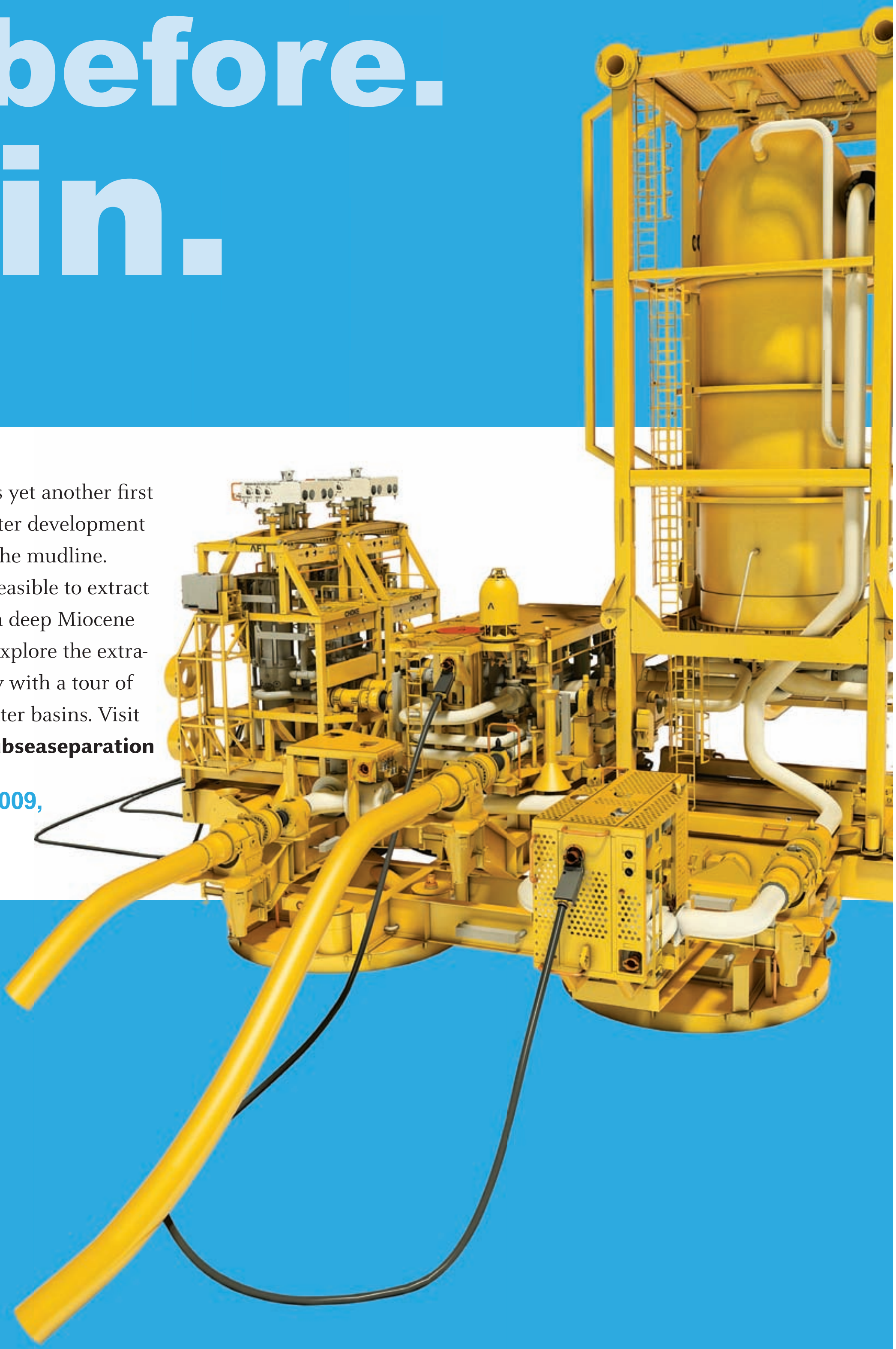

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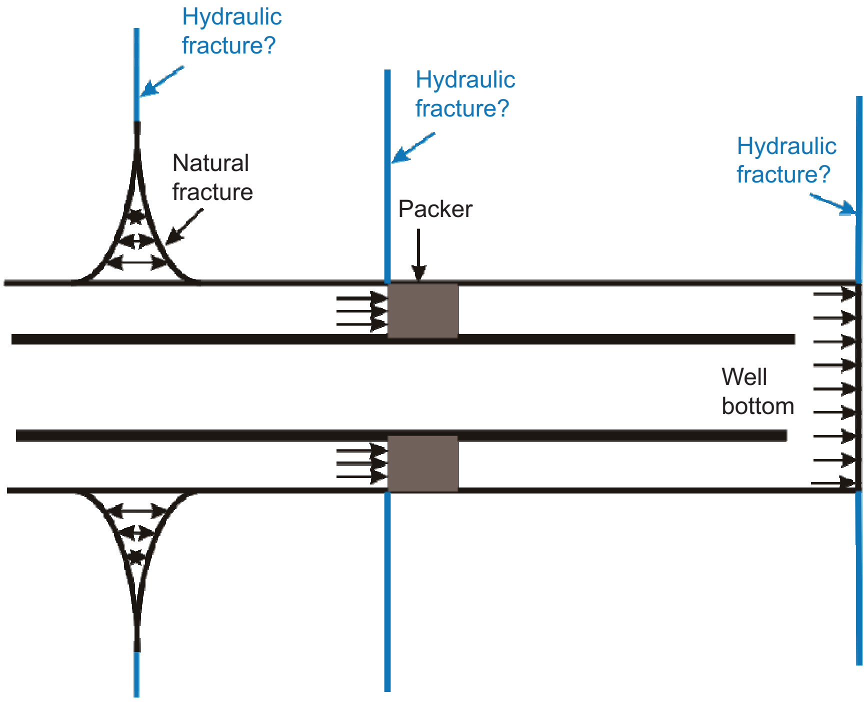


Fig. 2—Potential transverse fracture initiation sites in open horizontal wells.

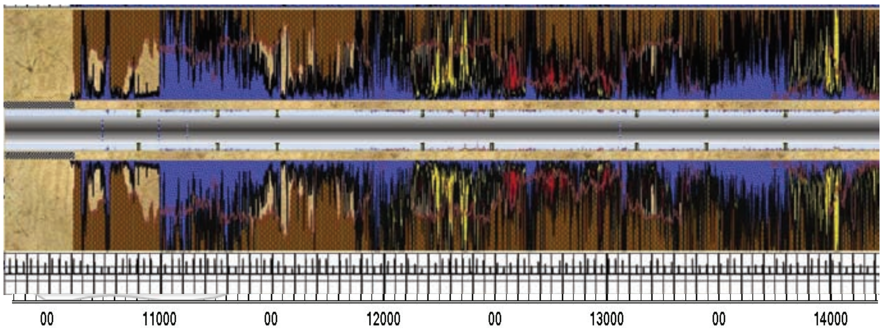
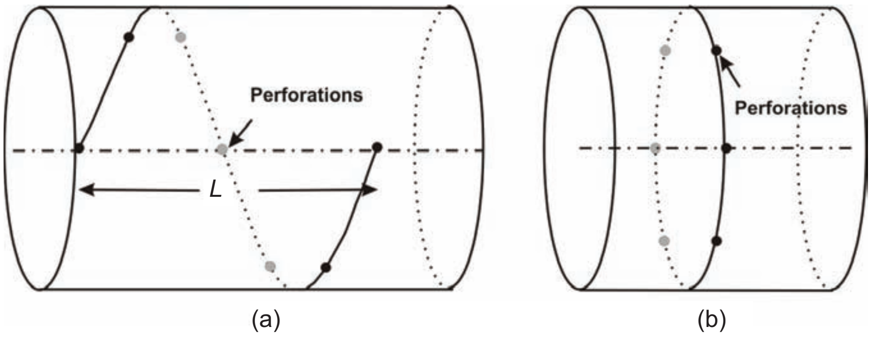


Fig. 3—Tracer log of a horizontal openhole fracture.



(a)

(b)

Fig. 4—Perforating schemes for horizontal wells: (a) perforations set on spiral pattern; (b) perforation clusters set on planes perpendicular to borehole axis.

covers more than 3,000 ft of wellbore length. Since a large volume of fluid and proppant has been consumed for the near-wellbore fracture, the remaining volume for transverse fracture extension is only a fraction of the total. This is one of the reasons why the industry has gradually moved to using larger fluid and proppant volumes for adequate production increases. The next consequence of this problem is the use of much less expensive fluids to contain the total cost of fracturing, even though these fluids are known for their reduced ability to carry the proppant far into the formation.

Axial fractures, if not perpendicular to the least in-situ principal stress, require higher fluid pressure for their extension. Because of their limited lateral extent, they also have narrower widths.

Cased-Hole Fracture Initiation

In cased-hole completions, the fracture has to initiate at the perforations. However, copying vertical-well perforating practices can jeopardize the successful introduction of transverse fractures in horizontal wells.

Helical Phased Perforations. These perforations cover the wellbore circumference **(Fig. 4a).**

The more common phasings are 60 and 120°. This is a continuation of vertical-well practices, which is used to compensate for unknown fracture orientation. Common lengths *L* in horizontal wells are 1.0 to several feet. The short spacing was first recommended by Abass et al. (1996). Another perforating pattern is 0/180° phasing and placing the perforations at the top and bottom of the horizontal well. This pattern assumes the intermediate principal stress is also horizontal and attempts to provide a better link between the axial fractures initiating from individual perforations. But this will not promote transverse fracture initiation. Even very short spacing between perforations impedes initiation and extension of transverse fractures. Injecting at sufficient rate into the fracture requires several perforations (to avoid high perforation friction). If separate fractures initiate from every perforation, their connection to the main fracture will consist of multiple very narrow paths,

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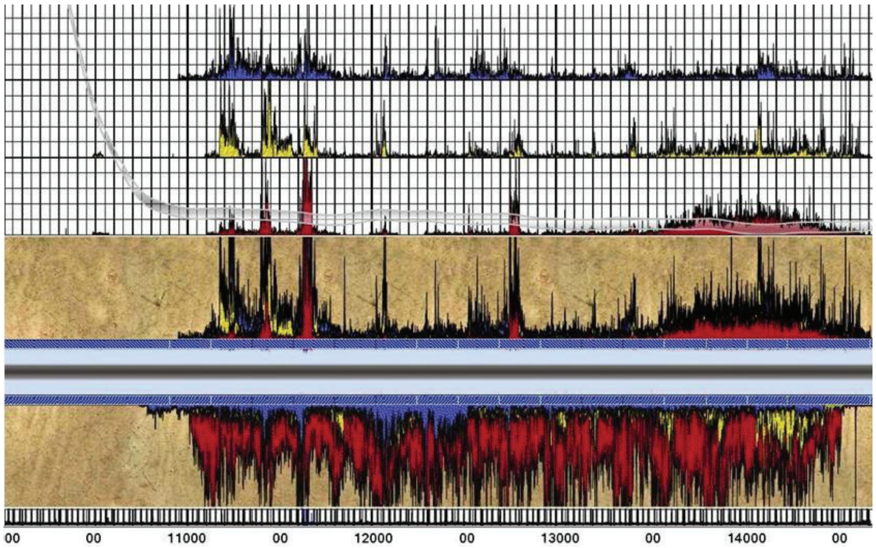

Fig. 5—Tracer log from a cased, cemented, and perforated horizontal well.

with considerable turbulence near the wellbore, resulting in high wellbore pressure. Field data indicate the presence of considerable axial fracturing in many cased holes. In the example shown in **Fig. 5,** perforated clusters were spaced 225 ft apart, each containing five perforations at 1 ft intervals. A radioactive tracer log shows that the fracture has covered the entire 3,500 ft of cased hole. While including several transverse fractures, the abundant axial fracturing will interfere with planned creation of separate fractures 225 ft apart. Extensive axial fracturing interferes with deep extension of transverse fractures.

Jet Perforating. In recent years, use of high-velocity jets has become popular for horizontal-well fracturing. At present, the two common patterns are perforating on a spiral (Fig. 4a), or cutting several short axial slots along the length of the wellbore. On the positive side, jet perforating creates larger-diameter perforations with smoother edges, thus reducing perforation friction. The perforation tunnel is also larger in diameter and penetrates deeper into the formation than shape-charge perforations. Both of these promote transverse fracturing and higher rate per perforation. The drawback of the spiral perforating scheme is the misalignment between the created transverse fractures at the

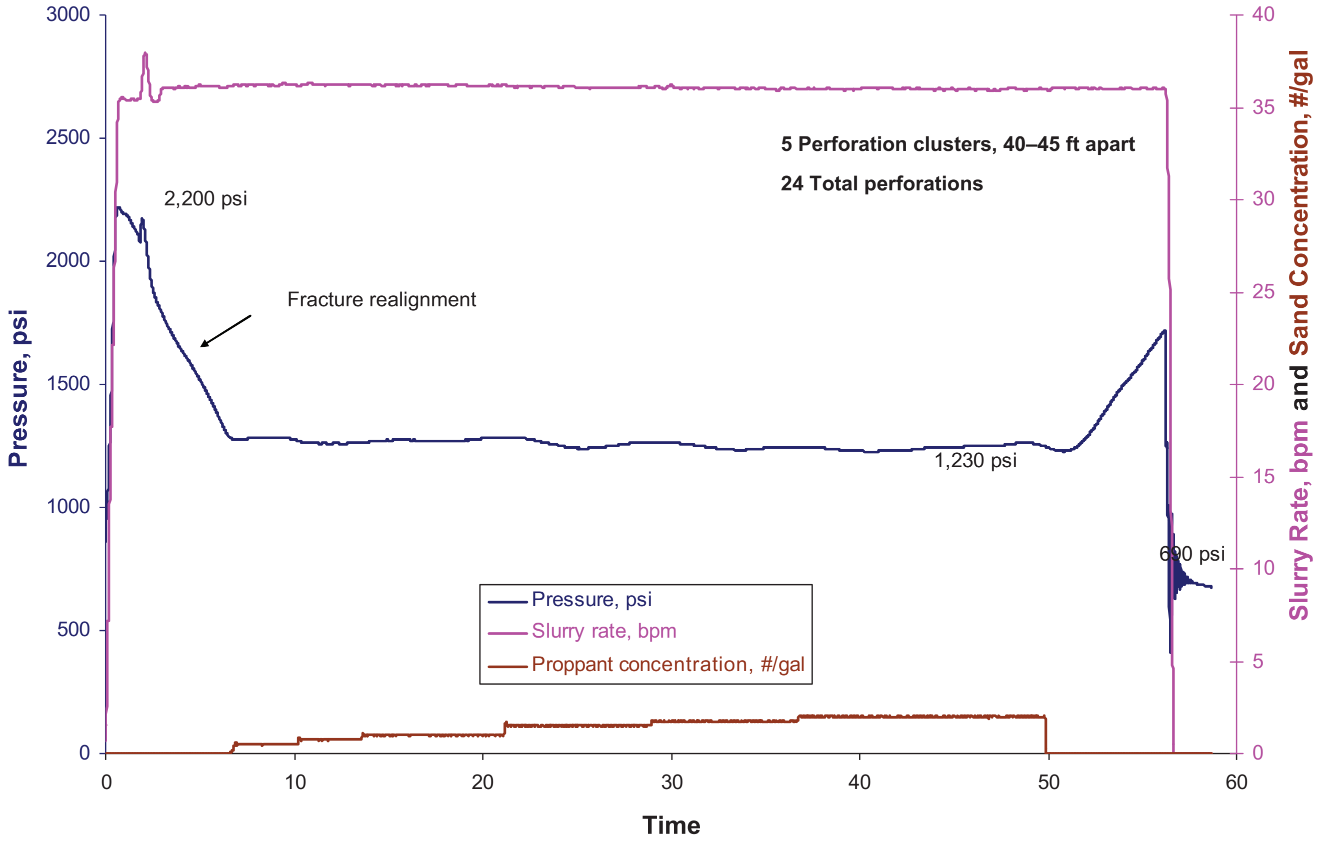

Fig. 6—Example of fracturing pressure variations in a horizontal well.

perforations. Slot perforations also could result in multiple transverse fractures. Nevertheless, both patterns appear to create less axial fracturing in actual operations. A better scheme, and the one recommended by this author, is to place all the perforations in each cluster in one plane perpendicular to borehole axis, as shown in Fig. 4b. This scheme has proven successful in several actual field applications.

Horizontal Fracture Extension

The extension pattern of the fracture in horizontal wells will be off-balance (Daneshy 2003) with considerable branching and shear fracturing. This observation is supported by field mapping of fracturing, including seismic techniques. This will be particularly true during fracture realignment. The off-balance growth can in fact aid in increasing the link between the fracture and formation, thus enhancing well productivity. However, off-balance fractures will still grow within a limited band and are not likely to extend too far away from their preferred orientation. Extensive axial fracturing will increase the degree of off-balance growth, since the axial fracture is constantly searching for a path to realign itself perpendicular to the least in-situ principal stress.

Fracturing-Fluid Pressure Variations

Field data show that in majority of horizontal-well fractures, the fluid pressure is much higher than those in adjacent vertical wells at the same depth **(Fig. 6).** There are two main reasons for this behavior. The first reason is the presence of axial (or at least nontransverse) fractures, as discussed earlier.

In the example given in Fig. 6, the relatively large pressure drop during the first 7 minutes of the treatment was caused by realignment of the main fracture from axial to transverse. Fortunately, the short transition time allowed early introduction of proppant. Sometimes, the transition to fully transverse fracture does not take place at all, or takes a long time (more than an hour), and attempts to introduce proppant during transition can lead either to higher pressures or even screenout. The author is aware of cases where fractures in horizontal wells have screened out with 0.25 lb/gal concentration of 100-mesh sand. The main cause of this is the presence of axial fractures and the obstruction of proppant in its complex path from the axial to the transverse fracture.

The second reason for high fracturing pressures is near-wellbore turbulent flow inside the transverse fracture. Assuming wellbore diameter of 6.5 in., injection rate of 10 bpm, and viscosity of 5 cp, the fluid will be in turbulent flow near the wellbore, with Reynolds number more than 20,000, which implies near-wellbore turbulence. Under similar conditions in a vertical well, the Reynolds number for a fracture with 50 ft height would have been approximately 174, which is clearly in laminar flow. In fact, the Reynolds number for horizontal wells was computed on the basis of an ideal intersection between the wellbore and the transverse fracture. In reality, the intersection will often have a tortuous path, with even higher turbulence and friction pressures. Perforating the well as shown in Fig. 4a will promote initiation of an axial fracture very similar to a vertical well. Because of its much lower near-wellbore friction, the axial or nontransverse fracture can propagate with pressures similar to what a transverse fracture will require because of its higher near-wellbore friction. The best way to avoid extension of the nontransverse fractures is to reduce the possibility of initiating axial fractures altogether. And the best way for accomplishing this objective is through proper well completion.

Other Fracturing Considerations

Through experience, the industry has observed that economic production from horizontal wells requires higher fracturing-fluid volumes. At least one reason for this observation is smaller depths of fracture penetration because of nontransverse fractures. The urge for cost reduction has also been the motivation for cheaper fluids, with slickwater (water plus friction reducer) gradually becoming the most common. Occasional screenouts led some to believe that fluid leakoff through natural fractures was a problem in horizontal wells. Thus, the vertical-well practice of using very fine proppant sizes (often less than 100 mesh) and starting in very small concentrations (less than 0.5 lb/gal) was gradually adopted for horizontal wells. In the author's opinion, the main cause of early screenouts is inadequate completion- and fracture-design practices. The reason for high fracturing pressures is poor connection between the wellbore and the transverse fracture, which causes high friction and promotes extension of nontransverse fractures. The poor connection also obstructs proppant movement near the wellbore and causes screenout. In such cases, the cause of screenout is not proppant concentration, but the limited capacity of the near-wellbore auxiliary fractures that link the wellbore to the main transverse fracture. Using smaller-concentration proppant does not remove screenout, it makes it happen at a higher fluid volume. Smaller proppant concentrations are not a requirement of horizontal-well fracturing. The author is aware of many treatments in which intentional screenout could not be achieved even with concentrations in excess of 15 lb/gal!

The first step for successful horizontal-well fracturing is proper completion design to direct the fracture along the correct path! Other changes can follow naturally and quickly. These include using smaller volumes and higher fluid viscosities to carry the proppant at higher concentrations and deeper into the formation. Both actions will reduce the costs to more reasonable levels. Lower volumes reduce the urge for high rates, since treatments can be completed within reasonable pumping limits.

Note: In some formations, the goal of fracturing is to maximize short-term production for early cash flow. One way of achieving this objective is by creating an extensive network of near-wellbore fractures. An effective way of achieving this objective is promotion of axial fracturing. If so, longer perforated intervals, together with high injection rates, low-viscosity fluids, and low fracturing costs may offer a better alternative to creation of selective, spaced transverse fractures.

Conclusions

Successful horizontal-well fracturing requires a different approach than fracturing the conventional vertical well. Details of well completion hold the key to creation of the desired type of fracture and planned drainage of the reservoir. With proper well completion, the details of fracture design can be adjusted to meet the production objectives of fracturing.

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