CT DEPLOYED HYDRAJET-PERFORATING PROVIDES NEW APPROACH TO MULTI-STAGE HYDRAULIC FRACTURING APPLICATIONS IN HORIZONTAL COMPLETIONS

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ABSTRACT

Horizontal completions in lower-permeability formations often necessitate effective hydraulic fracturing stimulations for these wells to achieve economic production levels. Cost constraints seldom allow the use of methods such as cemented completions and individual fracturing of numerous zones with bridge plug isolation. Some newer methods require expensive downhole "jewelry."

By implementing a coiled tubing (CT) deployed hydrajet perforating method and pumping the fracturing fluid slurry down the CT/casing annulus, the operator can use lower risk liner completions (cemented or not). Individual zones are perforated, fractured, and then sand-plugged one at a time. With the ability to reverse-up the CT between stages and after all fracs are completed, only one CT intervention and one frac mobilization are needed. The allowable frac rates can be quite high, and stimulation costs are greatly reduced by perforating/fracturing multiple times within the same day.

BACKGROUND

Successful fracture stimulation of horizontal completions is often necessary to achieve economic production rates. However, unlike most vertical well completions, it is often impossible to repeatedly and effectively control the placement of fractures along the horizontal section unless the lateral was cased and efficiently cemented, with multiple fracturing stages and numerous well interventions adding significant cost to the final completion.[1-6] In some cases, even the use of cemented liners and staged perforating are not fully successful in controlling the number and locations of hydraulic fractures along the lateral.[3] Many reservoirs cannot produce at sufficiently adequate rates to support the high cost increase of cemented casings and conventional methods of achieving multi-stage fracture stimulation treatments because of low effective permeability, low pressure, high water production, or some combination of these. For oil reservoirs, high oil viscosity is another limiting factor. Thousands of horizontal wells completed either openhole or with some form of non-cemented liner (typically either perforated, preperforated, or slotted) have only produced at marginally economic rates and many others will not achieve economic rates without stimulation. This is in addition to wells that do not have adequate reservoir properties or reservoir size to produce even if significant stimulation were actually achieved.

In ultra-tight reservoirs, such as the Barnett Shale for example, it is well known that fracture stimulation effectiveness is a requirement for economic horizontal completions.[7] However, in most of the conventional low-permeability reservoirs, it seems that many operators have begun only recently to realize that drilling and completion decisions must take into account the effectiveness of fracture-stimulation of many (if not all) horizontal wells in low to moderate permeability reservoirs. In a few such reservoirs, operators have reported achieving adequate fracture placement control with liners and limited-entry perforating methods (some cemented[6] and some not[8]). These few success stories appear to represent a small percentage of cases.

Same-day multi-stage fracturing processes are often the key to economic stimulation alternatives if the process can deliver effective placement control to single zones. Recently, a few of these reservoirs have been achieving adequate frac placement control to make the wells economically viable using external casing packers and techniques for step-wise opening of a single zone to the wellbore then sealing off with a ball and baffle after completing each frac stage. The downhole jewelry adds significant cost and additional risk in running the entire liner. There are limits also to the number of stages ball-and-baffle sealing techniques can achieve. This process can still result in excessive multiple fractures because a large section of open annulus is pressurized with no control over where fractures might initiate, except at existing weaknesses from natural selection or from events during the drilling process.

In vertical wells, some operators have had success placing perforating charges external to the casing and running this casing to total depth (TD). Done correctly, this process delivers an economical method for multiple-stage fracturing.[9-10] The downhole jewelry for such systems will add considerable completion cost, but successful deployment (a significant risk factor) can provide the isolation of the multiple-stage fracturing critical to effective stimulation of horizontal completions. Commitment to such a completion-stimulation process often must be made very early in the drilling phase, possibly even before the well is spudded.

Many operators need methods to effectively fracture-stimulate horizontal completions even though these costs are not projected in the approved AFE and the mechanical condition of the lateral is not subject to change. Many such wells have already experienced cost overruns by attempting methods that were not cost-effective and which sometimes were complete failures.

HYDRAJET-PERFORATING AND FRACTURING GOES HORIZONTAL

For horizontal wells without low-risk methods of mechanical isolation, such as openhole or liners that are entirely preperforated or slotted, only one consistently effective fracture-stimulation method has been developed. The hydrajet-fracturing (HJF) technique[11-20] incorporates hydrajet-perforating to force initial fracturing at a specific location along the lateral. Additionally, this process continues the high-differential-pressure hydrajetting throughout the entire fracture extension and growth processes, independent of whether an acid-frac or proppant-frac treatment is being used. Essentially all the frac fluid is pumped down a tubing string and through the hydrajet tool body, while a separate pumping operation places fluid (typically at lower rates) down the annulus to ensure that annular fluid leakoff into the reservoir above the frac point will be satisfied by the annular fluid. In most cases, excess fluid (more than is being lost to annular leakoff) is pumped down the annulus; therefore, this fluid will also move into the fracture being extended. For proppant-frac applications, this is a major factor in preventing the bottomhole assembly (BHA) from sticking by preventing proppant slurry from getting into the wellbore above the tool.

The HJF process has been used in more than 150 horizontal wells worldwide during the past few years. Because there are a significant number of technical papers available on this process, it is only briefly discussed here. **Fig. 1** offers a general concept of a typical wellbore configuration and the treating string and BHA that could be used to fracture-stimulate the well at multiple locations along the lateral during a single well intervention. **Fig. 2** shows a picture of an actual BHA used for such an application in a well in western Asia during September 2005. **Figs. 3a–3e** present drawings that illustrate the step-wise process used for hydrajetting perforations, followed immediately by hydrajet-assisted fracturing at that location. Within minutes of completing a fracturing stage, the BHA is repositioned to the next desired (uphole) target location and the entire process is repeated. If there is an extended delay before the next fracturing stage, the BHA is typically pulled out of the lateral and later repositioned for the next perforating and fracturing operation. This can reduce the risk of the tool sticking from any solids settling out of the vertical section into the bend of the wellbore.

Many horizontal completions are not candidates for fracture stimulation using the HJF process. Many well casings cannot withstand the pressure created within the annulus. In a few instances, a casing protection string can be installed to create a temporary annulus for the stimulation process. However, this is an added cost and is not feasible in many cases.

Another limitation is that the existing casing or lateral section (or both) might be too small to allow for an adequately sized treating string and/or jetting tool to achieve sufficiently high pumping rates for effective fracturing. In very tight formations, it might be possible to successfully extend and prop or fracture-acidize at rates as low as 5 bbl/min. However, as effective formation permeability increases, so does the minimum fracturing rate needed. Formations with permeabilities of only a few millidarcies might require injection rates well above 10 bbl/min for successful fracturing. If adequate hole opening size is available, fracturing rates through a large tubing string and tool can exceed 40 bbl/min. In some cases, the tubing rate can be supplemented with annulus rate. The highest total fracturing rate achieved to date with the HJF process is approximately 75 bbl/min, with most of this rate through the annulus.[20] This rate is only possible with a solid liner in the lateral above the point of fracturing, although it does not have to be cemented. Additionally, proppant has only been pumped through the tubing string with this process, causing additional frac rate supplied through the annulus to dilute the proppant concentration ultimately entering the fracture.

HYDRAJET-PERFORATING EXTENDED TO VERTICAL-WELL PINPOINT APPLICATIONS

The more hydrajet-perforating was used in horizontal well stimulation applications, the more promise it offered for vertical well stimulation applications. Conventional, explosive-charge perforating causes damage to the inside of the perforation tunnel. In many cases, this damaged zone can impede successful fracturing operations. In softer, higher-permeability reservoir rocks, the explosive perforations process is usually very effective with only limited impairment to the functionality of the perforation tunnel. However, most laboratory evidence suggests that as rock hardness increases, the degree of physical damage to the formation increases. This is not only true with respect to rock permeability, but the "stress cage" created around the perforation tunnel also makes this tunnel more difficult for hydraulic fractures to initiate from it. Studies show that hydraulic fractures in hard formations were not actually initiated from the perforation tunnel itself, but originated at either the cement-pipe interface or the cement-rock interface. Many scientists and practitioners believe this effect can greatly increase near-wellbore problems for hydraulic fracturing, such as tortuosity and excessive multiple fracturing.[21-26]

Hydrajet-perforating leaves the tunnel clean and free of mechanical damage[24] from the tremendous compaction force that is part of explosive perforating. This benefit offered tremendous opportunity for improved applications in vertical well fracturing. In the second quarter of 2004, a vertical well process was commercialized using a CT-deployed hydrajetting tool, immediately followed by a fracturing treatment pumped down the CT-casing annulus. This allowed the CT string and hydrajetting tool to remain in the wellbore to immediately move uphole and repeat the process.

Recently, technical papers introducing and expounding on this process in vertical wellbores have become available.[27-29] The success of this process opened the door to similar approaches for horizontal well applications. For either vertical or horizontal well applications, there must not be any open or perforated sections above the point to be fracture-stimulated because the fracturing operations will be pumped down the annulus.

Why were there concerns about hydrajet-perforating vs. conventional perforating? Past studies have illustrated the enhanced benefit of hydraulic fracturing through hydrajetted perforations, but not consistent economic return of the higher perforating costs. Therefore, industry had not supported this process as a commonly available service. Applications in the past usually performed the hydrajet-perforating as a separate process step, which greatly increased the cost. The incorporation of hydrajetting while the fracturing equipment is on location reduces this cost. The CT equipment provides more than hydrajetting tool deployment; it is also used to facilitate sand-plug isolation of previously fractured zones downhole, and post-frac well cleanout of the entire wellbore. In some cases, it contributed to post-frac flowback efforts also. Another useful benefit of having the CT string remain in the wellbore during fracturing operations is that when the CT injection rate is reduced to approximately 0.25 bbl/min, the string can then serve as a dead string and provide excellent bottomhole pressure data in real time. This data greatly improves understanding of downhole conditions while a fracturing treatment is being pumped.

An additional concern regarding hydrajet-perforating is that a smaller number of perforations are usually jetted and may choke production. This could later prove to be a valid concern in some higher-permeability reservoirs. However, in applications to more than 200 vertical wells at the time of this writing, this problem has rarely been reported, and was only an early concern. These applications have been mostly in low permeability reservoirs where typically 5 to 15 (or more) zones were individually hydrajet-perforated and then immediately fracture-stimulated, often within the same day.

THE NEXT STEP-CHANGE FOR HORIZONTAL WELL FRACTURING

The horizontal-hydrajet-perf-annular frac (Hz-HJP-AF) process enables individual fracture-stimulation at selected locations along the lateral in new horizontal completions with pinpoint precision.[30] Using a CT-deployed hydrajetting tool, the Hz-HJP-AF process combines the proven advantages of hydrajet-perforating with the well control and speed of coiled tubing operations. Combined with pumping the fracturing stages down the annulus of the CT and the casing, it allows completion of a large number of fracture-stimulation treatments during a single well intervention with typically only tens of minutes between completing a frac stage and starting the next one. The injection rate, fluid volume, and proppant types and sizes can be tailored for each stage. For fracture-acidizing applications, there is little, if any, restriction on the type of acid fluids placed—even foamed or emulsified acids can be placed, if desired. The process can even be applied in existing wells above previous completions or by squeezing off earlier, perforated sections. There might be future options available for using a temporary liner on some existing or new completions.

Compared to most through-tubing, horizontal fracturing processes, this new method allows for higher injection rates at lower treating pressures by pumping the frac slurry (or acid) through the annulus of the CT and the casing. **Fig. 4** gives an illustration of the components that make up the BHA typically used for this process. Because hydrajet-perforating is accomplished through the coiled tubing at much lower rates, high jet differential pressures do not affect the annulus treatment pressure. This makes the annulus the optimum flow path to achieve higher treatment rates at lower pressures. **Figs. 5–12**[30] show the steps for applying the Hz-HJP-AF process to achieve a four-stage fracture stimulation program in a horizontal well. These illustrations imply that the fractures are placed equidistant from one another and that they are the same final size, which is not necessarily the case. Each frac stage can be designed and pumped specific to the expected need or reservoir conditions at the selected frac location. The distance between each frac location can be varied, especially when the operator has data to indicate which specific locations along the lateral are best for fracturing. In some wells, there might be some limitation of how close the fractures can be to one another. It might be difficult to achieve and maintain zonal sealing after each frac if they are less than about 100 ft apart. This might become less of a concern with increased experience with the process.

Annular fluid velocity is limited to 20 ft/sec at the surface injection point to avoid erosion of the coiled tubing. Multiple wellhead injection points protect the CT from impingement erosion and increase the maximum allowable annulus rate. **Fig. 13a** illustrates one possible wellhead configuration below the CT injector, and **Fig. 13b** shows a photo of this same wellhead assembly used for this process while stimulating a horizontal well in Michigan.

SELECTING THE NUMBER OF FRACTURES

Selecting the number of fractures is far too broad a topic to be effectively addressed in this paper. The number and size of fractures that should be placed along any given lateral is very specific to a given reservoir and economic limitations.[3-4] Technology enabling reservoir simulation modeling of production from multiple fractures along horizontal wellbores must be significantly improved. Many current models are very simplistic. Before a multi-fractured lateral is modeled, the specific model should first be proven capable of matching production from a non-stimulated horizontal wellbore in the reservoir. In many cases, especially in thin reservoirs, the difference in longitudinal fracs and transverse fracs can be very pronounced unless the effective fracture lengths are short or the permeabilities are not very low. Several recent papers on fracturing horizontal wells have commented that their modeling of transverse and longitudinal fracture planes “showed little difference,” but very few have offered details of the reservoir simulator or their specific simulations.

Layering within the reservoir can create very significant vertical permeability problems that many reservoir simulation models can not effectively handle, even when the operator has valid, detailed geological data. Not only do many horizontal wellbores encounter significant reservoir rock variations along the lateral, but often the proximity to wet zones or the water table changes. These variables are important to the optimization of selecting desired fracture locations and the size of the fracture at each location.

CASE HISTORY INFORMATION

The first application of the Hz-HJP-AF process was in a horizontal Barnett shale well in early 2005. The well apparently was near or intersected a fault communicated to an aquifer and produced gas with high water rates, similar to a conventionally-completed well nearby. Although the gas production was disappointing, it appeared the stimulation process was effective. Because this was the first application of the process, learning experiences caused job delays and added costs.

A second quarter, 2005 application of this process on a well in Canada placed five frac stages of about 250,000 lb of proppant per stage. The result was even higher than anticipated production rates. However, the well data was later classified as “tite-hole” by the well operator and details of the reservoir, job designs, and well production cannot be presented.

At the time of this writing, the Hz-HJP-AF process has been used to fracture-stimulate eight horizontal wells. A very recent paper[30] contains the small amount of post-frac production data released for publication as of January 2006.

Future publications are expected to present more extensive production results from applications of the Hz-HJP-AF process in horizontal wells.

CONCLUSIONS

- Hydrajetted perforations have been shown to provide optimum connectivity to the reservoir through erosion of the rock in contrast to explosive perforating processes that lead to compaction damage of the formation rock surrounding the perforation tunnels.
- Methods of using hydrajet-perforating and fracturing operations that require the use of tubing large enough to allow adequate injection rates through the tubing to achieve fracturing have been restricted from application to many wells because of small ID limitations or weak casings.
- A new process for stimulation of horizontal wells that uses a CT-deployed, hydrajetting tool has been developed.
- The new Hz-HJP-AF process can be used in horizontal wellbores where the formation is not yet open to the casing (or liner) above the lowest location to be hydrajet-perforated and then fracture-stimulated through the CT-casing annulus.
- The CT string can provide real-time bottomhole pressure data to increase the understanding of formation response to the fracturing operation.
- The Hz-HJP-AF process requires no setting or moving of packers or bridge plugs.
- This new process currently uses end-of-stage screenout or wellbore sand plugs for isolation.
- The CT BHA allows for reverse-circulation and can clean proppant from the wellbore after the last frac stage in one well intervention.

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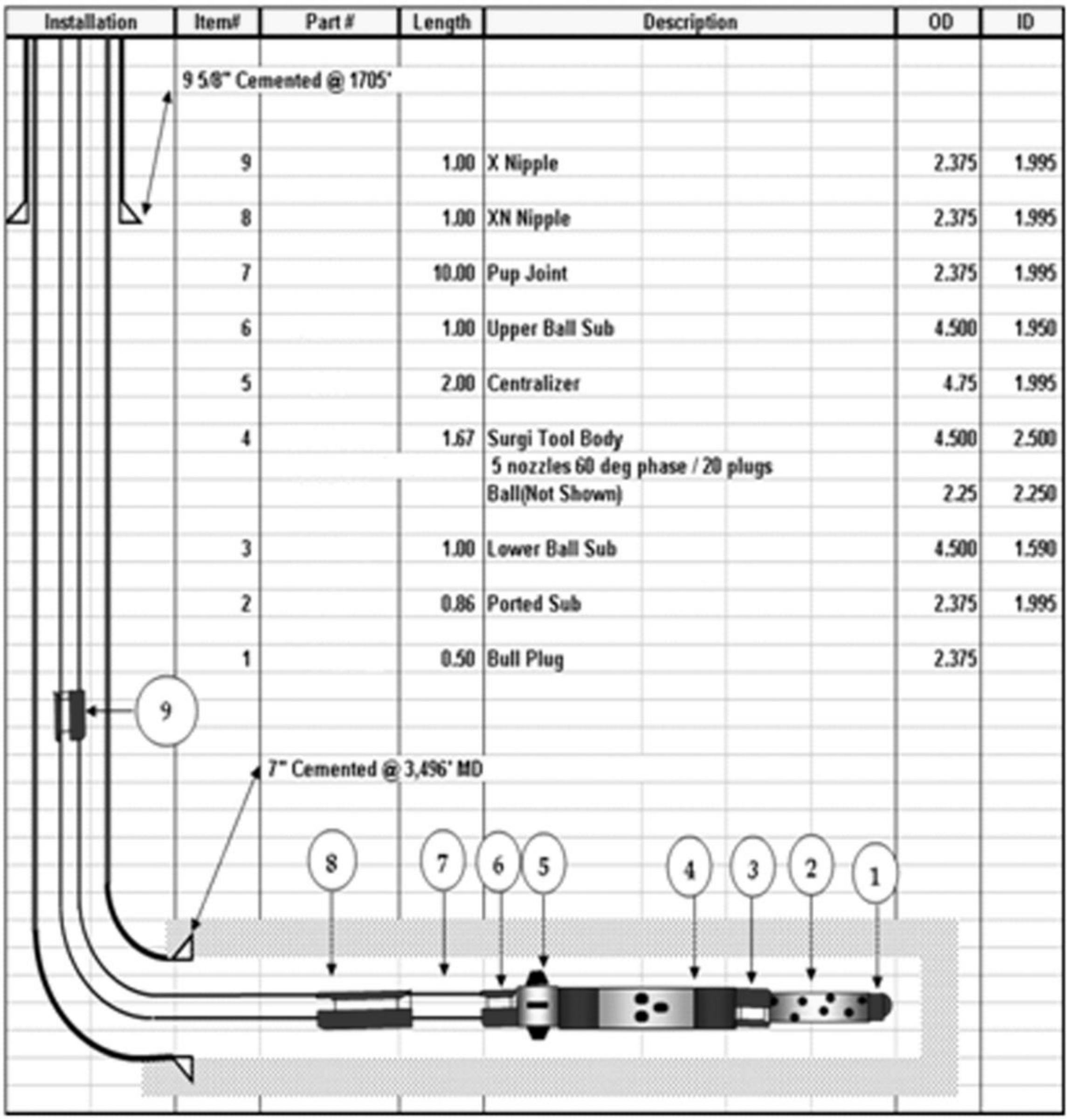

Figure 1—This schematic illustrates the treating string and bottomhole assembly used for hydrajet-perforating and fracturing a shallow horizontal gas well completed openhole.

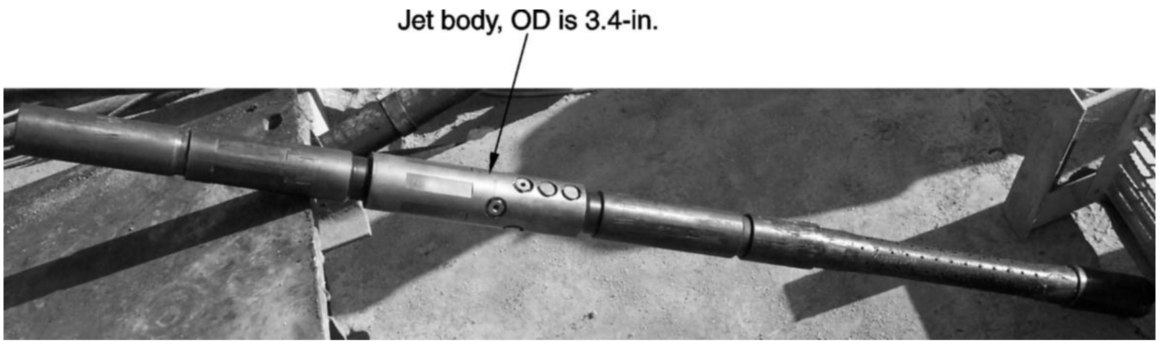

Figure 2—BHA used on recent jointed tubing hydrajet-fracturing treatment in western Asia.

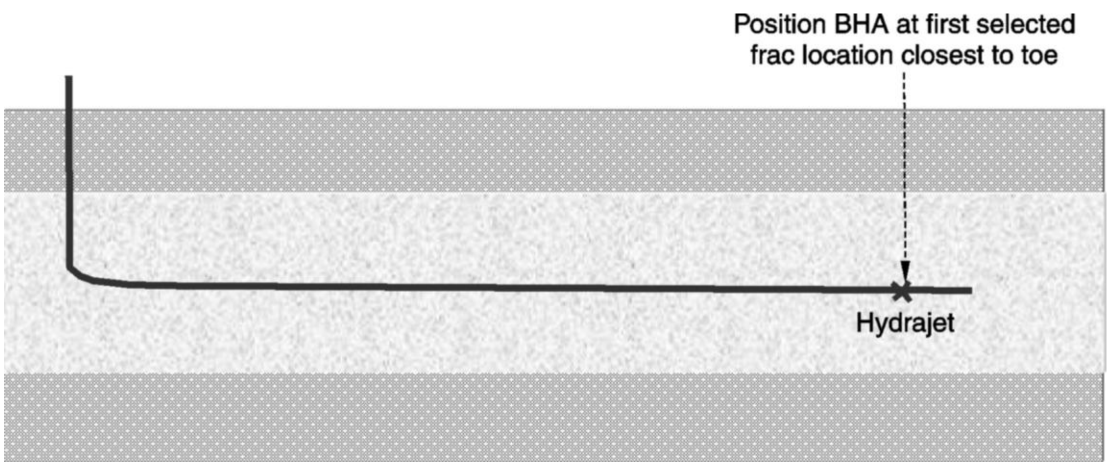

Figure 3a—Hydrajetting creates non-damaged, highly effective, highly localized “weak spot” and intensified pressure communication at a desired fracture location.

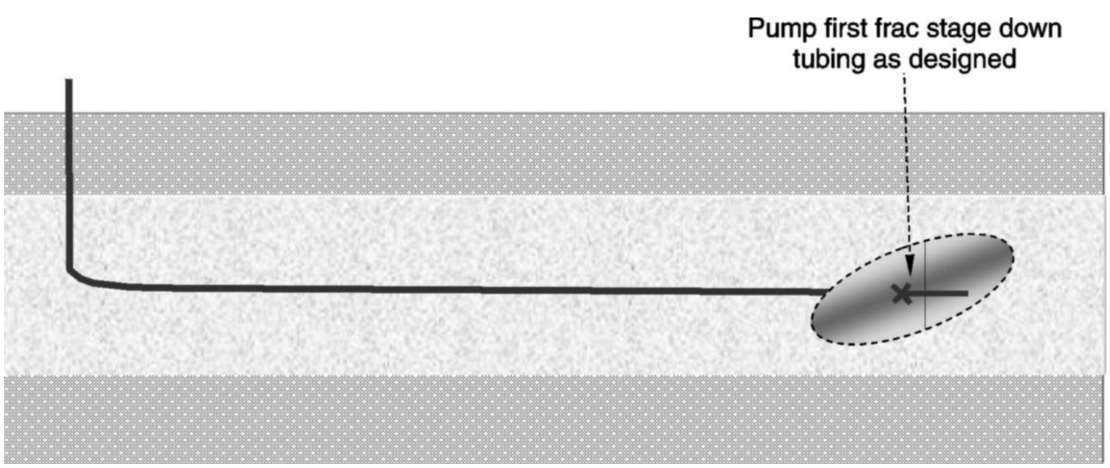

Figure 3b—Numerous earlier papers have described how the Bernoulli effect creates a “jet pump” effect to cause fracture growth to predominantly occur at the jetting location.

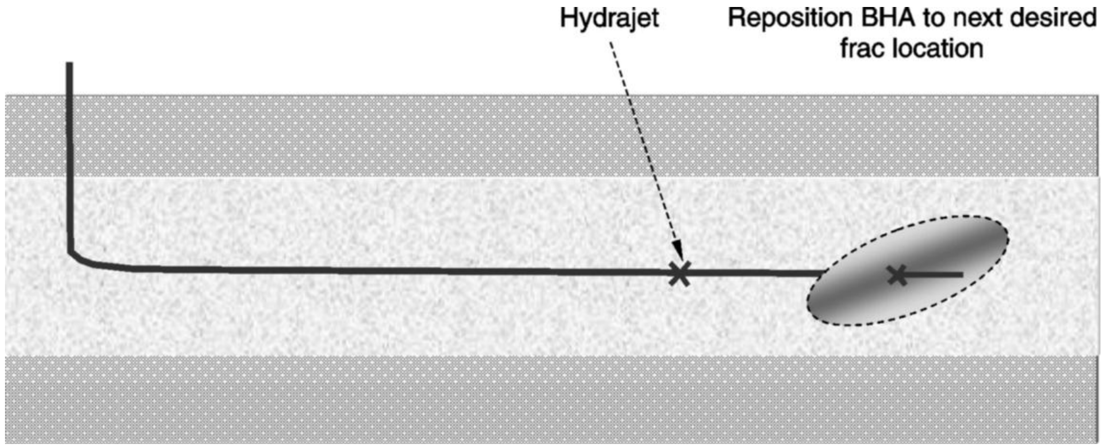

Figure 3c—The BHA is pulled back to the next frac location to begin the jetting operation for the next frac stage.

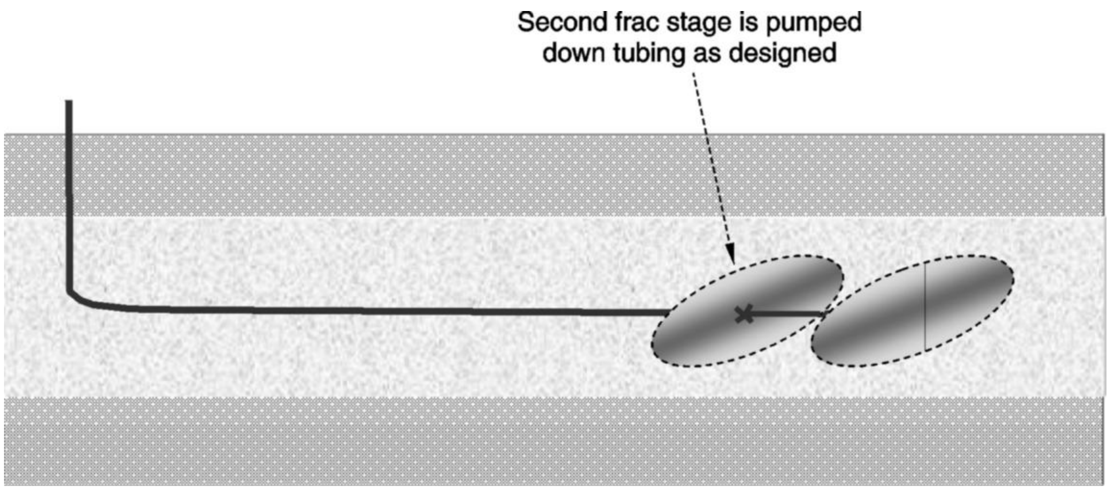

Figure 3d—With the slurry pumped through the jets, the Bernoulli forces create a “jet pump” effect to cause fracture growth to predominantly occur at the jetting location without needing a packer or BP to isolate lower intervals.

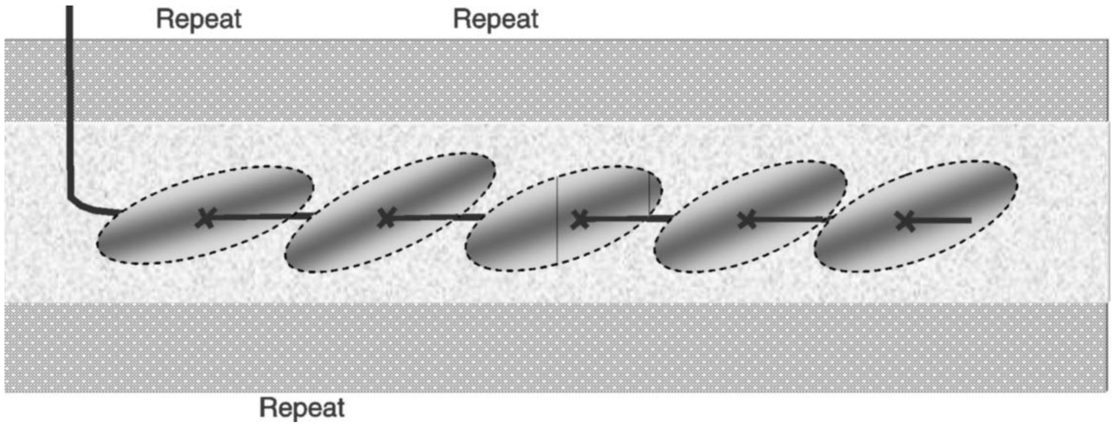

Figure 3e—The process (pull BHA, hydrajet, pump frac stage) is repeated until all stages are completed. After the final frac stage is pumped, the BHA is pulled into the vertical section of the wellbore (or completely out) and well flowback begins.

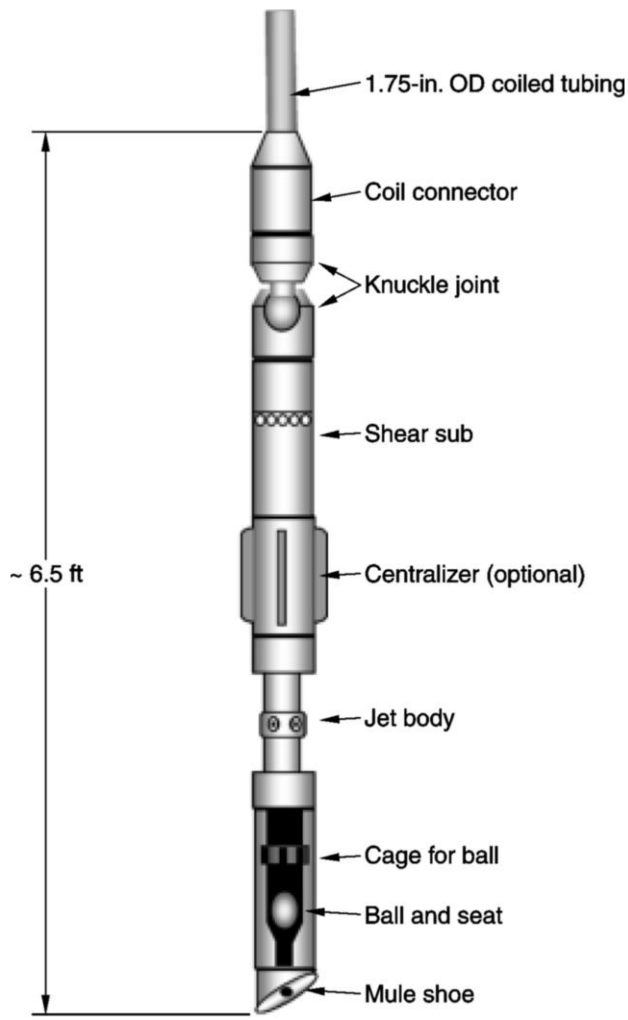

Figure 4—CT-deployed jetting BHA with reverse flow capability.

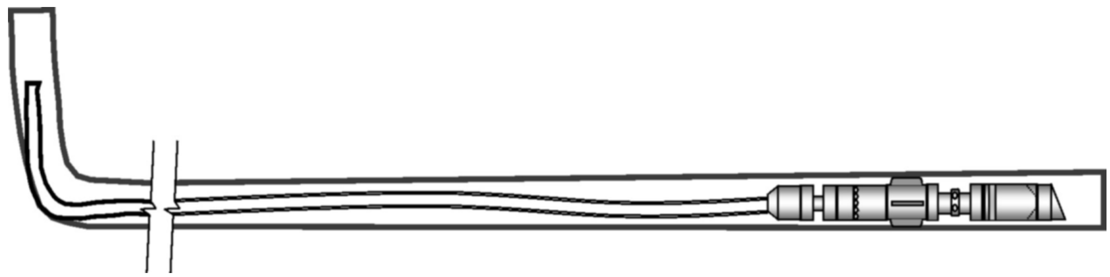

Figure 5—CT deployment of the jetting BHA to location in lateral for first frac stage in the lateral section.

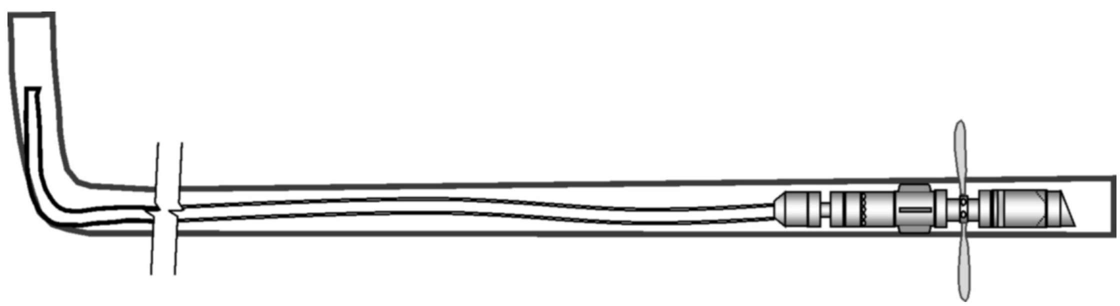

Figure 6—With the BHA positioned at the location where the first frac stage is desired, the perforations are hydrajetted using abrasive.
Jetting with clean fluid continues as the annulus is closed for frac initiation.

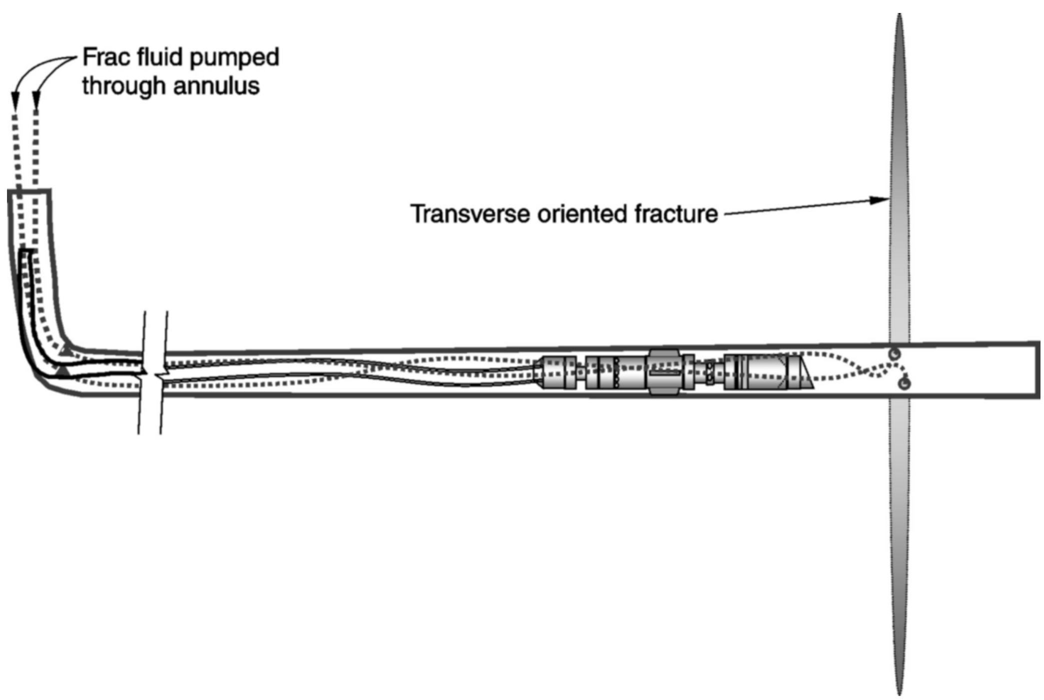

Figure 7a—The CT rate is decreased and the BHA is pulled back uphole from the perforated interval after the pad, or before the high-concentration proppant slurry gets to the perforations. At low rate, CT acts like dead-string for accurate frac pressure monitoring; screen-out is induced at the end of the frac stage.

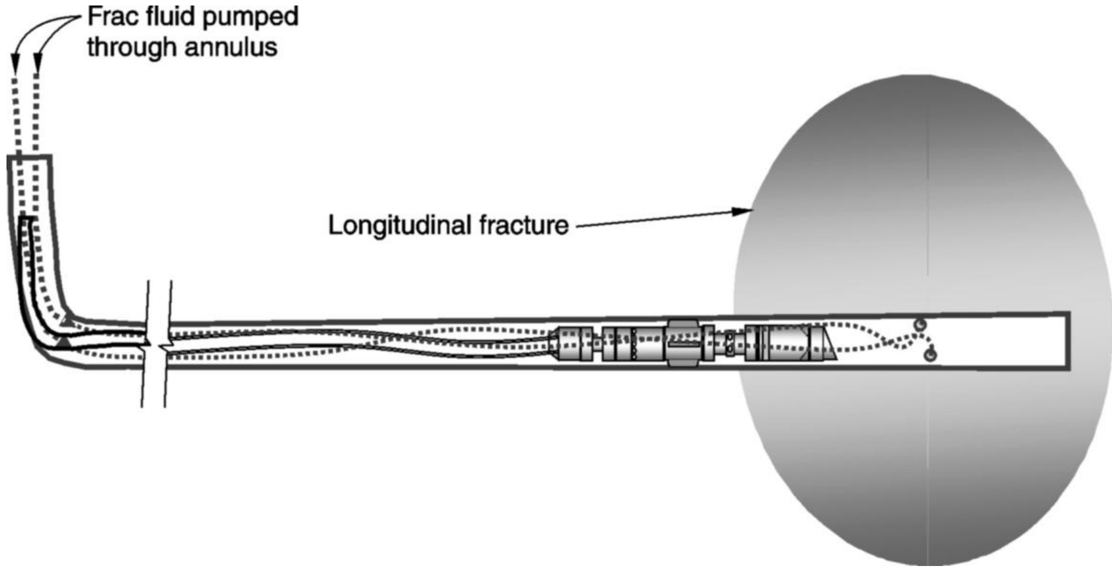

Figure 7b—The fractures created could be longitudinal instead of transverse to the wellbore depending on the preferred fracture plane at the specific location in the reservoir.

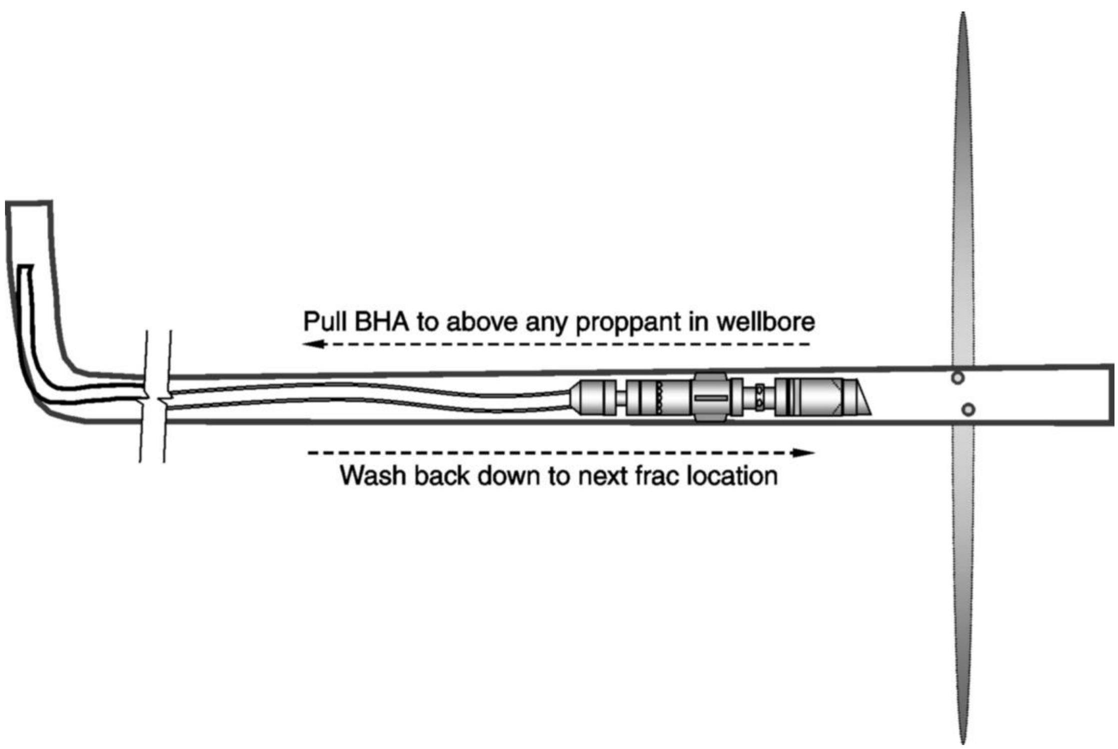

Figure 8—The BHA is pulled back above any proppant left in the wellbore after the frac stage is complete and shut in. Then the proppant is reverse-circulated out as BHA moves back down to the location for the next desired frac in the lateral.

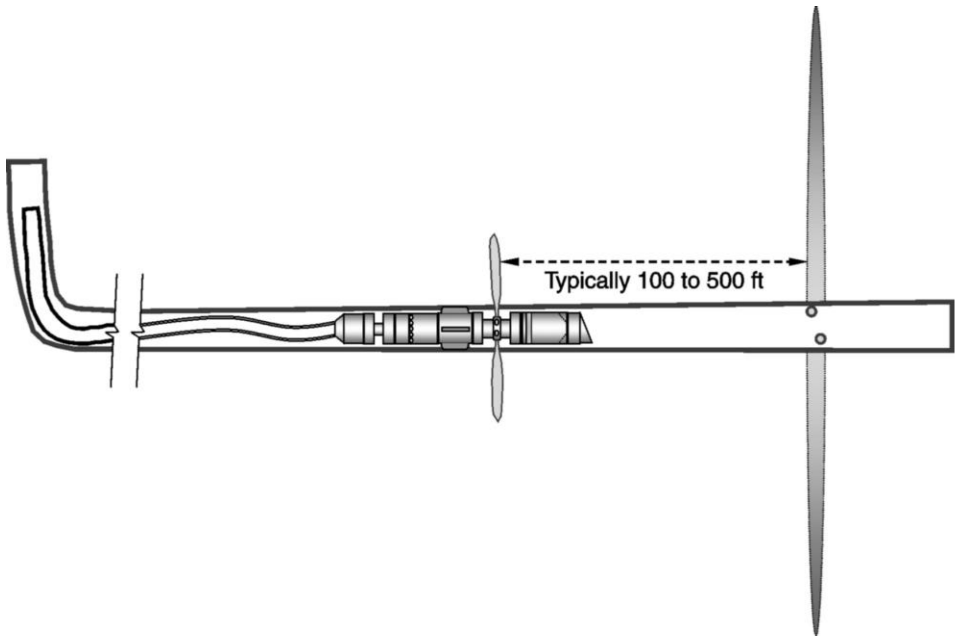

Figure 9—Perforations are hydrajetted for the next frac stage with annulus returns controlled to stay below frac pressure but not allow the previous frac states to flow back. The annulus is again closed, and the wellbore pressure is allowed to build for frac initiation, which may now require some annulus injection. Jetting action is maintained while pumping most of the pad volume for the fracturing treatment, possibly until near the end of the frac stage.

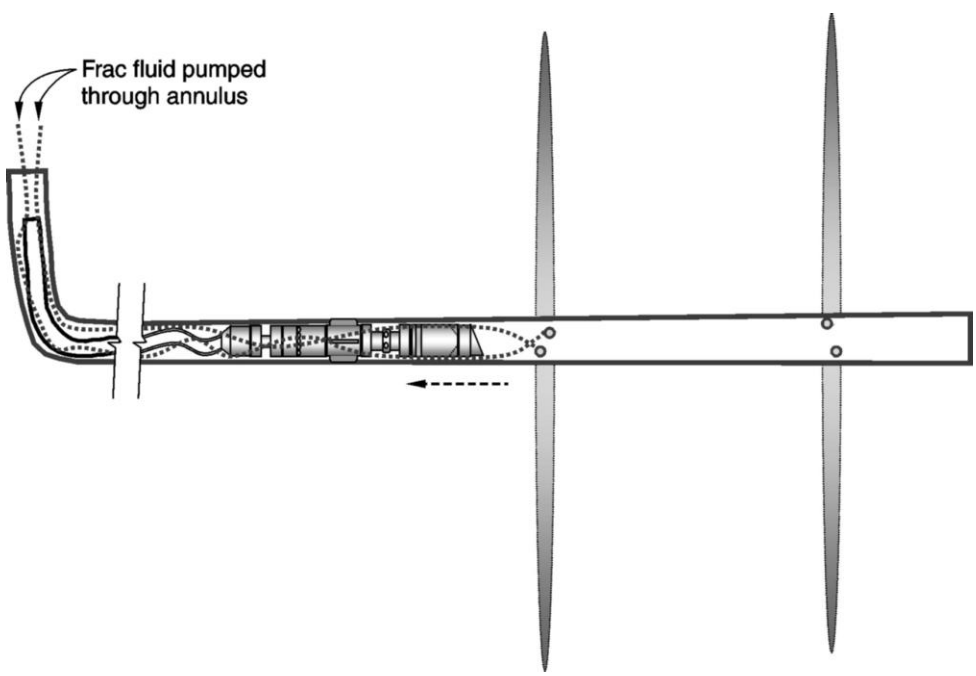

Figure 10—The CT rate is again lowered and the BHA is pulled back uphole, away from the perforated interval to act as dead-string for accurate frac pressure monitoring.
Screen-out is induced at the end of the frac stage.

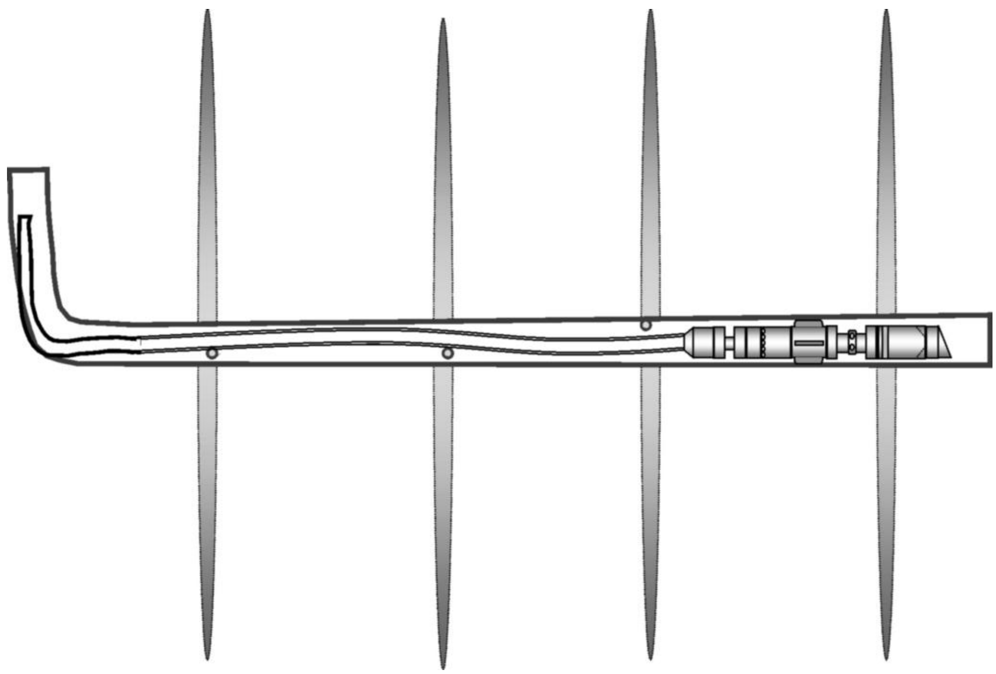

Figure 11—The final frac stage allows the fracture to close. The BHA is run back down to beyond the first frac location to reverse-out any proppant left in the wellbore.

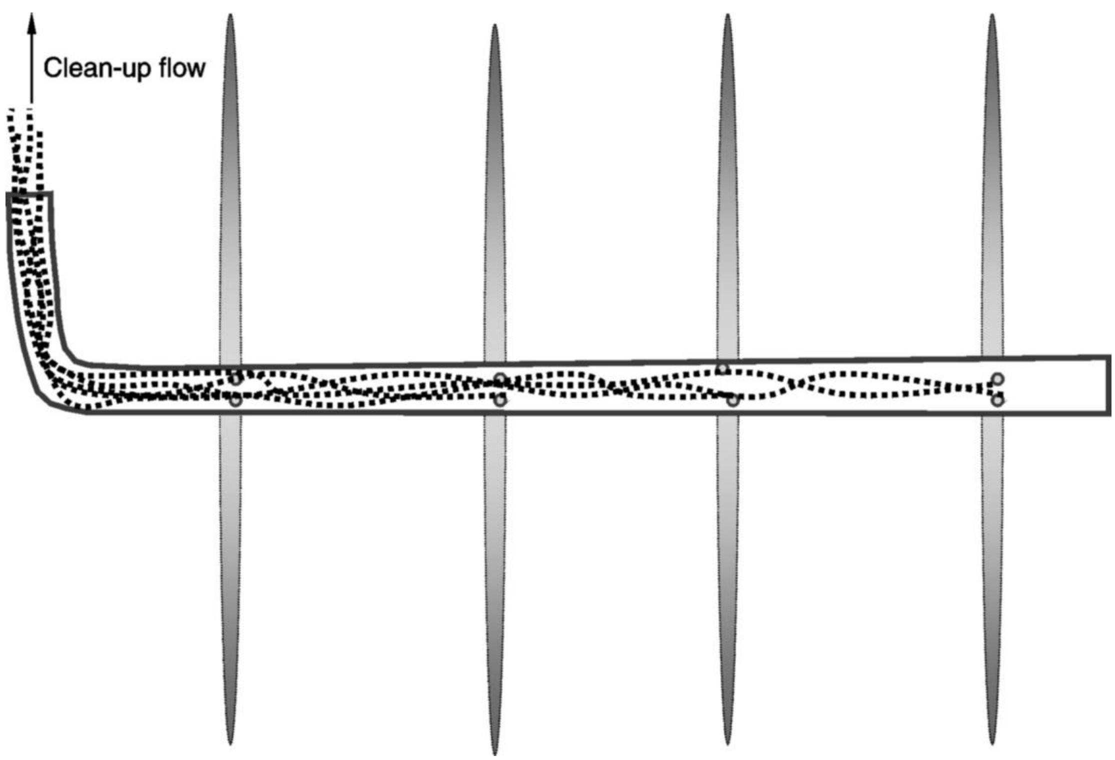

Figure 12—CT is pulled out of the well and frac cleanup is begun. If needed, CT can be used to kick off return flow.

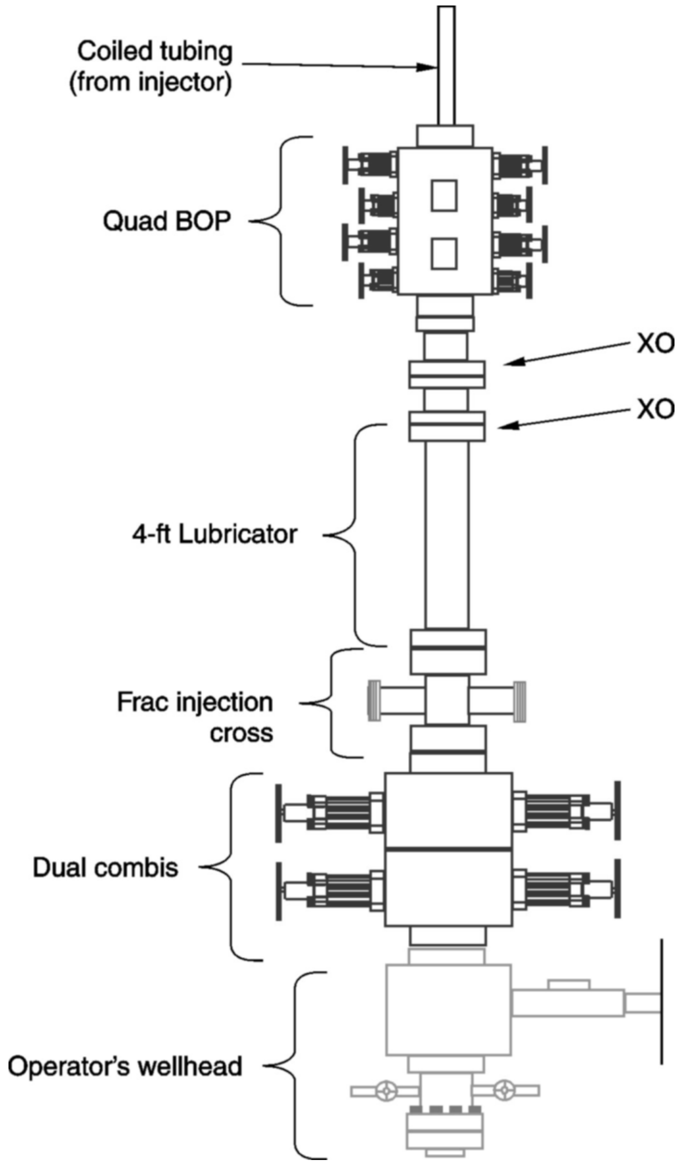

Figure 13a—A wellhead configuration below the CT injector.

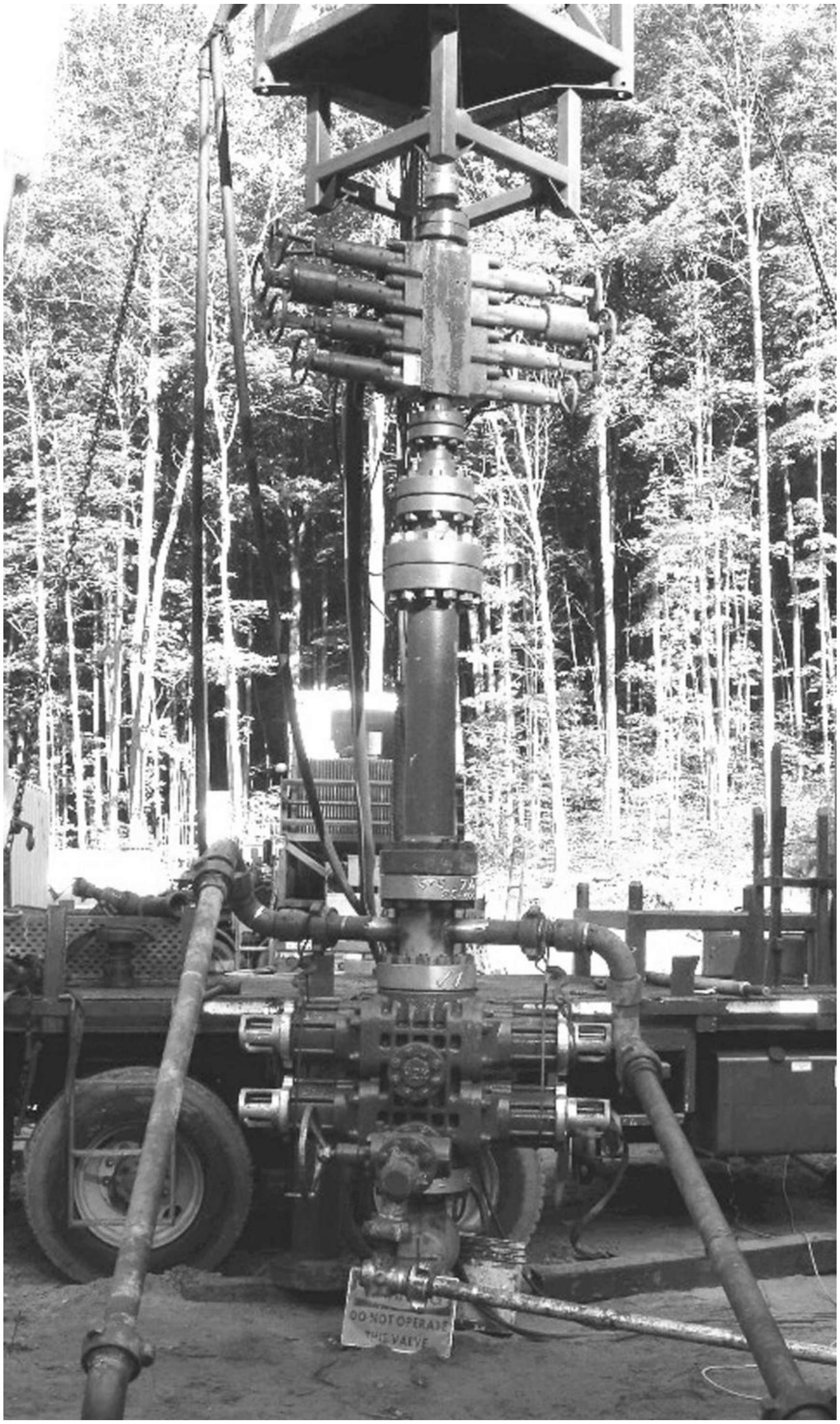

Figure 13b—Photograph of the same wellhead configuration shown in Figure 13a.