

SPE 86532

Alternate Path Completions: A Critical Review and Lessons Learned From Case Histories With Recommended Practices for Deepwater Applications

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This paper was prepared for presentation at the SPE International Symposium and Exhibition on Formation Damage Control held in Lafayette, Louisiana, U.S.A., 18–20 February 2004.

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Abstract

Since its introduction, over 700 alternate path sand control completions have been implemented around the world ranging from single zone cased hole gravel-packs to multi-zone frac-packs and fibre optic (DTS) enabled open hole horizontal completions. Over the last six years, the alternate path system has been field proven to provide high reliability in achieving complete packs as well as additional features allowing simultaneous cake cleanup, shale bypass and other contingencies that enable “doing it right the first time” in deep-water/subsea completions where interventions tend to be economically and logistically prohibitive.

This paper provides a critical review of those completions, capturing both successes and failures, along with the lessons learned in their design, execution and evaluation in relation to completion efficiency in sanding reservoirs. Furthermore, it details future development work and enablers that will allow the use of alternate path technology as the mainstay of intelligent well solutions, geometrical design improvements to provide optimal aspect ratios in the wellbore and its applicability in conjunction with water packing.

Introduction

Alternate Path is a technique that was developed to bypass any annular blocking that may occur during the completion process due to various reasons. Its original design consisted of steel rectangular tubes (also called shunt tubes) welded on screens, where the tubes had holes for exit of the slurry out of the tubes and into the annulus once the blocked annular

section is bypassed. This original design was intended primarily for use in cased-hole gravel packs. As such, this design (tubes with relatively small flow area and with holes drilled on) was sufficient for the pump rates, slurry volumes and the interval lengths that are commonly encountered in those applications. During the last six years, various improvements were made to the original design to address the specific needs for a variety of applications as discussed in the next section.

Although the initial applications of the alternate path technique have been directed towards improvement of gravel placement in cased holes, its current applications in frac-packing and open-hole horizontal gravel packing significantly outnumber cased hole gravel pack applications, in line with higher popularity of frac-packs and open hole gravel packs as reliable sand control techniques that yield high-productivities, particularly in deep-water/subsea environments. Thus, the review will focus primarily on alternate path case histories in these two areas, although examples of cased hole gravel packs will also be included for completeness.

The paper is organized as follows. First, we summarize the evolution of the alternate path system, highlighting the reasons for each improvement along with the benefits and potential disadvantages or limitations. We then continue with a discussion of the cased-hole followed by open-hole applications of the alternate path, providing some statistical information, along with a brief review of representative case histories as well as lessons learned for each application and some key considerations to ensure successful applications in the future. This is followed by a summary of further improvements that are currently being worked on. Finally we draw conclusions.

Evolution of the Alternate Path System

Optimization of Hole Size

The first improvement involved the optimization of the hole diameter on the shunt tubes. A series of yard tests were conducted with various hole diameters (3/32-in to 1/4-in) using gravels from 40/60 to 12/20 U.S. mesh. These tests indicated that bridging could occur when the hole diameter to mean gravel diameter ratio is less than approximately 5, preventing exit of the slurry out of the shunt tubes. Noting that the ratio of the largest to average grain diameter for each U.S. mesh gravel is approximately 1.3, this rule corresponds to 4 for the hole size to largest gravel size ratio. Thus, it is more

conservative than the conventional bridging rules that have been established based on single size particles,¹ and based on rules developed for flowing conditioned mud systems through wire-wrap screens.² On the other hand, if the holes are made too large, then leakoff through these holes (into either the base-pipe/wash-pipe annulus or into the formation) becomes excessive, dehydrating the slurry and resulting in gradual increase of gravel concentration downstream of the shunt tubes, and an eventual screen-out within the shunts; thus, the need for optimization of the hole size.

Nozzles replaced the holes on the shunt tubes in current alternate path screens as discussed below, although the findings mentioned above are valid and used in the nozzle design.

Introduction of Larger Tubes

The second extension of the alternate path evolved along with the popularity of frac-packing as well as long open hole horizontal gravel packs as sand control techniques. The original shunt tube design with 0.5x1.0-in external (0.31x0.81-in internal) dimensions did not provide sufficient flow area for the pump rates that are typically used in frac-pack applications, resulting in high frictional pressure drops through the shunt tubes.

Similarly, long open hole horizontal gravel packs may limit the pump rates due to increased frictional pressure losses. In both cases, the limitation is the burst pressure of the shunt tubes, which is currently 5,000 psi.

The tube dimensions were modified to 0.75x1.5-in external (0.56x1.31-in internal), yielding 3 times the flow area of the original design and reducing friction pressures over the rates of interest by approximately an order of magnitude, for long horizontal gravel packs. This of course was at the expense of a reduced base pipe diameter, which in many instances does not impact well productivity in either frac-packed or gravel-packed horizontal completions, although this should be verified through reservoir simulators that couple friction in the wellbore with the pressure drop through the reservoir.

Holes to Nozzles with Tungsten Carbide Inserts

The third improvement was the replacement of holes with nozzles with tungsten carbide inserts. This modification was a result of earlier experiments conducted with the original shunt tube design. In these experiments, shunt tubes with 30-ft length containing 22 holes of 1/8-in diameter were used with the end of the shunt tube blocked, forcing all the slurry through the holes. An 80-lb/1,000-gal HEC solution with 2.0-ppa 40/60-U.S. mesh gravel was injected at 2.0 bbls/min. The key observations can be summarized as follows:

1. Holes closer to the inlet section of the shunt erode very quickly, as most of the flow occurs through these holes, and
2. As those holes elongate (increased flow area) with further erosion, all of the slurry flow occurs through the first several holes,
3. After 5 mins (10-bbls) of slurry injection, the first hole had already elongated to 0.4-in, growing to 0.6 and 0.8-in after 10 and 20 minutes, respectively.

Based on these results, as the holes become larger due to erosion, the leakoff rates would be increasing, with the same result as in use of large holes to begin with; i.e., increased gravel concentration and bridging within the shunt tubes.

In order to eliminate this concern, the holes were replaced with nozzles with tungsten carbide inserts. **Figure 1** shows some of the results for erosion testes where nozzles with and without Tungsten Carbide inserts were submitted to extreme slurry velocities.

Based on the hole-size optimization tests, combined with the nozzle design as well as additional experiments for confirmation, the recommended nozzle diameters for commonly used gravel sizes are given in **Table 1**. Note that gravel sizes up to and including 16/30 U.S. mesh can be used with 1/4-in nozzles, while 3/8-in would be required for 12/18 U.S. mesh, with a nozzle length of 5/8-in in both cases.

Note also that an additional advantage of the nozzles is reduced leakoff due to a small-diameter linear flow cell packed with gravel, once the annulus in that section is packed, further minimizing the risk of bridging in the shunts due to increased gravel concentration downstream of the shunts.

Introduction of Packing & Transport Tube Design

Even with the nozzle design, gravel packing of long horizontal completions may be difficult due to leakoff through the packed nozzles and thus the increased gravel concentration downstream leading to screenout in the shunt tubes. Following calculations, rather simplistic but instructive, illustrate how simply using shunt tubes with nozzles can lead to a failure due to bridging in the shunt tubes.

Figure 2 shows the rheology profile of a typical viscoelastic surfactant fluid used in open hole gravel pack applications with the alternate path technique. As seen, the rheology profile follows the Carreau model, exhibiting low-shear and high-shear plateaus, with a high-shear Newtonian plateau of 40 to 50 cp for this particular fluid formulation. The value of the high-shear plateau as well as the shear rate value at which it is observed depends on various parameters, including VES type and concentration, brine type and density, and temperature. As the shear rates in the packed nozzles are for the most part in the region where the high-shear Newtonian plateau is observed, we shall use 40 cp for the fluid viscosity, for illustration purposes. Using a lower viscosity will further strengthen our arguments.

Consider an interval of 2,000 ft, that will be gravel packed with 2 transport tubes at 4-bbls/min using 5.0 ppa VES slurry, with the transport tubes having 5 nozzles (1/4-in diameter) per shunt joint and each joint being 30-ft in length. Assume further that a bridge formed at ~ 1,000 ft from the heel and the first 1,000-ft section was subsequently gravel packed. Considering 1-psi/ft of friction pressure at 2-bbls/min per transport tube, and assuming that the decrease in friction pressure due to reduced flow rate in the shunts as a result of carrier fluid leakoff through the nozzles will be balanced by the increase in friction pressure due to increased gravel concentration due to leakoff, the total leakoff rate can be shown to reach the value where all gravel particles have grain-to-grain contact (i.e., bridging inside the transport tube) at ~ 1,000-ft.

Consider now the packing and transport tube arrangement shown in **Figure 3**, with 5 nozzles of ¼-in diameter, first nozzle on the packing tube 1.5-ft away from the branching point of the transport tube. Considering the same example as above, with the same assumptions, it can be shown that the leakoff rate at the same 1,000-ft point would be reduced by more than an order of magnitude, thus no risk of bridging inside the transport tubes due to leakoff.

The advantages of the packing/transport tube arrangement include reduced friction through the use of larger tubes for transport, reduced leakoff through the use of smaller packing tubes that branch off the transport tubes, and reduced make up time due to lower number of connections between screen joints. These in turn yield longer distances to be packed in horizontal completions.

Leakoff Tubes

For gravel to be deposited in a given area, the slurry must dehydrate through leakoff either into the formation or into base-pipe/wash-pipe annulus. In open hole gravel packs, where there is a competent filtercake, appreciable leakoff can occur only into the base-pipe/wash-pipe annulus. Thus, at the connection area of the screen joints, the only way the gravel packing can proceed is if the fluid can leakoff through the deposited gravel pack and into the subsequent base-pipe/wash-pipe annulus.

The time it takes to pack the joint section will be a function of the pressure, pack permeability, fluid rheological parameters, annular area, and the length of the connection area. The latter can vary from ~ 3.5 to 5.5 ft in horizontal applications where premium threads are used. In order to ensure rapid packing of the connections, the leak-off tube concept was introduced. A small shunt tube with slots on it is currently being used as the leakoff tube to speed up the slurry dehydration (**Figure 4**). Note that in cased and perforated wells leakoff occurs externally and thus leakoff tubes are not needed.

Concentric versus Eccentric Design

One disadvantage of the alternate path system is the reduced base-pipe diameter due to presence of the shunt tubes. When the tubes are placed concentrically around a screen of fixed base-pipe diameter, the external dimensions become larger compared to when the tubes are placed eccentrically (**Figure 5**).

The key advantage of the eccentric design is the increased base-pipe size, allowing, for example, 5.5-in base pipe in an 8.5-in open hole. The disadvantage of the eccentric design is that the gravel pack thickness is lower on one side compared to the other.

Timed Premium Threads for Connections

Many horizontal applications, reservoirs with compaction problems and most deep-water environments require premium threads, to eliminate potential separation of screen joints during either installation or production (due to compaction). In addition, since there is no control over the circumferential

alignment from one joint to the next with the standard connections (leading to non-aligned shunts which could not be connected with jumper tubes), a timed premium thread was developed to torque the connection and align the shunt tubes simultaneously.

Manifold Design

In long horizontal completions, due to large number of joints and the jumper tube connections needed at each joint of screen, additional costs are incurred because of increased rig time. A manifold system was thus developed (**Figure 6**) to eliminate jumper connections and reduce rig time. With this design, the outer shroud and the inner base pipe are connected simultaneously, with the annular area between the outer and the inner strings creating a manifold. Although effective in reducing screen make up (thus rig) time; with the existing design, this system is limited to 4.5-in base pipe for 8.5-in open-hole applications. In addition, its heavy weight and cost of manufacturing are areas that need improvements for this design to be an attractive option for long horizontal completions.

Concentric Entrance

For horizontal gravel packs utilizing the eccentric design, another improvement of the alternate path system was the introduction of the concentric entrance, also known as Y-manifold, pictured in **Figure 7**. This design ensures that there is at least one transport tube in the top section of the horizontal well, providing a path for continuation of the gravel pack job in cases where long shut down periods may result in gravel settling and thus blocking of the entry to the shunt tubes, should the shunts end up on the low side.

Multi-Zone (MZ) Isolation Design

The MZ (multi-zone) packer, in **Picture 8**, was developed to allow for multiple zones to be completed in a single trip, with a single pumping stage, thereby saving significant rig time as well as eliminating the use of fluid loss control pills that are typically required in two or multi-trip completion operations. The MZ packer is a cup type packer with shunts in the cup/base-pipe annulus.

The upper zone is packed conventionally, while the lower zone is packed by diversion of the slurry through the shunts bypassing the cup packer. Because the cup-packer assembly is only 6-ft in length, it allows isolation in multiple sand bodies separated by relatively thin shale sections. This is compared to conventional stacked completions that require a minimum of 15 to 20 ft spacing.

This technique can be (and has been) used for frac-packing multiple zones, gravel packing multiple zones as well as frac-packing one zone and gravel-packing the other in one trip and one pumping operation. Fracturing or gravel packing of each individual zone is dictated by the rate of slurry diverted into each zone, which in turn is controlled by the frictional pressure drops within the shunts delivering slurry into each zone. For a given fluid composition and gravel concentration, friction and thus the pressure applied to each zone can be

controlled through the shunt tube dimensions (diameter and length) as well as the nozzle diameter and frequency.

The cup packer provides isolation of the casing/screen annulus (in a blank section), and thus an internal isolation would also be needed in order to selectively produce or isolate each zone. In many instances, this internal isolation is achieved by placing a sliding sleeve inside the screen across each zone. This allows for flexibility in terms of shutting off zones that are producing undesired fluids (water or gas). The same configuration can also be used to selectively produce each zone one at a time. Alternatively, an isolation string can be run to the lower of two zones below a production packer, and two tubing strings can be run above the production packer to simultaneously and selectively produce two zones.

There are two versions of the MZ-packer. The first one does not allow for a positive isolation, as there is hydraulic communication between the zones through the shunt tubes. In this case, limiting the production of undesired fluids relies purely on the linear flow cell created by the packed shunt tubes, which can reduce water production substantially as simple calculations using Darcy's law would indicate. The second version of the MZ-packer incorporates isolation valves to provide a positive isolation of the packed shunt tubes. These valves are actuated using a collet mounted to the wash-pipe. Driving the collet through the shifting sleeve in the down-hole direction opens the valve, while pulling it up through the shifting sleeve closes the valve.

Alternate Path with Fiber Optics

In line with the recent developments in downhole monitoring technology, a new alternate path screen was designed to allow for the installation of fiber optics in horizontal wells. In this design, the conventional alternate path protective shroud is dimpled (**Figure 9**) to allow the placement of a dual control line flat pack for post-job deployment of fiber optics for real time downhole temperature monitoring. This system, in its open hole version, was field tested recently, while its cased hole version is currently being developed.

Cased Hole Applications

Cased-hole alternate path applications account for approximately 86% of the worldwide job count to date (since 1996), totaling 624, with most of the applications in the Gulf of Mexico. Recent trends indicate an increasing acceptance of the alternate path technique in deepwater environments, in frac-packing longer intervals (over 200-ft of perforations) and wellbores with deviations above 70°.

Of the 624 cased-hole applications, 191 were conventional gravel packs, 163 were various applications of the multi-zone packer technology, and 270 frac-packs.

Multi-zone packer applications consisted of 19 frac-packs (4 with more than one multi-zone packers) and 144 gravel packs (9 with a multi-zone packers incorporating isolation valve).

Table 2 shows the screen lengths versus job count for cased hole frac-pack applications of alternate path. The kh varies in

the frac-pack applications varied up to 120,000 md-ft, and the fluids were crosslinked guar and viscoelastic surfactants in 90 and 10% of the cases, respectively. Well types range from oil or gas producers to water injectors.

Several variations of the technology are field proven, some of which are documented in the literature:

- Single and multi zone sand control,³⁻⁸
- Multi-zone sand control with zonal isolation (i.e., using the Multi-zone packer as isolation device),⁹
- Single-trip perforating and sand control treatment in single or multiple zones (with the Multi-zone packer),¹⁰⁻¹³
- Single-trip gravel packing and production,^{10, 12}

Case Histories

The case histories below are used to illustrate the versatility of the alternate path technology, illustrating some of the completion scenarios listed above.

Case history 1: Single Trip Perforating and Frac-Pack Treatment in 322-ft Gas Producer (Far East)

The completion of this gas well was described earlier by Burton et al.¹³ In this case, effective sand control was achieved with a 10 to 15% increased dry gas production versus initial projections (110 to 115 MMSCFD compared to 100 MMSCFD).

The deviation across the productive interval was 50° and the gross perforated length was 322-ft (284-ft net) with 18 spf underbalanced. Two large shunt tubes were used, eccentrically positioned on the screens.

In this application, 48% of the treatment (27,100 lbs of proppant) was pumped through the shunt tubes, at 12 bbls/min with 8-ppa slurry. This example illustrates the versatility of the alternate path system and how it can be of critical value in some completions.

Case history 2: Frac-Pack Treatment in a Deep-Water Gas Producer (Gulf of Mexico)

This gas well was successfully completed in the Gulf of Mexico in a challenging environment. This application was on a well with a measured depth of 15,144-ft, with a perforated interval of 230-ft at an inclination of 72°, a reservoir pressure and temperature of 7,612-psi and 220°F at a water-depth of 3,500-ft. The kh of this formation was 118, 000 md-ft.

Two large (transport) tubes were mounted on a 4.5-in base pipe screen. 180,000 lbs of 20/40 proppant were placed with 30-lbs/1,000 gal of cross-linked guar fluid (over 700 lbs per foot of perforation) at an initial pump rate of 40 bbls/min, which was reduced to 25 and 10-bbls/min upon indication of slurry diversion into the shunts. 24% of the total proppant was pumped through the shunts. This completion resulted in a near-zero skin with a sand free production of 80 MMSCFD.

Case history 3: Multi-Zone Gravel Pack (South America)

The alternate path multi-zone technology enabled optimization of reserves exploitation in several fields, where traditional selective completions (i.e., multiple trips for hardware installation and multiple pumping jobs) wouldn't be economically viable. These applications involve gravel packing multiple productive zones with a single tools-run followed by a single pumping stage.

The Dacion field case study is a representative example of this approach.⁹ Cost reduction associated with the elimination of completion trips as well as the optimization of the expected post-completion workover had a significant impact on the project economics of this field development. One of the case histories reported by Marshall et al.⁹ describes application of this technology to a well with three zones that are separated by thin shale sections, allowing zonal isolation which could not have been achieved with conventional stacked completions.

Case history 4: Frac-Pack Treatment in a Deep-Water Water-Injector (West Africa)

The subject well was completed with a 9.625-in. casing set at 12,000-ft measured depth, perforated nearly balanced with a 0.7-in perforation diameter and 12 spf. The perforated interval was 328-ft (measured) over a 166-ft zone (vertical). The single-trip perforating and packing technique could not be used due to lack of a rat hole. After perforating a crosslinked HEC fluid loss control pill was spotted to control losses during the trip. After running the completion assembly, which included 350-ft of alternate path screens, with two large tubes (0.75 by 1.5-inch) eccentrically placed on 5-in. base pipe, to TD, and setting the packer, an acid treatment was performed to break the fluid loss control pill. This was followed by a mini-frac. A 27-lb/1,000-gal borate crosslinked guar with an aggressive breaker schedule was used in the main treatment, with an initial pump rate of 35 bbls/min. 103,000-lbs of 20/40 ceramic proppant was placed below the crossover as per design. The reservoir pressure and temperature were 3,300-psi and 194°F, respectively, and the average permeability of the formation was 200 md. The resulting injectivity index in this completion was 26.3 bwpd/psi, with a skin of -1.4.

Lessons Learned and Recommendations

The high flow rates and large slurry volumes associated with frac-pack jobs introduce certain challenges to the alternate path technology, due to high velocities in the shunt tubes as well as the nozzles. The consequences of these flow conditions can be categorized as potential erosion, collapse, or burst, although the latter two are extremely unlikely in frac-packing applications. This is because there is always a hydraulic communication through the nozzles, which prevents exceeding the burst pressure limit, and use of shunted blanks of proper length minimizes the risk of exceeding collapse limit. Additional cased-hole specific concerns are related to the applications of multi-zone packer as discussed below.

The first, and crucial, learning is that the nozzles on each shunt tube attached to a screen (when using the eccentric design) must point outwards to avoid high velocity proppant hitting the other shunt tube. If this happens, the shunt tube will be eroded by the slurry, in addition to deflecting part of the flow to erode the screen jacket inducing loss of sand control. This effect was observed in a frac-pack job. After the treatment, the service tool and the wash-pipe were pulled out of the hole, and wash-pipe was visibly eroded and ruptured. After this observation, the screens were washed over and fished. Surface inspections of the retrieved screens confirmed erosion of one of the shunt tubes and the screen jacket in areas adjacent to the eroded shunt tube, due to improper nozzle positioning.

Erosion of the shunt tubes can also be induced by high flow rates through the shunts. Based on experiments conducted with shunt tubes, it was determined that erosion of the tubes themselves is not a concern as long as the flow rate is kept at or below 8 bbls/min and 2 bbls/min per tube for the large and small tubes, respectively. Above these rates, erosion becomes a function of total slurry volume passed through the tube. When/if an annular bridge forms, an increased fraction of the slurry diverts into the shunt tubes, as the resistance to flow increases due to continued packing above the bridge, resulting in a change in the slope of pressure versus time plot due to higher friction in the shunts. Cases where the slope becomes large ($>> 1$) indicate potential wellbore screenout. In such cases, the injection rate should be reduced to the rates given above.

In long shunted blank sections, where the tubes do not have nozzles, or when the tubes dedicated (i.e., without nozzles) to the lower zone in multi-zone completions are long, special attention must be given to the design. In such cases, due to large frictional losses in the tube (high rates and lengths) and full hydraulic communication in the annulus, the risk of exceeding the collapse pressure of the tubes must carefully be considered. This has been identified as the most plausible reason for a failure in a multi-zone frac-pack application. The collapse pressure of the large shunt tubes is 2,200 psi.

In the early designs of the multi-zone packer, difficulties were experienced while passing the elastomer cups through restrictions, such as the wellhead. This necessitated grinding the cups down on the rig floor, resulting in additional rig time. This was subsequently addressed by adding a beveled gauging below the lower elastomer cup.

Open Hole Applications

Open-hole alternate path applications account for approximately 14% of the worldwide job count from 1996 to date, totaling 101, while they accounted for approximately 30% of the total job count in 2003. In 92% of the open-hole applications, visco-elastic surfactant fluids were used, while the rest with 2 exceptions were gravel packed with an HEC fluid, the latter mostly in dry gas wells. 80 of the 101 applications were with open-hole section at an angle greater than 80°. In this paper, we will define horizontal as being greater than 80°.

Of the 80 horizontals, 7 were completed with the manifold design, while the remainder was with the eccentric design. Approximately 46% of the horizontal completions were in wells drilled with oil-based fluids, and 35% of those drilled with water-based fluids were gravel packed using the simultaneous gravel packing and cake cleanup technique, incorporating enzyme, chelating agent solution or both in the carrier fluid for filtercake cleanup. **Table 3** shows the screen lengths versus job count for open-hole applications of the alternate path.

The alternate path technique is an alternative approach to water-packing in cases where the latter historically had relatively high rates of incomplete packing, as well as in high-risk areas where remediation can be prohibitively expensive.¹⁴ The alternate path applications in open holes included:

- Conventional open hole gravel packs (using a wash pipe and in circulation mode),¹⁵
- Conventional open hole gravel pack in circulation mode but without wash-pipe,¹⁶
- Open hole gravel pack above frac pressure,¹⁷
- Partial cake cleanup prior to gravel packing a water injector,
- Open hole gravel pack with full losses in circulating position,¹⁸
- Open hole gravel packs with filtercake cleanup chemistry incorporated into the gravel packing fluid,¹⁹⁻²³
- Open hole gravel pack in squeeze position, below²⁴ and above frac pressure with¹⁷ and without²² filtercake cleanup chemicals in the carrier fluid,
- Open hole frac-pack,²⁵
- Open hole gravel packing of two sands separated by a long (530-ft) shale break,²³
- OHGP in wells drilled with OBM using water-based¹⁸ and oil-based²⁶ carrier fluids

In open-hole completions, rapid dehydration of the slurry through high leakoff rates into either the formation or the screen, as well as localized hole-collapse or excessive swelling in highly reactive shale sections can cause a premature screenout in the absence of shunt tubes.

High leakoff into the formation may occur due to various reasons including filtercake liftoff, filtercake erosion, inclusion of filtercake cleanup chemicals in the gravel pack carrier fluid, and exceeding the fracturing pressure of the reservoir. Filtercake liftoff occurs when an underbalance is encountered, for example during tool manipulations, and if the fluid in the wellbore is a solids-free fluid, and thus there is no material to reestablish the filtercake. Tool systems that provide hydraulic communication between the upper-hole and the open-hole, throughout the completion process, minimize this risk and should always be considered as an integral part of any open-hole completion. For environments with a small operational window for fracturing, valves that divert flow into the wash pipe at preselected positions can be utilized to provide a short cut for returns and thus minimize the risk of building excessive pressure (thus fracturing) during the beta-wave of a water-packing treatment.

Thus, although two of the problems historically encountered in water-packing have, to some extent, been

addressed, the others still remain as issues of concern for a successful outcome of water-packing treatments. Filtercake erosion, evidenced as a gradual loss of returns, does occur in some instances. A well-documented case is an application discussed by Gilchrist et al.²⁷ where a synthetic/oil-based reservoir drilling was followed by water-packing. Note that although cake erosion is more of a concern in wells drilled with S/OB fluids, it is also observed in water-based drilling environments. Unpublished experimental work²⁸ demonstrated that internal cakes formed by properly designed reservoir drilling fluids (RDF) can alone be sufficient to control losses into the formation, regardless of the fluid type (S/OB or WB). Considering that a properly designed RDF limits the invasion of solids into the formation to a few grain-diameters, it is postulated that cases where gradual reduction in return rates leads to a premature screenout in water-packing are formations with low compressive strengths. In such cases, erosion of a few layers of formation sand (similar to but more severe than wash-outs during drilling due to absence of cake forming materials during gravel packing) would lead to increased losses due to removal of the internal cake as well as the external cake.

Another potential reason for premature termination of the alpha-wave is the incorporation of filtercake cleanup chemicals into the carrier fluid (brine). This has been demonstrated through laboratory experiments by Brady et al. to be a risky technique for water-packing, where they proposed an alternative approach of using a post-gravel-pack circulation tool to spot cleanup chemicals immediately after water-packing.²⁹ Note that the simultaneous gravel packing and cake cleanup technique proposed in conjunction with the alternate path technique³⁰⁻³² has been applied in an appreciable portion (~ 35%) of the open hole gravel packs in wells drilled with water-based fluids.

Localized hole-collapse and reactive shale sections continue to be challenges for the application of water-packing technique in open-holes, where alternate path provides assurance. Although the shunt technique can provide this assurance for complete packing (e.g., bypass of collapsed, sloughed shale bridges, swelled shales, etc.) as well as minimizing risk of shale mixing with gravel due to lower velocities compared to water packing, the risk of shale mixing with gravel would still be present when gravel packing with water-based fluids unless some precautions are taken. There are at least two ways of handling this, if a water-based fluid (e.g., VES) is used for gravel packing:

1. Do not use wash pipe at all: This would ensure gravel packing from heel to toe including the shale sections. Main disadvantages of this approach would be: (a) Alternate Path is the only path, as gravel packing would be through the shunt tubes from the beginning to the end (see case history highlighted below), (b) No wash down capability, (c) No downhole gauges, and (d) Does not allow for displacements after RIH with screens, (e) Does not allow spotting of cleanup chemicals immediately after gravel packing. Main advantages are: (a) No extended exposure of shale sections to water base fluids as packing will proceed from heel to toe and shale sections can also be packed with screen across those sections, (b) Don't have to deal with losses while pulling the wash pipe

should losses occur, (c) Lower cost (rig time savings and rental), (d) No risk of stuck wash pipe.

2. Use a wash-pipe with holes across shale sections: Compared to no wash-pipe at all, this option would allow downhole gauges while ensuring bridging across the shales and subsequent packing of the shale section as well as downstream of the shales through the shunts. This would isolate the shale sections, and prevent mixing of shales with gravel.

An alternative approach in reactive shale environments would be to use a synthetic/oil-based (S/OB) carrier fluid, if reservoir drilling is performed with a S/OB fluid. Such an approach has recently been successfully implemented on a high-rate gas well, incorporating filtercake cleanup chemicals into the carrier fluid after drilling with a reversible S/OB-RDF.²⁶

Below are several case histories highlighting some of the unique applications of the alternate path technique in open-hole completions.

Case History 1: Open-Hole Gravel-Packing without Wash-Pipe (Kazakhstan)

The subject well was in a remote location, 300-km away from the nearest city, presenting a major logistical challenge.¹⁶ In addition, the 3,000-ft horizontal open hole combined with shallow reservoir meant that the screens would be 1,000-ft into the open hole before the gravel-pack packer was connected on the rig floor. The location had a limited water supply for completion operations, and the field economics necessitated that everything be working correctly the first time.

The open-hole section was drilled with an RDF consisting of CaCO_3 , Biopolymer and Starch. Subsequently, the open hole was displaced to a solids-free RDF and the cased hole to filtered brine, screens were run to TD and the packer set. As indicated by an increase in slope of pressure versus time plot, an annular bridge formed shortly after slurry arrival to the open hole, and the packing continued through the shunt tubes. Note that the packing with alternate path technique proceeds from heel to toe in high-leakoff conditions (either into the formation or into the base pipe (in the absence of a wash pipe) as demonstrated through yard testing. This well was gravel packed using a viscoelastic surfactant fluid, with 33% excess gravel based on gauge hole (no caliper log), using less than 10% of the brine volume that would have been needed for water packing. Production from this well, 1,250 bopd with an associated 35 bwpd, three times the production obtained from an offset well completed with a slotted liner.³³

Case History 2: Open-Hole Gravel Packing above Frac Pressure (Gulf of Mexico)

A 277-ft of open hole was drilled horizontally (85 to 90°) using an RDF consisting of CaCO_3 , Biopolymer and Starch.¹⁷ At TD, open hole was displaced to a solids-free RDF and the cased hole to a KCl brine. After running the screens in hole, setting and testing the packer, the slurry consisting of a viscoelastic surfactant solution and 8 ppa 40/60 resieved sand was spotted to within 5 bbls of the service tool, before shifting the tool to squeeze position. After pumping a significant portion of the slurry in squeeze, the rate was reduced and the

service tool was shifted to circulating position to achieve final screenout at 6,000 psi. Amount of gravel placed below the crossover tool was greater than 150% of the volume around the screens and the blank pipe.

The carrier fluid in this application also contained an enzyme for starch removal and a chelating agent solution for CaCO_3 dissolution. Initial production from this well was 12 MMSCFD, with a near zero skin. After a year, the well was still producing at 2.5 MMSCFD with an associated 2,300 bwpd sand-free.

Case History 3: Open-Hole Gravel-Packing in Oil-Based Mud Environment (West Africa)

The paper by Chambers et al.¹⁸ described the very first successful applications of gravel packing wells drilled with oil-based fluids. These wells were displaced to a solids-free viscous fluid in the open hole and a completion-brine in the cased hole, prior to running in hole with shrouded alternate path screens. After the screens were at TD, packer was set and tested, and the gravel pack treatment consisting of a viscoelastic surfactant carrier fluid and 30/50 ceramic-gravel was spotted in the work string in reverse position. The treatment was pumped with the tool in circulating position. In two of the three wells, significant losses were observed, although all three wells were completely packed. Resulting production rates were in excess of 10,000 bopd with a lower drawdown than all the previous horizontal wells drilled with water-based reservoir drilling fluids. In fact, the normalized PI's from these wells were up to three times higher than those obtained with previous practices, which included post-gravel-pack acid treatments.

Case History 4: Open-Hole Frac-Packing (Indonesia)

This was the first and only reported frac-pack application in an open-hole environment, to our knowledge.²⁵ A well in a very challenging high kh (~ 100,000 md-ft) formation in a low frac gradient environment with a very low reservoir pressure was almost going to be lost. Very high losses were experienced during drilling, the presence of a high-pressure, reactive shale section above the sand necessitated running a 7-inch casing prematurely, in order to isolate that section. Furthermore, collapse of the shale section resulted in setting the casing above the target exposing 70-ft of shales. Although the original intent was a cased-hole frac-pack, the events that occurred during drilling as well as completion attempts led to a change of direction towards open-hole frac-packing.

In this application, a multi-zone packer was utilized below the gravel-pack packer in order to bypass the exposed shale section through large shunt tubes without holes, forcing all the slurry into the shunts. The driver for this approach was prevention of shale mixing with the proppant (and the resulting poor fracture conductivity). Approximately 22,000 lbs of 20/40 ceramic proppant was placed below crossover ports. The open-hole interval was 224-ft, with a 47-ft of net target sand, at 70° inclination. The gross production rate from this well was 2,000bfpd, with a net in excess of 500 bopd, well beyond expectations. Note that high water cuts are typical of the wells in this area, regardless of the completion type. The

resulting PI compares very favorably to both cased hole frac-packs and open-hole horizontal gravel packs, particularly considering the excessive losses experienced while drilling this well.

Case History 5: Simultaneous Gravel-Packing and Cake-Cleanup of Two Sands Separated by a Long Shale Section (Deep-Water North Sea)

This is the longest open-hole gravel packing application with the alternate path technique to date. The subject well penetrated through two sand bodies separated by a 530-ft shale section, with a total open-hole length of 3,075-ft. The open-hole section was drilled with a CaCO_3 /Biopolymer/Starch RDF and gravel packed with a viscoelastic surfactant fluid containing an enzyme and a chelating agent solution, using a 30/50 ceramic proppant which was slowly ramped from 2 to 6 ppa in order to provide a smooth transition from pad to slurry properties. As detailed elsewhere,²³ this well was completely packed based on an average 8.63-in hole (nominal hole: 8.5-inch). With an initial production rate of 20,500 STB/D and an estimated skin of zero, the sand-free cumulative production from this well was 2.1 MMSTB as of mid-October, 2003.

Case History 6: Open-Hole Gravel Packs in High-Rate Gas-Wells (Trinidad)

The southeastern Trinidad gas basin has proven to be a challenging environment for sand control. During the development of these fields, standalone screen, frac-pack and cased-hole gravel pack completions have each been implemented with mixed success. Open-hole gravel-pack completions have provided the most effective solution in achieving life-of-well sand control integrity for new wells. After using the water-packing technique initially, the alternate-path technique was introduced for open-hole gravel packing in Trinidad, increasing the ability to achieve successful sand control treatments. Highlighted below are two of these case histories.

The first well was relatively shallow (5,310-ft TVD), with 10.75-in casing set at 90° in the target sand at 6,952-ft MD. The 1,667-ft open-hole was drilled and underreamed to 9.5-in with a 9.8-ppg water-based (biopolymer, starch, carbonate) RDF. The open-hole section was displaced to a solids-free RDF and the casing to brine prior to running the screens in hole. Open hole was displaced to brine prior to setting the packer. The carrier fluid used in this application consisted of an HEC solution with an oxidizer as the internal breaker. After pumping all the premixed HEC fluid, there was no screenout and approximately half of the gravel that was supposed to have been pumped was still in the silo. There was a problem with the surface mixing/monitoring system and as a result the gravel concentration in the slurry was half the targeted value. At this point, two alternative approaches could be taken: either reverse out the slurry in the work string, mix more HEC and proceed with pumping, or continue gravel packing with brine using lower gravel concentration (0.5 to 1.0 ppa). The second option was implemented, and the well was gravel packed successfully. The initial mechanical skin of approximately 20 had reduced down to a final skin of about 3.9 over a period of

several weeks (~ 4 to 6 weeks), with an initial production rate of 180 MMSCFD.

The second well was deeper (9,650-ft TVD), with 10.75-in casing set at 12,294-ft MD. The 507-ft, 9.5-in open-hole section was drilled with a 9.2-ppg water-based RDF of similar composition as in the first well. Again, the open-hole was displaced to a solids-free WB-RDF, the cased hole to brine prior to running in hole with screens, and the open hole displaced to brine prior to setting the packer. This well was gravel packed successfully, using a 9.2-ppg HEC as the carrier fluid, with an internal breaker. A post-gravel-pack cleanup treatment consisting of a chelating agent solution and an enzyme was spotted into the open hole, prior to pulling the service tool and wash-pipe out of the hole, using a post-gravel-pack circulation tool. This well resulted in a mechanical skin of 1 with an initial rate of 247 MMSCFD.

These results appear to indicate that the post-gravel-pack filtercake cleanup treatments in these *high-rate-gas wells* only accelerate filtercake cleanup that eventually occurs over a several-week (4 to 6 weeks) time period through flow back. It should be noted that many of these wells are either tubing limited or constrained by erosional velocity limitations of surface flow lines. Skin variations in the range of 1 to 4 results in a negligible change in production rates.

Lessons Learned & Recommendations

Typically longer hole lengths in open hole completions introduce certain challenges in designing gravel-packing treatments with the alternate path technique. In addition to the collapse considerations as discussed earlier, the burst pressure limitations of the shunts must be kept in mind, which can impose an upper limit for treatment rates once the slurry diverts into the shunts. While lower rates address this concern, they may create concerns as to gravel settling in the vertical and inclined sections of the work string, which imposes a lower rate limit for the treatment. In addition to settling, collapse and burst considerations, paying utmost attention to the fluid compatibility issues is critical to the success of gravel packing with the alternate path technique.

Gravel suspension characteristics of the carrier fluids for the alternate path technique has been identified as a key consideration since the early development of the concept. Poor suspension can lead to:

1. Gravel settling in work string: This has been identified as the reason for failure on three occasions. In one case, a new viscoelastic surfactant fluid was in field trial stages. This application was in a four-well gas development in the North Sea. In one of the applications, a rubber seal in the chiksan lines on the rig floor had blown, resulting in a 10-minute shutdown period. As detailed by Campbell et al.,¹⁵ post-job analyses through yard and laboratory testing indicated that this particular VES fluid had temporarily lost its visco-elasticity after passing through the pumping equipment, and the rehealing of the fluid (recovering viscoelasticity) was time dependent, taking longer at low temperatures. This loss of viscoelasticity resulted in settling of the gravel in the work string and bridging at the

crossover ports, yielding an incomplete pack on this well. An additive was subsequently identified to address this problem.²¹ Similar settling related problems have been identified in two other occasions as the reason for incomplete packing. In both of these cases, a shutdown had occurred as a result of either a surface leak or inability to feed gravel to the fluid due to wet-sand, and the shut down period was in excess of tolerable time period based on sand settling test results.

2. Gravel settling in the shunt tubes: Prior to diversion of the slurry into the shuts, a relatively small fraction of the slurry flows in the shunts as the flow is shared between the annulus and the shunt tubes based on relative friction pressures in each section. If the gravel settles in the shunt tubes, as more of the flow is diverted into the shunts, higher velocities will result in picking up the settled gravel and thus increased gravel concentrations in the slurry or pushing the bed downstream. This can result in bridging within the shunts, causing a premature screenout. Another mechanism that can lead to bridging in the shunt tubes is leakoff through the ports in sections that are already packed. This can lead to increased gravel concentrations downstream and eventual bridging in the shunts, thus a premature screenout. This has been addressed through the development of the packing and transport tube arrangement, which minimizes leakoff.
3. Gravel settling in shunted blank area: On one occasion, a shut down occurred and the slurry was reversed out of the hole after a portion of the slurry was below the cross over port. During the shunt down period, the gravel had settled above the entrance of the shunts, which were lying on the lower side of the casing. This resulted in development of the concentric entrance design.

Another issue that must be kept in mind in alternate path gravel packing treatments is the burst pressure limit of the shunt tubes, which is 5,000 psi. High friction in long intervals can necessitate reduction in flow rates in order to stay below this limit. This is one of the reasons why viscoelastic surfactant fluids are preferred in alternate path applications, as these fluids are lowest friction systems available in the industry as evidenced through their extensive use in fracturing applications through coiled tubing. Note that even with higher friction fluid systems, rate reduction can lead to complete packing without exceeding the burst limit of the shunts, when fluids with excellent sand suspension characteristics are used.²⁶

Fluid-fluid compatibilities are very critical to successful outcome of alternate path applications. The fluid trains involved in the treatment must be carefully evaluated for the entire completion process. For example, most commonly used VES fluids are sensitive to mutual solvents. In one application, a mutual solvent used for flushing the lines was left in the lines, and lack of communication between various service companies led to water-like VES slurry with 5 ppa gravel being pumped downhole, and an immediate screen-out at the

service tool as indicated by down hole gauges at the top of the screen. Other considerations include high-density brines or oil-based fluids in the wellbore. In such cases, VES formulations that are either insensitive to high-density brines or less sensitive to oil-based fluids should be used.

Future Applications

Current work for extending alternate path applications focus on gravel packing with brines as well as gravel packing with VES fluids in oil-based fluid environments. Extensive testing both in the laboratory and large-scale models indicate that some VES formulations are less sensitive to oil-based fluids contamination. Although these fluids lose their viscosities over time periods of interest in putting the well on production, they tolerate contamination within the time periods of gravel packing. The driver for this approach is the elimination of the requirement for displacement to water-based fluids prior to running the alternate path screens in the hole (and thus a predrilled liner run) when VES fluids will be used for gravel packing due to their unmatched retained permeability characteristics in areas where compatibility with the crude oil has been demonstrated.

Another area that is being worked on is the ability to gravel pack with the alternate path using brines. This involves modifications in shunt tube design. This approach is expected to be ready for field-testing early 2005.

Conclusions

Alternate path technique has evolved significantly since its introduction over eight years ago. With over 700 treatments, this technique is field proven for both cased (624 treatments) and open-hole (101 treatments) applications. Multizone packer applications of alternate path allow exploitation of otherwise uneconomic reserves through a single-trip completion of multiple zones. Alternate path also enhances applicability of frac-packing technique to longer intervals and offers additional assurance for complete gravel packing of open holes in challenging environments.

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Figure 1 – Shunt tube nozzles after erosion tests showing nozzles with (right) and without (left) Tungsten Carbide inserts.

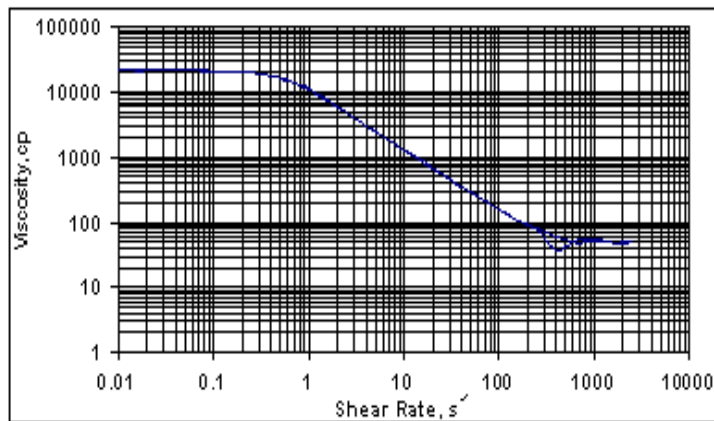


Figure 2 - Rheology profile of a VES fluid: 7.5% VES-HT in 9.8-ppg CaCl_2 brine, 170°F.

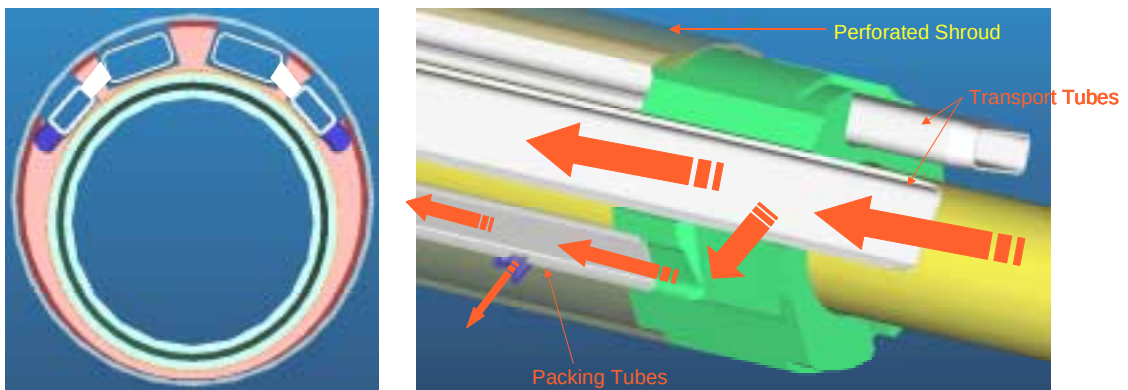


Figure 3 – Transport and Packing tube arrangement. Cross-sectional view (left) and flow pattern schematic (right).

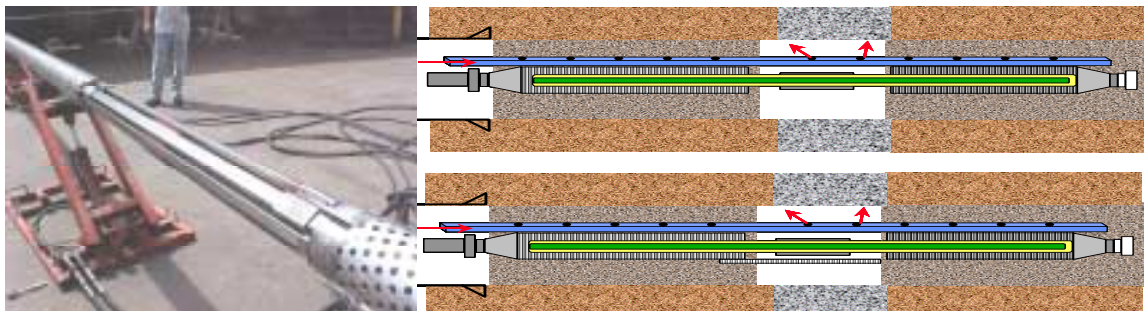


Figure 4 – Leak-off tube action (right) providing a pathway for fluid flow from blank area to screen jacket and installation photo (left).

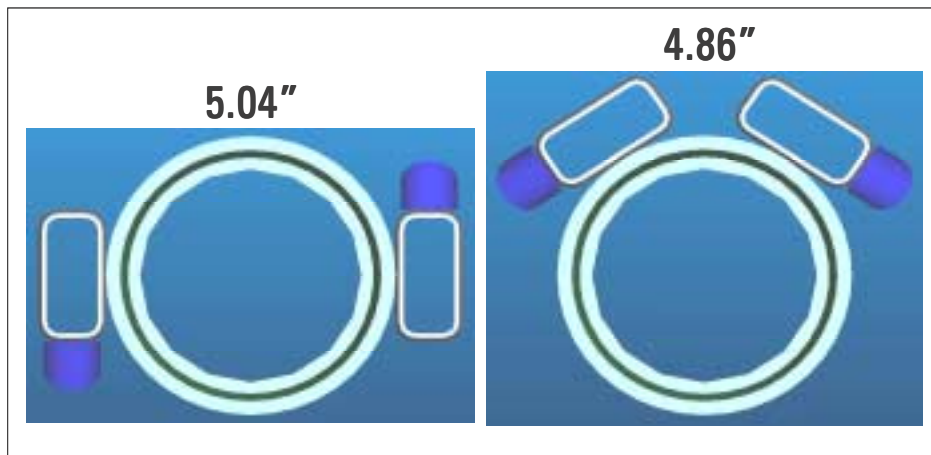


Figure 5 – Example of outer diameter reduction with eccentric design (right) versus concentric design (left).

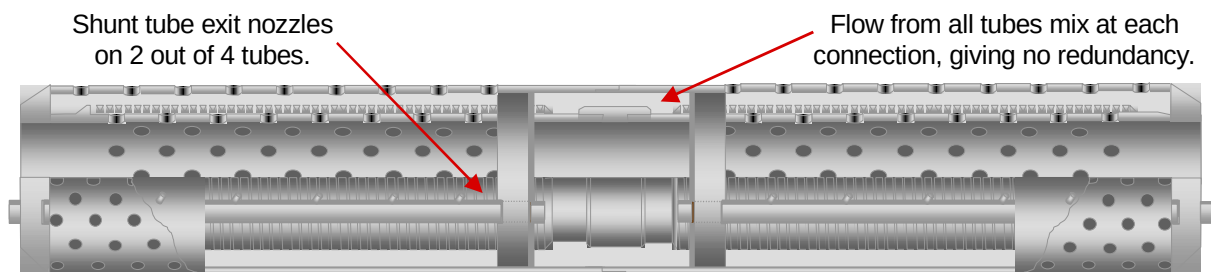


Figure 6 – Manifold connection schematic.

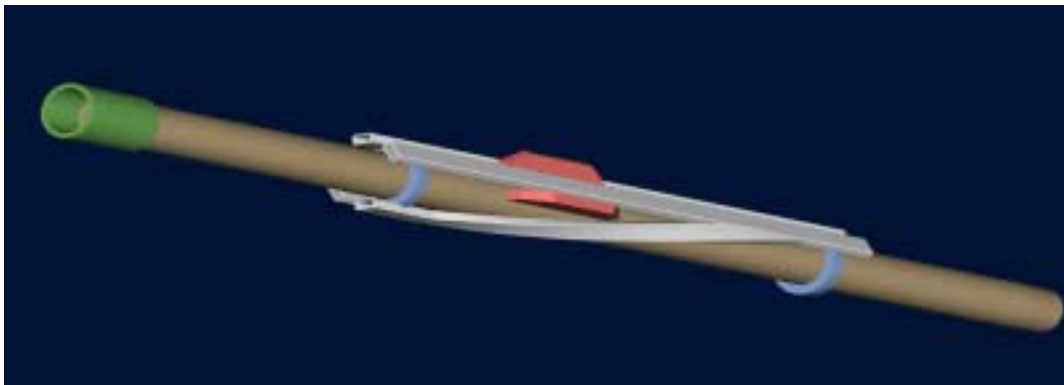


Figure 7 – Concentric Entrance (Y-manifold).

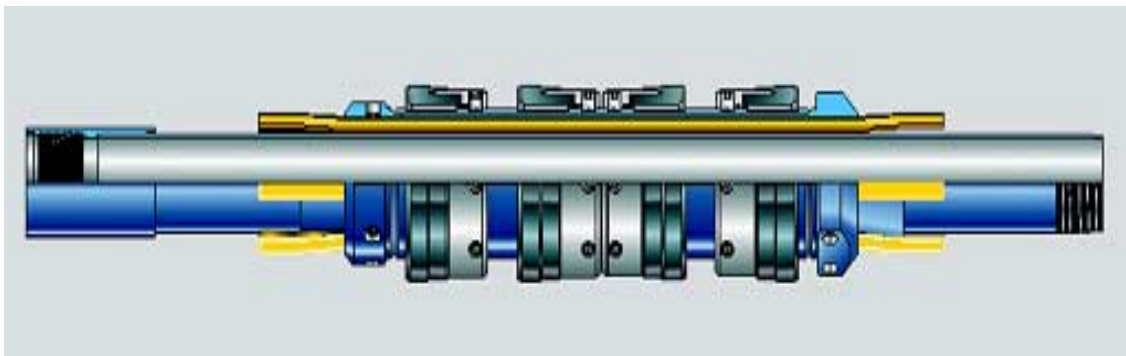


Figure 8 – Multi-zone packer. Note the beveled gauge ring close to the pin end.

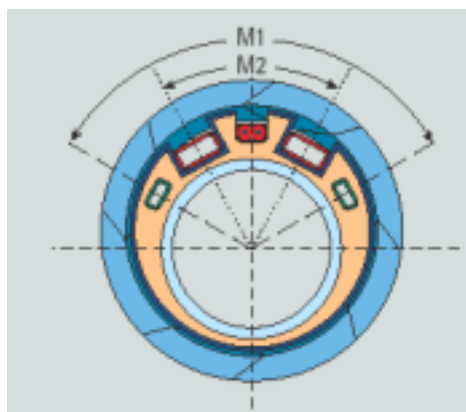


Figure 9 – Cross sectional representation of Alternate Path screens with a dimpled shroud for control line twin flat pack installation (in red) and later deployment of fiber optics.

Gravel U.S. Mesh	¼ -in Nozzles		3/8-in Nozzles	
	Nozzle-to-Mean Gravel Diameter Ratio	Nozzle-to-Largest Gravel Diameter Ratio	Nozzle-to-Mean Gravel Diameter Ratio	Nozzle-to-Largest Gravel Diameter Ratio
40/60	19.0	15.1	28.4	22.7
20/40	10.1	7.6	15.1	11.3
16/30	7.3	5.5	10.9	8.3
12/18	4.9	3.9	7.3	5.9
8/12	3.1	2.6	4.7	3.8

Table 1 - Nozzle Diameter versus Gravel Mesh Size.

Screen Length (ft)	Job Count
< 100	107
100 – 200	105
200 - 300	34
> 300	24

Table 2 - Screen Lengths in Cased-Hole Frac-Pack Applications of Alternate Path.

Screen Length (ft)	Job Count
> 2,000	7
1,500 - 2,000	5
1,000 - 1,500	15
500 - 1,000	35
< 500	39

Table 3 - Screen Lengths in Open Hole Applications of Alternate Path.