Gravel Pack Designs of Highly-Deviated Wells with an Alternative Flow-Path Concept


Abstract

Alpha-Beta gravel packing procedures have been used with a moderate degree of success in highly-deviated wells. Incorrect concentrations of gravel and/or pump rates can result in bridge formation in the open hole/screen annulus and Beta wave initiation prior to reaching the toe. If there is a high leakoff zone, gravel concentration will increase, and there may be insufficient velocity to transport the solids farther down the well. Either factor or a combination of the two can lead to formation of a bridge in the openhole/screen annulus and an early initiation of the Beta wave. Other effects that could lead to bridge formation include: flow restriction and blockage from collapse of an unstable open hole section, and changes in annular velocity transition from one hole size to another. Incomplete gravel placement and the presence of voids around the screen can result from all of the complications described above. To overcome these, an alternative flow-path system has been developed. If a bridge forms, the alternative path allows the slurry to bypass it. A number of physical models have been used to design and examine the effectiveness of the system, which has been validated in field applications.

A numerical model has also been developed to assist with the gravel pack designs in highly-deviated wells. The model simulates the alternative flow-path concept as well as conventional gravel packing in open hole or cased-hole completions of arbitrary deviation. Details of the alternative flow-path scheme as well as the formulation of the numerical model are presented in this paper. Simulation results were compared to observations in the physical models.

Introduction

Since the early 1990s, long horizontal well completions have become more viable for producing hydrocarbons, especially in deepwater reservoirs. As opposed to the screen-only approach, gravel packing with screens has become a standard method of providing assurance for sand control in open hole horizontal completions. Operators depend on a successful, complete gravel pack in the wellbore annulus surrounding the screen to control production of formation sand and fines and thus prolong the productive life of the well.

The presently accepted method of placing a gravel pack in highly-deviated wells is the “AlphaBeta” technique. This method primarily uses a brine carrier fluid that contains low concentrations of gravel. A relatively high flow rate is used to transport gravel through the workstring and crossover tool. After exiting the crossover tool, the brine-gravel slurry enters the relatively large wellbore/screen annulus, and the gravel settles on the bottom of the wellbore, forming a dune. As the height of the settled bed increases, the cross-sectional flow area is reduced, increasing the velocity across the top of the gravel bed. The velocity continues to increase as the bed height grows until the minimum velocity needed to transport gravel across the top of the bed is attained. At this point, no additional gravel is deposited and the bed height is said to be at equilibrium. This equilibrium bed height will be maintained as long as slurry injection rate and slurry properties remain unchanged. Fig. 1 shows a simulation of the Alpha-Beta wave. The flow is from left to right and the gravel bed is shown in red. The wire-wrapped screen is identified by dotted black lines and the blank pipe by solid black lines.

Changes in surface injection rate, slurry concentration, brine density, or brine viscosity will establish a new equilibrium height. Incoming gravel is transported across the top of the equilibrium bed, eventually reaching the region of reduced velocity at the leading edge of the advancing dune. In this manner, the deposition process continues to form an equilibrium bed that advances as a wave front (Alpha wave) along the wellbore in the direction of the toe. When the Alpha wave reaches the end of the washpipe, it ceases to grow, and gravel being transported along the completion begins to back-fill the area above the equilibrium bed. As this

References at the end of the paper.
process continues, a new wave front (Beta wave) returns to the heel of the completion. During deposition of the Beta Wave, dehydration of the pack occurs mainly through fluid loss to the screen/washpipe annulus.

Successful application of the Alpha-Beta packing technique depends on a relatively constant wellbore diameter, flow rate, gravel concentration, fluid properties, and low fluid-loss rates. Fluid loss can reduce local fluid velocity and increase gravel concentration. Both will increase the equilibrium height of the settled bed or dune. Additionally, fluid loss can occur to the formation and/or to the screen/washpipe annulus.

In this paper various factors that cause premature development of a Beta wave in the wellbore, resulting in incomplete gravel placement and voids around the screen, are discussed. The use of an alternative flow-path system to overcome these problems was first investigated with physical models. A numerical model was developed to help enhance the ability to foresee potential problems with gravel pack designs in a timely and economical manner. The formulation of this model is presented. Results obtained from gravel pack treatment designs from the physical and numerical models are compared and discussed. Field testing results for this new alternative flow path from the modeling designs are also presented.

Problems Encountered during Gravel Packing
Excess Fluid Loss to Formation and Screen. Because fluid loss reduces local fluid velocity and increases gravel concentration, equilibrium bed height will increase, which can terminate the Alpha wave and allow the Beta wave to start prematurely, leaving the remaining wellbore unpacked. Damage to the filter cake can cause fluid loss outward to the formation. Fluid loss can also occur inward to the screen/washpipe annulus. This type of fluid loss can be controlled with a large-OD washpipe. The typical washpipe OD/basepipe ID ratio should be greater than 0.80 to create sufficient backpressure in the basepipe/washpipe annulus to regulate the flow in that annulus.

Wellbore Size Variations. Completions in poorly consolidated, shaly zones can have wellbore stability problems, which can lead to other problems during the subsequent gravel-pack operation. The well can slough in, or it can be washed out adjacent to the shale, resulting in nonuniform wellbore size. Either can prevent complete placement of gravel in the annulus. Recently, early screenouts have been attributed to ratholes in several wells located in the North Sea, Gulf of Mexico, and South America. A rathole is defined as a section at the bottom of a drilled hole that is left uncased. For example, a \( \frac{1}{4} \)-in. hole is drilled, and a \( \frac{3}{4} \)-in. casing is run almost to the bottom of the well and cemented into place. The \( \frac{1}{4} \)-in. hole below the casing seat is called the rathole. An \( \frac{1}{2} \)-in. openhole is then drilled to total depth (TD).

Transition Zones. Gravel-laden fluid passes through the rathole as it flows from the cased hole/screen assembly annulus to the openhole/screen assembly annulus. The relatively large flow area in the rathole causes annular flow velocity to drop, resulting in a higher Alpha wave. When the flow transitions to the smaller openhole section, annular velocity increases and Alpha wave height drops. However, as the flow passes from one annular area to another, a pinch point can form at their junction. Annular velocity tends to increase in the immediate area around this transition zone, which causes a dip in Alpha wave height as gravel moves into the normal openhole section. The Alpha wave height peaks (a hydraulic jump), then levels out to a normal Alpha wave height for the hole size and slurry rate. If the peak reaches the top of the openhole, a Beta wave can be triggered, causing early termination of the gravel-packing operation. A washout in the open hole section could create the same type of scenario.

Shale Zones. Horizontal completions often contain shale zones, which can be a source of fluid loss and/or enlarged hole diameters with subsequent potential problems during the gravel pack completion. In addition, shale zones may complicate selection of the appropriate gravel pack sand and wire-wrapped screen gauge. Another potential problem of shale zones is sloughing and hole collapse after the screen is placed.

Alternative Flow-Path System
To help overcome the problems described above, a concentric alternative flow path system was developed. The alternative flow-path assembly consists of a standard screen andwashpipe, with the addition of an external perforated shroud (Fig. 2). Overall shroud dimensions and perforation diameter/distribution are specially designed to help provide optimum packing conditions. The alternative flow-path concept can provide a means of increasing the flexibility of the Alpha-Beta wave packing technique. It provides a secondary flow path between the wellbore and screen, which allows the gravel slurry to bypass problem areas such as bridges that form as the result of excessive fluid loss or hole geometry changes. The flow is split among the three annuli. A gravel slurry is transported in the outer two annuli (wellbore/shroud and shroud/screen), and filtered, sand-free fluid is transported in the inner annulus (screen basepipe/washpipe) (Fig. 3). If either the wellbore/shroud or shroud/screen annulus bridges off, the flow will be reappropriated among the annuli remaining open. The velocity in the annulus that is still open to flow increases with a resulting increase in friction pressure. As soon as possible, the flow will again reappropriation beyond the bridge such that the pressure equalizes in the three annuli again. The increase in velocity in the annulus remaining open to flow and the reappropriation of the flow at the leading edge of the bridge may assist in breaking down the bridge.

The flow split between the wellbore/shroud and shroud/screen annuli can be adjusted by the choice of shroud size and perforation size. Physical and numerical modeling results have provided guidance concerning the best selection of the shroud parameters to give the optimum packing efficiency. Perforation size and number of perforations in the shroud will affect fluid movement between the casing/shroud and shroud/screen annuli. The casing/shroud and shroud/screen annuli act as one annulus if there is an unlimited number of relatively large
perforations in the shroud. A relatively small pressure differential will develop as the number of perforations and/or perforation diameter is reduced. By continuing to reduce the number of perforations and/or perforation diameter, we can control, to some extent, movement of fluid between the annuli. The slurry will continue to flow down the parallel annuli until a sand bridge or other wellbore condition causes an abnormal pressure loss in one of the annuli. Once the pressure rises above that required to force flow through the perforations and the friction pressure in the annulus remaining open to flow, the slurry will re-apportion itself to the annulus open to flow. The overall design process balances the reduction in number of perforations and size in the shroud against inflow requirements when producing the well.

**Physical Modeling**

The alternative flow-path concept was validated with both small-scale and large-scale physical tests using models ranging from 5 to 1,000 ft in length. Problems related to wellbore variations (i.e. transition zones and washouts) and high fluid losses were examined with a 40-ft acrylic model (Fig. 4). Problems associated with localized areas of high fluid loss were studied using a 40-ft and a 1,000-ft model (Fig. 5). Problems caused by shale zones were investigated with a 300-ft model. The typical test scenario was to start the test series with a baseline test (without the alternative flow path assembly) and identify the problem and any potential solutions. Tests with the alternative flow-path system were then run and the test results were compared to determine the benefits of the new assembly.

A number of tests were performed in a 40-ft model to determine the effect of the alternative flow path system on packing with high fluid loss. These tests demonstrated conclusively that the alternative flow path system will help bypass high fluid-loss areas. Tests performed in a 1,000-ft model demonstrated the same results.

Baseline tests in the 40-ft model were designed based on an annular velocity of 1 ft/sec. This is on the low end of the typical rule-of-thumb, 1 to 3 ft/sec superficial annular velocity to propagate an Alpha/Beta wave. Tests in the 300-ft and 1,000-ft model were designed with an initial annular velocity of 1.25 ft/sec. This annular velocity was reduced by fluid loss at specific points along the model. After each fluid-loss point, annular velocity decreased, and gravel concentration increased. Both changes increased Alpha Wave height.

Starting with an initial annular velocity and gravel concentration of 1.25 ft/sec (superficial annular velocity) and 1.65 lbm/gal, respectively, a reduction in the annular velocity to 0.35 ft/sec terminated the Alpha wave immediately without the benefit of the alternative pathway system. Starting with the same initial conditions without the alternative pathway system, a reduction in annular velocity to 0.60 ft/sec allowed the Alpha wave to propagate beyond that point. However, this reduction in flow rate and increase in gravel concentration increased Alpha wave height, which increased system pressure over time. The increase in system pressure caused additional fluid loss, and an early Beta wave started one or two joints (20 to 50 ft) below the area of fluid loss.

With the alternative flow path system, the Alpha wave could not be sustained past fluid-loss areas that reduced the annular velocity to 0.35 ft/sec, which is similar to the results obtained in the baseline tests. However, we were able to effectively bypass fluid-loss areas that lowered the annular velocity to 0.60 ft/sec with the benefit of the alternative flow path system.

A concentric bypass formed by a nonperforated shroud and bounded by external casing packers (ECPs), can be placed adjacent to problem shale zones with typical alternative flow path annuli above and below the shale zone to isolate the shale zone during gravel packing. Tests in a 300-ft model indicated that we could successfully pack the areas above and below a 100-ft isolated section, simulating collapsed shale, through the concentric ring formed by the nonperforated shroud and the screen. The Alpha wave propagated through the concentric bypass and the Beta wave packed back through the concentric bypass allowing a complete pack on either side of the bypass and in the concentric bypass itself.

**Numerical Modeling**

The numerical model is a pseudo three-dimensional model of gravel and fluid flow in deviated wells. The model solves the equations of volume and momentum conservation for the incompressible slurry in the wellbore. The formulation allows the liquid and solid velocities to differ through particle settling, fluid loss to the screen and/or formation, and liquid flow through packed solids. The details of the model and the solution algorithm are presented in Appendix A.

As the flow is split among the three annuli, the three flow channels are in constant communication, and their pressure equalizes. The pressure along and across each annulus is calculated, and rate/pressure calculations can be combined with a critical settling velocity correlation to determine Alpha wave heights in the outer two annuli.

Gravel deposition in the outer annuli and fluid leakoff to the open hole or perforated interval will change the rate/pressure balance at every point along the length of the completion. When modeling the alternative flow path process, annular rates and gravel deposition are continuously calculated as the Alpha wave progresses to the toe of the well and as the Beta wave returns to the heel of the well.

If either the wellbore/shroud or shroud/screen annulus bridges off, the flow will be re-apportioned among the annuli remaining open. As soon as possible, the flow will again re-apportion beyond the bridge such that the pressure tries to equalize in the three annuli. Reapportionment of the flow at the leading edge of the bridge may assist in breaking down the bridge.

The simulator provides qualitative and quantitative information about the effects of well geometry (casing, rathole, openhole, washpipe, screens, shroud, and shroud perforations), fluid and gravel properties, and pumping rates on gravel placement. The simulator can handle gravel packs in wells with deviations varying from vertical to horizontal. It can simulate both openhole wells or casdhole wells with perforations. The simulator has been used as an aid in the interpretation of model test results, to help
design optimum shroud parameters and to design actual gravel pack field treatments. An input form in Appendix B shows the information required to run a simulation.

**Grid Geometry.** The model divides the wellbore into a number of smaller axial segments, or grid cells along the wellbore length. This allows the user to zoom in on sections of interest, e.g. transition zones, washouts, high leakoff zones, and hole collapse. Division into grid cells along the length of the well also allows the model to treat blank sections of base pipe between joints of wire-wrapped screen. At these blank sections, the fluid loss to the washpipe is zero.

The model considers flow of fluid and gravel within the screen-washpipe annulus, the wire wrap ID-basepipe OD annulus, the screen-shroud annulus and the shroud-wellbore annulus. Gravel is allowed to settle to the low side of the well, both in the screen-shroud annulus and the shroud-wellbore annulus, thus reducing the hydraulic area open to the flow.

**Assumptions Made.** The radial pressure drop across the screen to the washpipe is considered zero until the bed covers the screen. The pressure around each annulus is assumed to be uniform. The radial pressure drop across the shroud is governed by the number and size of the holes in the shroud. The split of flow within the various annuli is controlled by the wall friction along the annuli, the radial friction across the shroud, and the amount of leakoff into the formation.

**Model Calibration.** The model was calibrated based on a number and variety of physical model tests. Model tests included 40- and 300-ft test sections, a number of screen and washpipe sizes with and without the alternative flow path system, and a variety of shroud sizes and perforation patterns and perforation diameters. Calibration and validation was based on pack efficiency and the location and size of voids in the pack.

**Comparison of Physical and Numerical Modeling**

The simulator results compare favorably with the results from the 40-ft physical model and the extended length model. The disruption in flow patterns noted with a transition zone in the 40-ft model were also noted in the plots of the simulations of those tests. The void at the very end of the model, adjacent to of the end of the washpipe, also shows up in the plots of each simulation.

**Simulations of a Transition Zone in the 40-ft Physical Model.** A series of physical tests were performed in a 40-ft physical model that incorporated 20 ft of 12 1/4-in. “rathole” followed by 20 ft of 8 1/2-in. “open hole”. In the tests a higher Alpha wave was observed in the 12 1/4-in. rathole followed by the dip and then a peak in the Alpha wave height as the Alpha Wave transitioned from the 12 1/4-in. rathole to the 8 1/2-in. open hole. The Alpha wave then levelled out at a slightly lower point (compared to the peak) adjacent to the 8 1/2-in. section of the model. Depending on the test parameters the Beta wave could start just downstream of the transition zone. In those tests the dip in the Alpha wave height was followed by a peak in Alpha wave height that would reach the top of the model thus initiating an early Beta wave.

Using the parameters of the 40-ft transition model we have performed a number of numerical simulations to calibrate the model and interpret the test results. In the set of simulations we changed the parameters one at a time in order to analyse the effect on the packing. The first simulation had the following parameters:

- Pump-in rate - 3.5 bbl/min
- Return rate - 3.25 bbl/min
- Carrier fluid - brine with a viscosity of 1 cP
- Gravel concentration - 1 lb/gal
- Screen - 5-in. (5.05-in. OD wire wrap, 5.01-in. wire wrap ID, 5-in. 15# basepipe)
- Washpipe - 2 3/4-in. OD and 3 1/2-in. OD

**Fig. 6a** shows the results of the first simulation. The figure shows higher Alpha wave adjacent to the 12 1/4-in. section followed by the dip in the Alpha wave just downstream of the Transition Zone. The flow is from left to right and the packed bed is shown in red. In the figure, the wire-wrapped screen is identified by the dotted black lines and the blank pipe by the solid black lines. The Alpha wave then levelled out at a slightly higher point, compared to the dip, adjacent to the 8 1/2-in. section (Fig. 6b).

As the Alpha wave propagates in the 8 1/2-in. open hole the Alpha wave levels out. The Beta wave begins just downstream of the transition zone as the leakoff starts affecting the Alpha wave (Fig. 6c).

**Fig. 7** shows the final pack. The increase in pump rate has increased the velocity of the fluid above the critical settling velocity in the transition zone and has allowed complete packing. The packing efficiency for this case was 99.6%.

**Washpipe.** In the next simulation, we repeated the second simulation that had a pump rate of 4 bbl/min, return rate of 3.25 bbl/min, but reduced washpipe OD from 3 1/2 to 2 3/4-in. **Fig. 8** shows the results from this run. The figure indicates that the smaller washpipe resulted in a decrease in packing efficiency. The smaller washpipe allowed more of the flow to be diverted to the screen-washpipe annulus due to lower friction pressure in that annulus. This resulted in a lower velocity in the outer screen-open hole annulus, with the effect that the velocity fell below the critical settling velocity. The packing efficiency for this case was 79%.
A smaller washpipe can be expected to cause decrease in the friction pressure during the Beta wave in an actual job. However, a smaller washpipe can also be expected to allow more leakoff to the screen-washpipe annulus during the Alpha wave, which, as we have shown, can cause a lower velocity in that annulus and a reduced packing efficiency. Depending on the volume of leakoff to the formation (determined by the reservoir parameters), this additional loss to the screen-washpipe annulus may be sufficient to raise the sand concentration, lower the open hole/screen annular velocity and increase the Alpha wave height to the point where an early Beta wave will be initiated.

**Gravel Concentration.** In the next simulation, we repeated the second simulation that had a pump rate of 4 bpm, return rate of 3.25 bpm, but increased the gravel concentration from 1 ppg to 2 ppg. Fig. 9 shows an incomplete packing for this case. The packing efficiency was 78% compared with almost 100% for the 1-ppg case.

**Fluid Viscosity.** In the next simulation, we repeated the first simulation but increased the viscosity from 1 cP to 5 cP. Fig. 10 shows that the increasing viscosity yielded an improvement in the packing efficiency when compared to Fig. 6d. This effect was also observed in the physical tests. The viscosity is, again, a direct function of the critical settling velocity equation and thus this increase in packing efficiency should be expected.

These results support the general rules for gravel packing horizontal wells, namely:

1. Increase the initial annular flow velocity (if possible)
2. Increase the washpipe OD
3. Lower the gravel concentration

**Wire-Wrap ID/Basepipe OD Annulus.** The simulator also simulates the leakoff to the wire-wrap ID/basepipe OD annulus. Changing the wire-wrap OD from 5.01 to 5.125-in. (5-in. all welded screen with 5-in. OD Basepipe and 5.505-in. OD wire wrap) with a 3 1/2-in. washpipe in the first example above resulted in a slightly better pack (Fig. 11). A larger wire-wrap ID/basepipe OD annulus will allow additional leakoff through this annulus, thus reducing the leakoff to the formation in the example problem. In this case a better pack was obtained. However, depending on the volume of leakoff to the formation (determined by the reservoir parameters), this additional leakoff to the wire-wrap ID/basepipe annulus may be sufficient to raise the sand concentration, lower the open hole/screen annular velocity and increase the Alpha wave height to the point where an early Beta wave will be initiated.

**Fluid Loss –40-ft Model.** Changing the return rate from 3.25 bpm to 3.0 bpm with a 3 1/2-in. washpipe and a wire-wrap ID of 5.01-in. resulted in a better pack (Fig. 12). The current version of the simulator allocates the available leakoff to the entire interval. In this case, reduced loss to the screen-washpipe annulus resulted in higher flow velocity in the screen-open hole annulus. Reducing the pump-in rate to 3 bpm with a 3 1/2-in. washpipe and a wire-wrap ID of 5.01 and maintaining 100% returns allowed for a good pack.

**Alternative Flow Path Liner.** The simulation of the first case, i.e., 3 1/2-in. washpipe, a wire-wrap ID of 5.01-in., a pump rate of 3.5 bpm and a return rate of 3.25, but with the addition of an alternative flow path liner resulted in an improved pack (Fig. 13 compared to Fig. 6d).

**300-ft and 1,000-ft Model, 6-in. ID.** A total of eighteen physical modeling tests were performed with 2 7/8-in. OD slotted pipe and 4.5-in. OD (3.998-in. ID) perforated pipe inside 6-in. ID steel tubing containing perforations at selected intervals. The length of the model was initially 1,000-ft. To reduce cycle time between tests, we shortened the model to 300 ft. Tests in the extended length model were similar to the tests in the 40-ft model. These tests appeared to confirm the hypothesis that we should match the perforation size and number of perforations in the perforated shroud to the carrier fluid viscosity and the pump rate to help optimize the ability of the perforated shroud to increase the packing efficiency.

Simulations using the model geometry and pumping schedules used in these tests reaffirmed the importance of these variables. **Note:** In these particular simulations we treated the model as a perforated pipe rather than an open hole. Leakoff points were placed at the same points used in the physical model.

**Simulation of a Sample Horizontal Gravel Pack Completion–Without Alternative Flow-Path System.** The following parameters were utilized in the simulations below:

- Rathole: 12 1/4-in.
- Open hole: 8 1/2-in.
- Length of open hole: 500 ft
- Length of wire wrap per joint of basepipe: 29 ft and 39 ft
- Length of joint of basepipe: 39 ft
- Pump-in rate of 6.00 bpm
- Return rate of 5.50 bpm

Fig. 14a shows the Alpha wave. The 10-ft length of blank pipe between sections of wire wrap (29 ft) accounts for the variations in the Alpha wave height. The simulator does not allow flow across the screen at the blank joint sections. This results in an increased annular velocity adjacent to the blank sections during the Alpha wave propagation at those locations. The higher velocity at the blank sections results in a lower Alpha wave there.

Fig. 14b shows the completion of the Beta wave. The figure shows voids in the pack. These voids are adjacent to the blank sections at the screen joints. As the Beta wave backfills the area open to flow above the top of the Alpha wave it will fill back to the downstream side of a blank section between wire-wrap sections. The only avenue for leakoff adjacent to the blank pipe is either to the formation or to the wire wrap on either side of the blank section. The flow will pick the path of least resistance. This will be through the wire wrap on the upstream side of the blank section. Packing the blank pipe with the Beta wave would require the Darcy Flow pressure drop through the packed bed adjacent to the blank section be less than the pressure...
drop through the wire wrap on the upstream side of the blank section, which, of course, it is not.

In the case where there are long blank sections between wire-wrap sections, a lower pump-in rate results in a higher pack efficiency. This is due to the higher Alpha wave and thus the reduced packing requirements at the screen joints during the Beta wave.

Changing the Wire Wrap length such that it is equal to the baseline length results in a much smoother Alpha wave (Fig. 14c) and Beta wave (Fig. 14d). (Note: The area around the rathole seems to have the potential for creating an early Beta wave in this particular simulation.)

Simulation – Horizontal Gravel Pack with and without Alternative Flow Path System. The following parameters were utilized in the simulations below:

- Rathole: 12 1/4-in.
- Open hole: 8 1/2-in.
- Washout: 13-in.
- Length of open hole: 500 ft
- Length of wire wrap per joint of basepipe: 29 ft
- Length of joint of basepipe: 39 ft
- Pump-in rate of 5 bpm with alternative flow path system and 5 and 5.72 bpm (to attain the same annular velocity) without alternative flow path system
- Return rate of 3 bpm with alternative flow path system and 3 and 3.42 bpm (to attain the same fluid loss percentage) without alternative flow path system

The Alpha wave, without the benefit of the alternative flow path, and pumped at 5 bpm input rate and 3 bpm return rate is as follows. A peak in the Alpha wave height can be seen at the washout in Fig. 15a. The Beta wave, in Fig. 15b, shows a void from the washout down to the toe of the well.

The Alpha wave with the benefit of the alternative flow path and pumping at 5 bpm input rate and 3 bpm return rate is as follows. Fig. 15c shows that the Alpha wave has propagated to the toe of the well. Fig. 15d of the Beta wave shows an almost complete pack, which indicates that the alternative flow path was successful in bypassing the bridge.

Returning to the completion without the alternative flow path assembly, it could be argued that the annular velocities are not the same and therefore the comparison is not valid. The annular velocity in the open hole section is 1.83 ft/sec for the 5-bpm input rate with the alternative flow-path geometry. To attain that same annular velocity in the openhole section without the alternative flow-path liner would require a rate of 5.72 bpm. To attain the same percentage of fluid loss would require a return rate of 3.42 bpm.

The Alpha wave with a 5.72 bpm input rate and 3.42 bpm return rate is shown in Fig. 15e. The Alpha wave again peaks at the point of the washout. The Beta wave (Fig. 15f) shows a little better packing efficiency but not as complete as with the alternative flow path system. This indicates that the alternative path perforated liner helps with potential problems in changing hole geometry.

Field Tests
The alternate flow path screen assembly has been used in four completions as of 10/23/01. Two of these jobs have been frac packs and two have been gravel packs. As we write this paper a third gravel pack is being pumped and several jobs are in the planning stages. The gravel pack simulator discussed in this paper was used as one of the tools to help design the screen/shroud assembly and the pump rates, etc., in the gravel pack completions. The simulator predicted an early screenout without the use of the alternative pathway screen design. The alternative pathway screen design was used in these completions. Field results indicate that the sand was successfully placed as the simulator predicted.

The current version of the simulator is a wellbore simulator only. However, the simulator has also been used to review the design of screen/shroud assemblies for the gravel pack portion of FracPack completions.

Conclusions
1. The concentric alternative flow-path concept has been shown in model tests to overcome some of the limitations of the Alpha-Beta wave concept of gravel packing wells. A numerical simulator of this concept has supported the model test results.
2. The numerical simulator can be a useful tool for determining the effects of various parameters when designing gravel pack completions. These parameters can include, but are not limited to, the following:
   - Pump rate
   - Return rate
   - Sand concentration
   - Fluid loss
   - Carrier fluid viscosity
   - Hole geometry changes
   - Screen assembly geometry changes
   - Design of a concentric alternative flow path assembly
   - Eccentricity of the assembly
   - Reservoir conditions
3. The simulator can be used to find trends and help focus attention on various aspects of the gravel pack design rather than being considered to be a perfect forecaster of 100% operational success.
4. The simulator is a useful tool for examining aspects of a proposed test and providing a direction for physical testing rather than just performing a large number of physical tests which is extremely expensive.
5. The simulator can be useful for inputting information from a job and doing a post job analysis.
6. The alternative flow-path concept has been used successfully in a number of field jobs.

Nomenclature
- \( A \) Area, \( m^2 \)
- \( A_f \) Free area of the holes in a porous plate, \( m^2 \)
- \( A_k \) Coefficient in Equation A-29
- \( A_p \) Total cross sectional area of a porous plate, \( m^2 \)
\( A_D \)  Total cross sectional area of a porous plate, \( m^2 \)

\( A_H \)  Area open to the flow, \( m^2 \)

\( B_{ik} \)  Coefficient in Equation A-29

\( C \)  Orifice coefficient

\( C_D \)  Particle drag coefficient

\( C_f \)  Coefficient in Equation A-27

\( C_z \)  Coefficient in Equation A-28

\( d \)  Pipe diameter, \( m \)

\( d_{A} \)  Diameter based on area, \( m \)

\( D_H \)  Hydraulic diameter, \( m \)

\( d_g \)  Gravel diameter, \( m \)

\( dt \)  Time step, \( s \)

\( F \)  Factor used in viscosity enhancement Equation A-9

\( f \)  Fanning friction factor

\( F_D \)  Drag force on a particle, \( N \)

\( Fe \)  Fraction of eddies with velocities greater than hindered settling velocity

\( F_s \)  Ratio of gravel to fluid density

\( g \)  Acceleration due to gravity, \( m/sec^2 \)

\( H_{bed} \)  Bed height, \( m \)

\( K \)  Fluid consistency index, Pa\cdot s\(^n\)

\( k \)  Gravel permeability, \( m^2 \)

\( n' \)  Power law exponent

\( P \)  Wetted perimeter, \( m \)

\( p \)  Frictional pressure, \( Pa \)

\( Ph \)  Hydrostatic pressure, \( Pa \)

\( Pr \)  Reservoir pressure, \( Pa \)

\( Pw \)  Pressure at the wellbore-formation face, \( Pa \)

\( q_l \)  Pump rate, \( m^3/s \)

\( q_{L} \)  Leakoff rate, \( m^3/s \)

\( q_{Gl} \)  Volumetric pump rate of gravel, \( m^3/s \)

\( q_{gB} \)  Volumetric rate of gravel bed formation, \( m^3/s \)

\( q_d \)  Drainage radius, \( m \)

\( Re \)  Reynolds number

\( Re_{em} \)  Modified Reynolds number

\( Re_{p} \)  Particle Reynolds number

\( r_i \)  Radius stage i has penetrated into the formation, \( m \)

\( r_w \)  Wellbore radius, \( m \)

\( t \)  Time, \( sec \)

\( v \)  Velocity, \( m/s \)

\( v_{fc} \)  Critical velocity for bed formation, \( m/s \)

\( v_{H} \)  Volume open to the flow, \( m^3 \)

\( v_{f} \)  Liquid velocity, \( m/s \)

\( v_{r} \)  Radial velocity; relative velocity, \( m/s \)

\( v_{t} \)  Terminal velocity, \( m/s \)

\( v_{10} \)  Settling velocity in the clean fluid, \( m/s \)

\( v_{w} \)  Radial velocity at the well

\( v_{z} \)  Axial velocity, \( m/s \)

\( \alpha_g \)  Gravel volume fraction

\( \alpha_{gbed} \)  Gravel volume fraction of the bed

\( \alpha_l \)  Liquid volume fraction

\( \gamma \)  Strain rate, \( s^{-1} \)

\( \partial_r \)  Partial difference operator with respect to the radial direction

\( \partial_z \)  Partial difference operator with respect to the axial direction

\( \Delta \)  Distance along the wellbore, \( m \)

\( \theta \)  Well deviation angle.

\( \mu \)  Apparent viscosity, \( PA\cdot s \)

\( \mu_l \)  Liquid viscosity, \( PA\cdot s \)

\( \mu_r \)  Reservoir fluid viscosity, \( PA\cdot s \)

\( \mu_s \)  Slurry viscosity, \( PA\cdot s \)

\( \phi \)  Porosity of the gravel pack

\( \phi_F \)  Porosity of the formation

\( \rho_f \)  Liquid density, \( kg/m^3 \)

\( \rho_g \)  Gravel density, \( kg/m^3 \)

\( \rho_s \)  Slurry density, \( kg/m^3 \)

**Subscripts**

- \( i \): Grid cell center index in radial direction
- \( i_f \): Grid cell face index in the radial direction
- \( k \): Grid cell center index in axial direction
- \( k_f \): Grid cell face index in the axial direction
- \( p \): Particle
- \( r \): Radial
- \( z \): Axial

**Superscript**

- \( n \): Time level

**References**


Acknowledgements
The authors would like to express thanks to the management of Halliburton Energy Services and Jaycor for permission to publish this paper.
Appendix A
Gravel Packing Simulator
Equations and Solution Algorithm

Slurry Transport
The equation for volume conservation of the slurry is
\[ \int \nu \cdot dA = q_l - q_B \] (Eq. A-1)
where the integral is over the area, A, open to the flow in the axial and radial directions, \( \nu \) is the slurry velocity, \( q_l \) is the pump rate and \( q_B \) is the rate of liquid return or lost to the formation.

The model is pseudo three-dimensional in that the properties of the slurry are allowed to vary along the wellbore length and radially outward, but gravel is allowed to settle to the low side of the well.

Conservation of momentum gives the relation of velocity to the pressure drop. Acceleration effects at the velocities involved in gravel packing are negligible and can be ignored. The relation of velocity to frictional pressure drop is
\[ 4f_\mu s \frac{v^2}{2D_H} = -\nabla p \] (Eq. A-2)
where \( f \) is the friction factor, \( \rho_s \) is the slurry density, \( D_H \) is the hydraulic diameter, \( p \) is the frictional pressure and \( \nabla p \) is the gradient operator. The friction factor can be the pipe friction, orifice friction due to passage through holes in a liner or the friction due to flow through a packed bed. The hydraulic diameter is defined as
\[ D_H = \frac{4A}{P} \] (Eq. A-3)
where \( A \) is the area open to the flow, and \( P \) is the wetted perimeter.

The hydrostatic pressure, \( p_h \), is obtained by
\[ \Delta p_h = \rho_s g \Delta z \cos \theta \] (Eq. A-4)
where \( \rho_s \) is the slurry density, \( g \) is the acceleration due to gravity, \( \Delta z \) is the total vertical depth along the wellbore, and \( \theta \) is the well deviation angle. The hydrostatic pressure is added to the frictional pressure to get the total pressure.

The local gravel concentration is obtained by solving an equation for the conservation of volume of the gravel. The model assumes that the gravel is transported along the well with the same velocity as the fluid but can settle out and form a bed on the low side of the well. The integral equation representing the gravel volume balance is
\[ \frac{\partial}{\partial t} \int \alpha_g dV_H + \int \alpha_g \nu \cdot dA = q_{gI} - q_{gB} \] (Eq. A-5)
where \( V_H \) is the volume available to the flow, \( \alpha_g \) is the volume fraction of gravel, \( q_{gI} \) is the volumetric pump rate of gravel and \( q_{gB} \) is the rate of gravel deposition on to the bed.

Friction Factors
Wall Friction
Wall friction causes the pressure drop along the wellbore. Non-Newtonian viscosity and gravel concentration effects complicate the prediction of the wall friction factor.

The pressure drop arising from the shear stress at the wall is related to the friction factor according to Equation A-2. The friction factor is a function of the Reynolds number, the hydraulic diameter, and the slurry viscosity.

The Reynolds number is defined as
\[ \text{Re} = \frac{\rho_s D_H \nu}{\mu_s} \] (Eq. A-6)
where \( \mu_s \) is the slurry viscosity.

If the Reynolds number is less than 4000, the flow is laminar, and the Fanning friction factor is
\[ f = \frac{16}{\text{Re}} \] (Eq. A-7)
If the Reynolds number is greater than 4000, the turbulent friction factor is used:
\[ f = \frac{0.3164}{4\text{Re}^{1/4}} \] (Eq. A-8)

Solids Concentration Effects
When solids are present in the fluid, the slurry viscosity increases. The effect of solids on viscosity is based on a correlation by Keck [6].

The increase in the slurry viscosity is
\[ \mu_s = \mu_f \left(1 + \frac{1.5 \phi g}{1 - 1.5 \phi g} \right)^2 \] (Eq. A-9)
where \( \mu_f \) is the liquid viscosity, and the factor \( F \) is
\[ F = 0.75 \left( e^{1.5n_1} - 1 \right) e^{-1(1+n_1)\gamma} 1000 \] (Eq. A-10)
where \( n_1 \) is the viscosity power law exponent. The shear rate is
\[ \gamma = \frac{8v}{d} \] , pipeflow \[ \gamma = \frac{12v}{d^2 - d_1^2} \] , annular flow \[ \gamma = K(\gamma_f)_{n}^{-1} \] (Eq. A-12)
where \( K \) is the fluid consistency index.

Radial Pressure Drop
The radial pressure drop is generated by the flow through the holes in the liner. The pressure drop across the liner is calculated as that across a perforated plate. The pressure drop across the plate is given by [7]
\[ \Delta p = \frac{1}{2} \frac{\rho \nu^2}{C^2} \left(1 - \left(\frac{A_l}{A_p}\right)^2\right) \] (Eq. A-13)
where \( A_l \) is the free area of the holes and \( A_p \) is the total cross sectional area of the plate. \( C \) is the orifice coefficient which is a function of the plate thickness, hole diameter, hole pitch and Reynolds number based on hole diameter.

Pressure Drop Through Packed Bed
Darcy’s law as expresses fluid flow through a porous medium
\[ \nabla p = \frac{1}{k} \frac{\mu \nu \phi}{\gamma} \] (Eq. A-14)
where \( \gamma \) is the actual (not superficial) fluid velocity in the bed, \( k \) is the gravel permeability, and \( \phi \) is the porosity of the gravel pack.

The viscosity of a power-law fluid is given by A-12. The shear rate in a porous medium is [8]
\[ \gamma = \frac{8v_f}{\sqrt{32k\phi}} \] . (Eq. A-15)
Using the equation for viscosity and shear rate, a friction factor is defined similar to Equation A-2.

Bed Deposition
Drag Coefficient
The model treats the gravel as being transported along the wellbore by the liquid but the gravel can settle to the low side of the well. The drag force on a particle flowing in a fluid is

$$ F_D = C_D \frac{1}{2} \rho_f v^2 A_p $$

(Eq. A-16)

where $C_D$ is the drag coefficient, $\rho_f$ is the fluid density, $v$ is the relative velocity between the fluid and particle, and $A_p$ is the frontal area of the particle.

When gravity is the only force acting on the particle, the drag coefficient can be determined to be

$$ C_D = \frac{2}{3} \frac{\rho_p - \rho_f}{\rho_f} \left( \frac{g}{v} \right)^{2-n'} $$

(Eq. A-17)

where $g$ is the acceleration due to gravity, $v$ is the terminal velocity, $d_p$ is the gravel particle diameter, and $\rho_p$ is the gravel density. The particle Reynolds number, $Re_p$ is

$$ Re_p = \frac{d_p v}{\mu} $$

(Eq. A-18)

where $\mu$ is the apparent viscosity of the liquid defined as

$$ \mu = K (\dot{\gamma})^{n-1} $$

(Eq. A-19)

$K$ is the fluid consistency index, $\dot{\gamma}$ is the strain rate, and $n$ is the power law exponent. The strain rate $\dot{\gamma}$ is defined as

$$ \dot{\gamma} = \frac{1}{d_p} \frac{v}{g} $$

(Eq. A-20)

Shah [9] experiments on settling of particles in stagnant and moving fluids found that the parameter $\sqrt{C_D \cdot \frac{2-n'}{Re_p^2}}$ could be correlated with the generalized particle Reynolds number as shown in Fig. A-1. Since the function $\sqrt{C_D \cdot \frac{2-n'}{Re_p^2}}$ is independent of terminal velocity and only a function of gravel and fluid properties, we first calculate this function and determine the particle Reynolds number from Figure A-1.

From the function and the Reynolds number we can then determine the drag coefficient. From the drag coefficient the terminal velocity can be found from Equation A-17. Since data for only six $n'$ values are available, the drag coefficients for other $n'$ values are determined based on interpolation between these values.

**Concentration Effects**

The settling of particles in slurry is different from that in a clean fluid. Experimental tests have shown that as the particle concentration in the slurry increases, the settling rate decreases. This settling velocity decrease (or drag increase) is due to the increased viscosity of the slurry and the higher slurry density. The change in settling velocity with proppant concentration is taken from Novotny [10], and can be summarized as

$$ v(t_0) = \alpha_1^2 \frac{v_t}{v_t_0} \left( \frac{\rho_p}{\rho_f} \right)^{2} $$

where $v_0$ is the settling velocity in the clean fluid and $\alpha_1$ is the liquid volume fraction. The terminal velocity is reduced accordingly with proppant concentration.

**Bed Deposition**

Once the terminal velocity is found the change in bed height can be determined. If the slurry velocity is less than a critical velocity, the gravel will settle and the bed will increase in height. The increase in bed height is calculated according to

$$ dH_{bed} = \frac{v_t d\alpha}{\alpha_{bed} \sin(\theta)} $$

(Eq. A-22)

where $H_{bed}$ is the bed height, $dt$ is the time step, $\alpha_{bed}$ is the gravel volume fraction of the bed, and $\theta$ is the well deviation angle.

The critical velocity for bed formation is from a correlation found in references [11-13].

$$ v_{dc} = 1.85 \sqrt{\rho_p \rho_f} \left( 1 - \alpha_k \right) \left( \frac{\rho_f}{\rho_k} \right)^{0.364} \left( \frac{d_p}{k_F} \right)^{0.576} \left( \frac{R_{em} P_e}{0.3} \right) $$

(Eq. A-23)

where $\rho_{dc}$ is the ratio of gravel to fluid densities, $\rho_g / \rho_f$, and $d_p$ is the diameter based on area; $\Psi$ is the fraction of eddies with velocities exceeding the hindered settling critical velocity and is set to 0.95; and $R_{em}$ is the modified Reynolds number

$$ R_{em} = d_p \frac{\rho_f \left( \Phi - 1 \right)}{\mu} $$

(Eq. A-24)

**Fluid Leak Off into the Formation**

The leakoff model has two options: either a non-pressure dependent leakoff or a value controlled by the pressure difference between the well and the formation.

**Fixed Leakoff**

If the non-pressure dependent option is chosen, the total leakoff is calculated as the difference between the pump rate and the return rate. The local leakoff is the total leakoff times the local permeability of the formation divided by the height averaged permeability over the total leakoff area.

**Pressure Dependent Leakoff**

Pressure dependent fluid leakoff into the formation is based on the model of flow of non-Newtonian fluids through a porous medium [8]. Darcy’s Law for a power-law fluid is

$$ v = \frac{n \Phi_F}{3 \Phi_F + 1} \left( \frac{8 k_F}{\Phi_F} \right)^{\frac{1}{2n+1}} \left( \frac{\rho_p}{2K} \right)^{\frac{1}{3n}} $$

(Eq. A-25)

where $k_F$ is the permeability of the formation and $\Phi_F$ is the formation porosity. Assuming a radial flow into the formation, then $v = v_{rad} \frac{r}{r_w}$, where $v_{rad}$ is the radial velocity at the well, $r$ is the distance into the formation and $r_w$ is the wellbore radius. Equation A-25 can be integrated to yield the pressure drop between the wellbore and the pressure at some distance $r$ in the reservoir

$$ p_{e} - p_r = \sum_{n} \left( \frac{\Phi_F}{n} \right) \left( \frac{\rho_p}{8 k_F} \right)^n \left( \frac{r}{r_w} \right)^n \times 2 K \left( v_{rad} \right)^{\frac{n}{2}} \frac{d r}{r^n} $$

(Eq. A-26)
The first term in Equation A-26 represents the pressure drop due to each stage that has leaked off and the summation is over each fluid stage in the formation. Each sequential fluid stage that has leaked off is tracked to give its front, \( r_i \), in the formation. The second term in Equation A-26 represents the pressure drop due to the reservoir fluid. \( r_d \) is the drainage radius where the pressure is taken to be the reservoir pressure.

Equation A-26 is used as a boundary condition for the system of equations when the pressure dependent leakoff option is chosen.

**Wellbore Geometry**

A schematic of the cross section geometry of the wellbore is shown in Fig. A-2. The liner and screen need not be concentric with the wellbore or each other. The bed height between the wellbore and the liner is not necessarily the same as the bed height between the screen and the liner. The area open to the flow is the area above the beds. Equation A-3 defines the hydraulic diameter for the area open to the flow and the perimeter not covered by the bed.

![Fig. A-2—Schematic of wellbore cross-section showing eccentric liner and screen and gravel beds in the liner-screen annulus and the wellbore-liner annulus.](image)

**Solution Algorithm**

The assumptions made in the model are: the pressure is uniform around the circumference of each annulus and the pressure drop across the screen is zero until the bed completely covers the screen. However, even though the pressure drop across the screen is zero, the axial velocity along the screen-washpipe annulus is different from the velocity along the wellbore-screen annulus (or wellbore-liner and liner-screen annuli if there is a liner) because of the different wall friction values in the annuli.

The well is divided into a number of axial and radial cells. Fig. A3 shows a computational grid cell. The pressure, density and volume fractions are defined at the cell centers, and the velocities are defined at the cell faces. Equation A-1 is cast in finite difference form as,

\[
\Delta_p A_H r v_r + \Delta p A_H z v_z = q_1 - q_L \quad (A-27)
\]

where \( \Delta \) is the partial difference operator, \( A_H r \) is the area open to the flow in the axial direction along the wellbore, \( A_H z \) is the area open to the flow in the radial direction, \( v_r \) is the slurry radial velocity, \( v_z \) is the axial velocity, Equation A-2, the relation between velocity and pressure, is cast in finite difference form as

\[
\frac{4p_s v_r^2}{2D_H} = -\frac{\Delta p}{\Delta r} \quad (Eq. A-28)
\]

Equations A27 – A-29 are solved simultaneously using the axial and radial friction factors defined above.

\[
\begin{align*}
   & A_{ik} = A_{ik} p_{ik}^z + A_{ik} p_{ik}^r + A_{ik} p_{ik}^{z+1} + A_{ik} p_{ik+1}^{z+1} = B_{ik} \quad (A-30)
\end{align*}
\]

where \( A_{ik} \) and \( B_{ik} \) are coefficients. Equation A-30 is an equation for the pressure at the new time level. The pump rate, leak off rate and return rate serve as boundary conditions for the equation. Equation A-30 can be solved by Cholesky decomposition. Once the pressures are determined the axial and radial velocities can be determined from Equation A-28 and A-29.

The wall friction is used to determine the axial flow until the bed completely fills an annulus, at which point Equation A-14 is used to determine the friction. Also if the bed rises above the top of the liner, Equation A-14 is used to determine the radial friction factor. In addition, if the bed height rises above the top of the screen, the pressure drop across the screen is no longer considered zero. At this point Equation A-14 is used to determine the radial friction, and a pressure drop across the screen is calculated. If the bed fills an annulus or covers the screen or liner, the bed friction becomes quite large, and the flow at these locations is reduced to a negligible level.

Once the velocities are known, Equation A-5 is solved in finite difference form for the gravel concentration. Next Equation A-22 is solved for the increase in local bed height. The areas open to the flow and the hydraulic diameters are then determined and the process is repeated for the next time step. The cycle is repeated until the pump schedule is completed or the gravel completely covers the top of the screen.
# Appendix B

## Gravel Pack Simulator Input Form

<table>
<thead>
<tr>
<th>Open Hole (Yes/No)</th>
<th>Bottom of Hole or Sump Packer MD (ft)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top MD (ft)</td>
<td>Bottom MD (ft)</td>
</tr>
<tr>
<td>Workstring</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blank Pipe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washpipe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screen Base Pipe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire Wrap ID (inches)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire Wrap OD (inches)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screen (Base Pipe) Joint Length (ft)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire Wrap Length per Joint (ft)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Screen Centralizer OD (inches)</td>
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## Deviations (Maximum of 10)

<table>
<thead>
<tr>
<th>MD (ft)</th>
<th>Deviation (degrees)</th>
<th>TVD (ft)</th>
<th>User Defined TVD</th>
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<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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## Open Hole Parameters

<table>
<thead>
<tr>
<th>Open Hole ID (inches)</th>
<th>Isolation Section Top MD (ft)</th>
<th>Isolation Section Bottom MD (ft)</th>
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</table>

## Washouts (including Rathole)

<table>
<thead>
<tr>
<th>Number</th>
<th>Washout Top (ft)</th>
<th>Washout Bottom (ft)</th>
<th>Washout OD (inches)</th>
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</table>

## Perforations

<table>
<thead>
<tr>
<th>Top MD (ft)</th>
<th>Bottom MD (ft)</th>
<th>Penetration (inches)</th>
<th>Diameter (inches)</th>
<th>Shots/Foot</th>
<th>Phasing (Degrees)</th>
<th>Perfs/Plane</th>
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## Perforated Shroud

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<tr>
<th>Shroud Top MD (ft)</th>
<th>Shroud Bottom MD (ft)</th>
<th>Shroud ID (inches)</th>
<th>Shroud OD (inches)</th>
<th>Holes per Foot</th>
<th>Hole Diameter (inches)</th>
<th>Hole Phasing</th>
<th>Holes per Plane</th>
<th>Centralizer OD (inches)</th>
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## Pumping Schedule

<table>
<thead>
<tr>
<th>Rate In (bpm)</th>
<th>Pumping Time (minutes)</th>
<th>Return Rate (bpm)</th>
<th>Gravel Loading (ppg)</th>
<th>Fluid n’</th>
<th>Fluid K’ (lbs/ft^2*sec^2)</th>
<th>Fluid Viscosity (cp)</th>
<th>Fluid Specific Gravity</th>
<th>Gravel Type</th>
<th>Gravel Specific Gravity</th>
<th>Gravel Mesh Size Upper</th>
<th>Gravel Mesh Size Lower</th>
<th>Permeability (mDarcy)</th>
<th>Porosity (fraction)</th>
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</table>

## Reservoir Parameters (Maximum of 10)

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<th>TVD to Top (ft)</th>
<th>TVD to Bottom (ft)</th>
<th>Permeability (mD)</th>
<th>Porosity (fraction)</th>
<th>Reservoir Pressure (psi)</th>
<th>Viscosity (cp)</th>
<th>Drainage Radius (ft)</th>
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<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** You can either provide n’ and K’ or Viscosity (cp)
Fig. 1—A simulation of Alpha-Beta wave shows the formation of gravel bed filling the wellbore/screen annulus

Fig. 2—A closeup view of perforated shroud with screen inside

Fig. 3—A cross-section of the alternative flow path system

Fig. 4—40-ft acrylic model

Fig. 5—1,000-ft steel model
**Fig. 6a**—Higher Alpha wave adjacent to the 12-1/4-in. section followed by the dip in the Alpha wave just downstream of the Transition Zone

**Fig. 6b**—As the Alpha wave propagates in the 8-1/2-in. open hole the Alpha wave levels out

**Fig. 6c**—Beta wave begins just downstream of the transition zone as the leakoff starts affecting the Alpha wave

**Fig. 6d**—Beta wave propagates back to the start of the wire wrapped screen

**Fig. 7**—Increasing flow rate helps improve packing efficiency

**Fig. 8**—Smaller washpipe decreases packing efficiency

**Fig. 9**—Increasing gravel concentration decreases packing efficiency

**Fig. 10**—Increasing viscosity improves packing efficiency
Fig. 11—Slightly better pack by changing wire wrap OD from 5.01-in. to 5.125-in.

Fig. 12—Changing the return rate from 3.25 bpm to 3.0 bpm resulted in a better pack.

Fig. 13—The addition of alternative flow path perforated liner resulted in an improved pack.

Fig. 14a—Alpha wave forms in the annulus. The wire wrapped length is less than joining length.

Fig. 14b—Completion of Beta wave with voids in the pack.

Fig. 14c—A much smoother Alpha wave is formed after matching the length of wire wrapped screen with that of basepipe.

Fig. 14d—A complete pack with Beta wave.
**Fig. 15a—**Alpha wave without alternative flow path system

**Fig. 15b—**Beta wave quickly formed without alternative flow path system

**Fig. 15c—**Alpha wave with alternative flow path system

**Fig. 15d—**Beta wave shows an almost complete pack with alternative flow path system

**Fig. 15e—**Alpha wave without alternative flow path system but with increased annular velocity

**Fig. 15f—**Beta wave without alternative flow path system but with increased annular velocity