Dissertation Report

On

SAND CONTROL USING GRAVEL PACK, EXPANDABLE SAND SCREENS AND TIP SCREEN OUT IN VERTICAL AND HORIZONTAL WELLS

(Dissertation Submitted In the partial fulfilment of degree in Applied Petroleum Engineering –Upstream)

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CERTIFICATE

This is to certify that Mr. Himanshu Kukreja (r010208071) and Mr. Sai Rakesh Varma (r010208049) final year students of B.Tech APE –Upstream has carried out a Project **"SAND CONTROL USING GRAVEL PACK, EXPANDABLE SAND SCREENS AND TIP SCREEN OUT IN VERTICAL AND HORIZONTAL WELLS"** under my supervision and this was done only for academic purposes and is not published any were else

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ABSTRACT

Forming the Hydrocarbon Reservoir matrix, occurrence of sand with HC production is quite obvious under favourable conditions. Forces induced by HC production on sand grains when exceeds that upholding them in place, results in its undesirable production.

Most of worlds HC produce from sandstones or carbonates. Even though approximately 60% of the world's oil and gas production comes from carbonates, 90% of hydrocarbon wells are in sandstone reservoirs. Around 30% of these sandstones may be weak enough to produce sand (Walton et al., 2001), this statement is not limited to unconsolidated formations, presence of enough drag forces on consolidated formations also call for sand isolation measures. Some carbonate reservoirs may also produce solids (Wulan et al., 2007), for example presence of chalk in carbonates may result in its production.

Unexpectedly produced sand can lead to problems along the HC flow path from the Reservoir to surface separators in form of permeability impairment, erosion, and loss of integrity and potential fatalities. This leverages a platform for installation of sand control equipment at the sand face. Conversely, unnecessarily installing sand control can be expensive and detrimental to productivity and reservoir management.

The ability to predict when a reservoir will fail and produce sand is fundamental to deciding whether to use downhole sand control and what type of sand control to use. The production of sand is very complex process controlled by formation properties, types of In-situ formation stress and fluid flow regime. Knowledge of these if often limited hence the ability to predict sand production is an imprecise process.

For sand control, there are myriad of options to choose from, but selection of a suitable method is subjected to both technical and economical scrutiny. A technologically well suited method may not be the economically best suited one. So any selection procedure should examine all these aspects.

A brief study of science behind sand production, various available options for sand control is carried out and the same is mentioned in the report that follows. A detailed study of Sand control measures, a criterion of their selection for South Kadi field operated by ONGC has been carried out and suitable suggestion are made. The extent of a greater detailed study along with case studies for each is limited to Gravel packing, (ESS) Expandable Sand Screens and TSO.

OBJECTIVE

The main objective of this report is providing the reader with one point reference about sand control procedures of Gravel Packing, Expandable Sand Screens, and Tip Screen Out.

Sand Production - a plaguing problem for oil and gas industry should be studied in detail from the view of geological and formation characteristics that vary with the production trend to establish a layout for selection criteria of a suitable sand control procedure. Main focus is laid upon understanding the causes of sand control and all the experimental studies are limited to South kadi field, operated by ONGC for selecting a suitable sand control procedure for the same.

Understanding of Gravel Packing, Expandable Sand Screens (ESS), Tip Screen Out (TSO) procedures in details form designing of these jobs to point of their execution in form of successful case studies, is provided in the report.

STATEMENT OF PROBLEM & SCOPE

It is a well known fact that the hydrocarbon demand increases by the day. Now, in order to meet this ever increasing demand it is essential for us to produce from geologically tough reservoirs, unconsolidated formations, and at greater flow rates. All of these above mentioned being the root causes for sand production.

The production of formation sand into a well is one of the oldest problems plaguing the oil and gas industry because of its adverse effects on well productivity and equipment. It is normally associated with shallow, geologically young formations that have little or no natural cementation to hold the individual sand grains together. As a result, when the wellbore pressure is lower than the reservoir pressure, drag forces are applied to the formation sands as a consequence of fluid production. If the formation's restraining forces Are exceeded, sand will be drawn into the wellbore. The sand either plugs the well or is produced. Produced sand has essentially no economic value. On the contrary, formation sand not only can plug wells, but also can erode equipment and settle in surface vessels. Controlling formation sand is costly and usually involves either slowing the production rate or using gravel-packing or sand-consolidation techniques. Operators spend millions of dollars each year to prevent the production of formation sand and to deal with other sand-related problems. Expenditures of this magnitude obviously have a significant impact on profits. In spite of these costs, effective sand-control practices have yielded oil and gas from wells that otherwise would have been shut-in. Measures should be taken against this problem to avoid any type of losses.

This study is undertaken to investigate the effects of various parameters causing sand production, and to understand sand control methods Gravel packing, ESS and TSO along with their application to real world cases.

The objectives of the study are;

- Discuss in detail the causes for sand production and remedial methods in use.
- In-depth studies of Gravel pack design, TSO and ESS.
- Application of these methods to real world cases.
- Review of ONGC operated south Kadi field sand control measures

PROJECT DESCRIPTION

1. INTRODUCTION

The production of formation sand into a well is one of the oldest problems plaguing the oil and gas industry because of its adverse effects on well productivity and equipment. It is normally associated with shallow, geologically young formations that have little or no natural cementation to hold the individual sand grains together. As a result, when the wellbore pressure is lower than the reservoir pressure, drag forces are applied to the formation sands as a consequence of fluid production. If the formation's restraining forces are exceeded, sand will be drawn into the wellbore. The sand either plugs the well or is produced. Produced sand has essentially no economic value. On the contrary, formation sand not only can plug wells, but also can erode equipment and settle in surface vessels. Controlling formation sand is costly and usually involves either slowing the production rate or using gravel-packing or sand-consolidation techniques. Operators spend millions of dollars each year to prevent the production of formation sand and to deal with other sand-related problems. Expenditures of this magnitude obviously have a significant impact on profits. In spite of these costs, effective sand-control practices have yielded oil and gas from wells that otherwise would have been shut-in.

As the value of non-renewable Hydrocarbon reserves and the Costs of remedial work increase, a renewed emphasis is being placed on proper well completion techniques. Maximum reliability and productivity are essential. These objectives are difficult to attain in unconsolidated sand formations, which are always subject to structural failure. The sand production mechanism is exceedingly complex and is influenced by every completion operation. This part of the project will summarize the major problems encountered in unconsolidated sands, as well as current techniques and technologies employed in sand face completions. The techniques and equipment described have been field-proven in thousands of oil and gas wells. Sand flow and the multitude of inconveniences, production losses, and Serious well damage it can cause is discussed with a view toward understanding fundamental causes and implementing early preventive measures.

2. LITERATURE REVIEW

Causes of Sand Production

In considering sand control, or formation solids control, one must differentiate between load-bearing solids and the fine particles (fines) that are not usually considered a part of the mechanical structure of the formation. Some fines are probably always produced with the well fluids, which, in fact, is beneficial. If the fines move freely through the gravel pack, they will not plug it. Thus, "sand control" actually refers to the control of the load-bearing particles, those that support the overburden. The problem then is deciding what is excessive sand production, a decision that involves many factors. Sand production higher than 0.1 % (volumetric) can usually be considered excessive, but depending on the circumstances, the practical limit could be much lower or higher.

- **Fluid Flow**

  The major stresses that tend to cause sand production usually result from fluid flow, which is proportional to the pressure drop between the wellbore and the reservoir. The drag force imparted by fluid flow is related to the product of fluid velocity and viscosity. Whether the sand is water-wet or oil-wet may also affect its tendency to be produced. Inter granular bonds provide the major restraining forces against these stresses. For this reason, a well's production rate and the degree of natural consolidation present in the formation are the chief determinants in sand production. Sand arches may also form around perforations to reduce sand production. Experience has indicated that these arches usually are unstable and tend to degrade easily with time and changes in producing conditions. As a result, they tend to exist only temporarily but may re-form later, only to break down again as conditions change.

- **Geographic and Geologic Factors**

  Sand production has been experienced in almost every area in the world where oil or gas production occurs from sandstone reservoirs; thus, the problem is worldwide. Sand production is most common in Tertiary Age sand reservoirs. Because these reservoirs are geologically young and are usually located at relatively shallow depths, they are no more than moderately consolidated (± loo-psi compressive strength). Because older reservoir rocks tend to be better consolidated, sand production problems are not as severe. Nevertheless, depending on well rates, drag forces may be sufficiently high to cause formation sand production in reservoirs in which the formation's compressive strength is well over 1,000 psi. However, this is uncommon.

- **Production Rate**

  When fluids are produced from sandstone reservoirs, stresses are imposed on the sand grains that tend to move them into the wellbore along with the produced fluids. These stresses are caused by pressure differences in the formation, fluid frictional forces, and the weight of the overburden. When the combined strength of these stresses exceeds the strength of the formation, sand will be produced. The implication is that, for many wells, there is a threshold production rate (and associated pressure drawdown) below which sand will not be produced and above which the formation will fail. Unfortunately, this rate is often below the economical producing rate. In these situations, some means of sand control must be included as an initial or remedial part of the well completion. The mechanism that causes a consolidated sand to fail is believed to result from a combination of pressure drawdown and fluid flow. Because these mechanisms are closely tied to each other, determining the actual mechanism may be a moot point.

- **Natural Consolidation**

  Opposing the fluid forces are the restraining forces that act to hold sand grains in place. These forces arise from intergranular bonds (natural consolidation), intergranular friction, gravity forces, and capillary forces. Internal pore pressure (reservoir pressure) helps support the weight of the overburden, thereby acting to relieve some of the stress on the sand grains. Of these forces, the intergranular bonds are the most important factor in preventing sand production. The compressive strength of formation sand is probably the best measure of the intergranular bond. If good completion and production practices are followed, formations with a compressive strength exceeding 1,000 psi will generally produce sand-free, as noted above. The exception is the case where the pressure drawdown around the well is high. If the pressure drawdown is low, however, sands with much lower compressive strengths may also produce sand-free.

- **Time Dependence**

  Predicting the sand-producing tendency of a formation is complicated, not only because data on the various factors to be considered are limited, but also because many factors change with time. Some examples of time-related changes follow.

  - Decreasing reservoir pressure increases the overburden stress on the sand grains.
  - Water production may dissolve natural cementing materials and weaken intergranular bonds or change the capillary pressure.
  - Permeability reductions resulting from relative permeability effect or fines invasion, paraffin and asphaltene deposits, etc., may increase the stresses induced on the sand grains by fluid flow at a given rate.
  - Because the problem is complex, the most meaningful prediction of potential sand problems is usually a correlation based on the performance of offset wells producing from the same reservoir.

- **Multiphase Flow**

  In many cases, sand production increases substantially when wells begin to produce water or gas with hydrocarbon fluids. Several theories have been given to explain this behaviour.

  - The produced water may dissolve part of the cementing material so that sand is produced.
  - The change in water saturation reduces capillary pressure (interfacial tension) to the point that the sand grains are not held together by causing excessive sand production.
  - When an interface moves through a pore space, a localized pressure disturbance is created.
  - Water movement may also mobilize fines and ultimately cause plugging of the pore structure.
  - Relative permeability effects may also account for these sand producing tendencies and may increase the pressure drawdown for a given well rate.

  In most sand formations, the tiny particles are water-wet and move with the water phase. Studies have clearly shown that multiphase flow can cause excessive sand production and mobilize the fines that create formation plugging, thereby reducing well productivity.

- **Thermal Effects**

  Thermal effects can also destroy intergranular bonds and influence sand production. The effects of high temperature associated with steam injection and combustion oil recovery projects have demonstrated that many wells experience high sand production not previously encountered in these operations.

Consequences of Sand Production

Several operational problems can arise if a well produces sand. All are troublesome and costly, but the degree of severity varies widely. Probably the least severe problems are solved simply by periodic removal of sand from such surface facilities as flow lines, manifolds, and separators. The more serious consequences relate to erosion of surface equipment, casing damage, and productivity losses.

- **Surface Equipment**
  Removal of sand from surface equipment is common in sand-producing regions. Perhaps only troublesome in land-based operations, sand disposal can become an acute problem offshore. Special treating facilities are required to remove the sand from the oil before offshore disposal. The problems arising from produced sand become more severe when the entrained sand is carried at velocities sufficient to erode surface equipment, such as valves and chokes, necessitating periodic replacement of these items. By far the worst complication of sand production is the erosion of surface equipment to the point that it fails, allowing high pressure gas and/or oil to escape. This situation obviously constitutes a severe safety and pollution hazard. Equipment erosion by sand is much more severe when the well stream is in turbulent flow than in laminar flow.

- **Tubular Damage**
  Casing failure may accompany the production of formation sand in the producing interval, meaning the loss of a well. As sand is produced, slumping of the overlying casing bearing formations can subject the entire casing string to abnormal loads. Such loads can lead to severe buckling when the lateral restraint provided by the surrounding sand is lost during sand production. In an example from offshore Louisiana, 7-in. casing was deflected 8 in. within a vertical distance of 5 to 10 ft Produced sand has also caused rod pumps to seize and rod strings to erode. Produced sand accelerates corrosion processes by exposing bare metal to the corrosive well fluids. Produced sand can also damage downhole equipment, such as the wire-wrapped screen

- **Productivity Loss**
  Productivity is lost when a sand bridge forms in the production tubulars. This sanded-up condition occurs when the fluid velocity is insufficient to suspend the produced sand completely and flow it from the well. In settling out of the produced fluids, sand can then fill the production tubing and block the flow.The amount of sand fill sufficient to plug the tubing and to stop flow depends on well conditions.

Effects of Sand Production on Formation

A question that generates considerable debate is what happens to the formation when sand is produced? Some people believe that a cavity forms opposite the perforations. Others think that the sand, being essentially an infinite body, expands slightly with an infinitesimal increase in porosity to prevent cavities from forming. A third explanation is that the overburden subsides to fill any void regions created by sand production. The answer to the above question is of considerable importance to both well performance and subsequent work over operations. Experiments were conducted to characterize the behaviour of sand when it fails under stresses induced by fluid flow. These experiments were performed by placing 5-in.-diameter, 3-in.-long samples of consolidated sand in a high-pressure vessel. The bottom faces of the samples were placed next to an O.5-in.-diameter hole, which simulated a perforation. Fluids were then flowed downward through the core at increasing flow rates (and pressure drops) until sand was produced through the perforation.
Two important conclusions were drawn from this study: fluid-flow stresses alone can cause sand production and cavities tend to form outside the perforation when sand is produced from formations with some degree of natural consolidation.

Sand Control Techniques

Giving a broad picture following are the sand control mechanisms used globally

- **Mechanical Retention**

  One obvious method of preventing formation sand from being produced is to restrain its entry into the wellbore flow stream. Many types of mechanical devices have been used for this purpose in the water-well and oil industries. Spherical particles will not flow continuously through rectangular slots twice as wide as the diameter of the particles, or through circular holes three times their size, as long as they flow in mass and have individual grain-to-grain contact. The particles tend to "bridge" across such openings and prevent further particle movement. If the size of the particles varies, retention of the larger particles causes the smaller particles to bridge behind them. All methods of mechanical retention are based on the principle of retaining a certain portion of the formation material to prevent the remainder from entering the well. Devices used by them to restrict sand movement usually are called screens or slotted liners. The placement of large, clean sand particles (actually called gravel because they are much larger than formation sand particles) between the screening device and the formation is referred to as gravel packing.

  Regardless of which approach is selected, all mechanical sand control methods are based on the bridging theory. The formation sand bridges against some sort of filtering medium, which allows the passage of fluid but prevents the production of formation sand. In addition to screens, other equipment used to control sand ranges from louvered casing to torch-cut and milled slots. 7 If only a slotted liner or screen is used to control formation sand, sand bridges should form against the slot when the slot opening is about 2.5 times the sand grain diameter. Experiments have shown, however, that these bridges are not stable and that, for maximum effectiveness, the individual sand grains should bridge on, rather than in, the slot openings.

  A screen or slotted liner run in a well to control formation sand usually is unsuccessful in controlling sand and/or maintaining the well's productivity for long periods of time. The exception to this is when the screen or liner is used where clean, relatively coarse grained, high-permeability sand is present and a certain amount of formation sand production can be tolerated to produce the well economically.

  The problem with screen-only completions relates to the manner in which oil and gas wells are completed with this technique. Here, the screen or slotted liner is simply run into position and the produced sand allowed to bridge around it. Because no back-surging or pump-in treatments are normally used (as is sometimes done in water-well completions) the finer particles are not effectively removed from the sand face of the near-wellbore sand mass. If these particles are retained on the

screen or slotted liner, they can eventually plug it and substantially reduce well productivity. If they flow through the screen or slotted liner and do not plug it or form a sand plug in the well, the well may be produced indefinitely despite the fact that sand production has not been completely eliminated. A technique used on reasonably large-grained formation sand with limited success involves sizing the screen so that it will bridge particles larger than those at the 10th-percentile point on the respective sieve-analysis curve. This sizing allows the finer particles to be produced, resulting in a natural gravel pack formed from the larger sand grains. One problem with this approach is that the 10th percentile point for many formation sands is smaller than 0.003 in., which is smaller than the openings on most commercial well screens. Consequently, it is not a practical application for many completions and is used only occasionally when gravel packing is not practical or when the formation sand is reasonably large. Even though the screen/slotted-liner-only technique has been used to control sand temporarily, it is generally not recommended over gravel packing in terms of both productivity and sand control.

- **Gravel Packing**

  Gravel packing, the most popular mechanical sand-control technique, was used in the water-well industry long before it was used in oil or gas wells. It involves running a mechanical device such as a screen or slotted liner in the well and placing accurately sized gravel around the screen or slotted liner. This placement allows the entry of fluids through the gravel but filters the formation sand from the flow stream so that sand free production is possible. In most gravel packs, however, a finite amount of solids is produced, but they consist of the very fine particles that can move through the gravel pack. When performed properly, gravel packs yield long-life, high-productivity completions.

- **Chemical Sand Control**

  Chemical sand control (plastic consolidation) involves the use of plastics to cement the formation sand grains together artificially for several feet around the well so that formation fluids can be produced sand-free. To be effective, the plastics must, Wet the sand surfaces and adhere to the sand grains, Yield a high compressive strength upon curing, and Maintain high well productivity. In most field consolidation treatments, acid (mud acid), preflush (to remove residual water so that the plastic wets the sand grains), plastic resin, and then catalyst are pumped into the well. The well is then flushed and shut in to cure the plastic. The plastics usually are epoxies, furans, or phenolic resins.

- **Combination Sand-Control Techniques (Resin-Coated Gravel)**
  Several combination sand-control techniques use both gravel and plastic. The intent is to consolidate the gravel pack after it is placed but without the use of a screen or slotted liner. These processes are marketed under several trade names. All contain sand as the solid constituent and use epoxy, furan, or phenolic plastics. The epoxy and furan techniques involve resin-coated gravel mixed at the surface and pumped into the well. The gravel plastic slurry is then allowed to settle and cure. After curing, the residue is drilled out of the well before it is placed on production. The phenolic resin-coated gravel processes involve phenol coated gravel that is partially polymerized. Upon being subjected to temperatures higher than 135°F, the resin cure is completed so that the gravel is consolidated. Unlike the epoxy and furan processes, the phenolic resin-coated gravel is dry and can be handled much like ordinary gravel.

3. Gravel-Pack Productivity

Introduction

Controlling sand in wells originated with the water-well industry because early water-well completions in shallow formations commonly produced sand. Gravel packing was introduced in the water-well industry in the early 1900's, but the technique was not used in oil wells until the early 1930's. It involves placing accurately sized coarse-grained material (gravel) against the formation sand to prevent the production of the finer-grained material while fluids are produced. A screen/slotted liner is located concentrically inside the layer of gravel to prevent gravel entry into the well. In the early completions, the mechanical devices included torch-cut slots, perforated casing, a louver-type screen, and machine-slotted pipe. More recently, several varieties of wire-wrapped screen have been used for this purpose. The technology used in gravel packing oil and gas wells was borrowed from the water-well industry. Unlike most oil and gas wells, water wells usually were completed by developing a natural gravel pack, which involved alternately surging and producing the formation. The finer particles were ultimately produced from the well, which left the uniformly graded sand or gravel with higher porosity and permeability surrounding the screen or slotted liner.

Effective development of a water well by this method might take several weeks, and the effectiveness depends on the sand characteristics, well-screen design, and the driller's skill. Fig 3.1 is a schematic of a natural gravel pack Water wells that were not developed to form a natural gravel pack but needed sand control usually were gravel-packed.

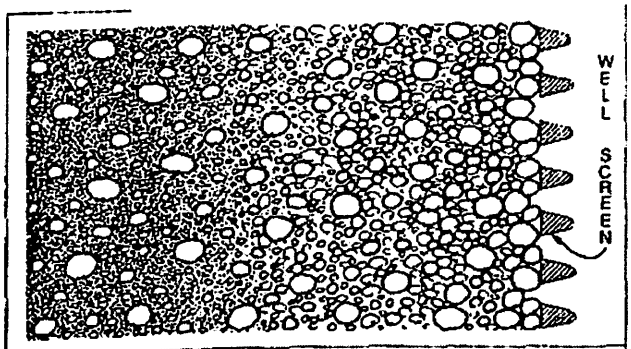


Fig. 3.1—Schematic of a natural gravel pack after developing (courtesy Johnson Div., UOP Inc.)

Because the gravel-packing technology was borrowed, early oil and gas completions were similar to those of water wells and at first included running only a slotted liner to prevent sand production. Open whole gravel packing was the most commonly used alternative if slotted liners proved ineffective. Oil- and gas-well completions opened a new dimension in gravel packing. Perforated-casing completions became popular with the advent of gun and

jet perforating. In these cases, screens were run inside a well's casing and gravel was packed around them.

Gravel-Packed Completions

Gravel packing consists of installing a downhole filter to exclude formation sand. Fig 3.2 shows two basic gravel-pack geometries currently in use, the open hole and cased-hole techniques.

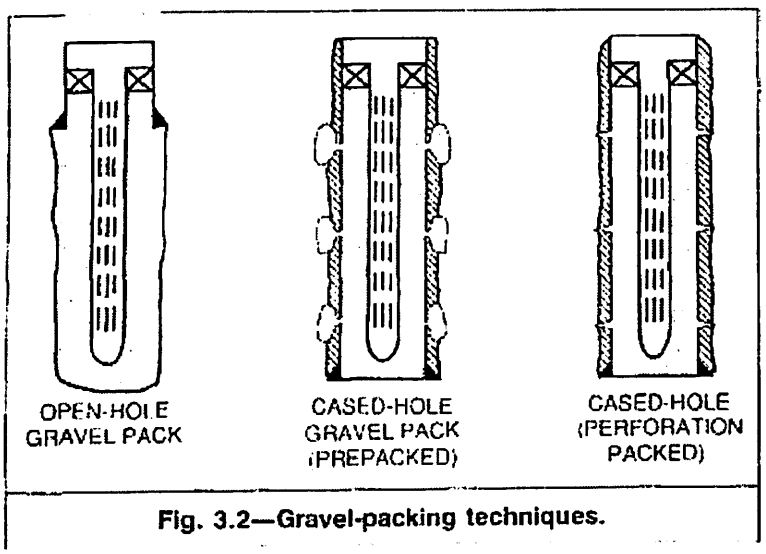


Fig. 3.2—Gravel-packing techniques.

Openhole Gravel Packs

In openhole gravel packs, there is no casing between the gravel pack and the formation sand. This completion has the highest productivity of all gravel-packed completions and is surpassed only by openhole completions. The primary disadvantage of the openhole gravel pack is the difficult task of isolating extraneous fluids, such as gas or water, at the sand face. A second limitation is that not all sand formations are physically structured to accommodate this type of completion, causing hole instability. In these cases, the sand formations are usually cased off before completion. The openhole gravel pack is the preferred mechanical sand control technique for high-productivity wells. It is most effective in long-life completions where hole stability or the production of water and/or gas will not present a problem.

Cased-Hole Gravel Packs

The cased-hole gravel pack consists of a screen or slotted liner that is gravel packed inside perforated casing this completion is the most widely used gravel pack in oil and gas wells because, upon initial completion, operators are not always certain whether wells will produce formation sand. Consequently, the casing is perforated and the wells are produced. If no sand appears, a gravel pack is not necessary. A cased-hole gravel pack can be performed later, however, if sand production is not manageable. Furthermore, this completion is better adapted to exclude water and/or gas if the need arises. Drilling and

workover considerations often dictate that a cased completion is more desirable. For these reasons, cased-hole gravel packs are more common than openhole gravel packs.

The primary disadvantages of the cased-hole gravel pack are that it is not as well suited for high flow rates as the openhole gravel pack and that it is much more difficult to perform correctly. These limitations arise from fluid flow through sand-filled perforations. The cross-sectional area through the perforations represents only a few percent of the area exposed in openhole completions, even at extremely high perforation densities (such as 24 shots/ft). There-fore, it is important that all perforations and the regions outside them contain gravel of the highest permeability that will control formation sand effectively. Gravel packing outside the perforations is commonly referred to as Prepacking but should not be confused with prepacked screens. Prepacking is important for achieving high-productivity, long-life completions.

Table 3.1 compares open- and cased hole productivities Note that, for this example, the openhole gravel pack has a much higher productivity than the cased-hole gravel packs. Also, the cased-hole gravel pack, with gravel placed through and outside the perforations, has a higher productivity than the case without prepack. For his example, the cased-hole gravel packs were perforated from 4 to 6 shots/ft and do not reflect the productivities possible with current perforating technology. Productivities would have been higher had high-density, large-diameter perforating practices been used.

TABLE 3.1--GRAVEL-PACK PRODUCTIVITY[1]

	PI (BOPD/psi)	
	Well LL-5*	Well LL-3*
Openhole gravel pack	48.4 (14)	6.4 (13)
Gun-perforated casing	36.6 (20)	5.2 (14)
Cased-hole gravel pack (with prepack)	12.9 (19)	3.2 (12)
Cased-hole gravel pack (without prepack)	4.0 (14)	1.7 (3)

*Miocene reservoirs, Venezuela. ( ) = number of wells.

As a result of problems associated with gravel-pack productivity, a whole new dimension in gravel packing arose with the cased-hole gravel-pack completion because substantially different techniques and procedures are required. Sand control is not difficult in cased-hole gravel packs, but in many instances the wells are rate-limited because improper techniques and procedures were used. By contrast, openhole gravel packs are not limited by flow through gravel-filled perforations.

The productivity limitations encountered in cased-hole gravel packs prompted numerous investigators to begin work to define and solve related problems. Early work on the proper gravel size required for effective sand control indicated that gravel/sand ratios

from 5 to 10 should be used. Design points anywhere from 10 to 70 % cumulative were recommended. Additional work confirmed that the main restriction to flow was sand-filled perforations. For maximum productivity, plugging the perforation with formation sand must be avoided. The solution has been to pressure-pack the perforations with gravel of the highest permeability capable of preventing the production of formation sand.

New emphasis has been placed on gravel packing, particularly when cased-hole packs are required. This interest has evolved because of the new high-rate fields under development that will require sand control. Examples are fields in the North Sea, the Middle East, and Southeast Asia. Some of the wells in these areas are capable of producing at rates exceeding 200 BFPD/ft. Research on cased hole gravel-pack performance has also accelerated because of higher water and gas cuts associated with produced oil in older fields, a circumstance tending to have adverse effects on productivity and sand production.

Completion Productivity

Studies have been conducted to determine the magnitude of productivity losses associated with screens and slotted liners with gravel packed around them. Test results (fig 3.3 and 3.4) show that the flow rates were extremely high, but pressure losses were quite low. Wire-wrapped screens had higher flow capacities than slotted liners; however, at realistic field rates, the pressure drop through the screens or liners was small. Note also that the flow capacity of slotted liners is proportional to the number of slots per foot, and not to the liner diameter as with screens. The implication of these tests is that the screen/slotted liner and gravel pack offer no significant restriction to well productivity, UN-less they become plugged. Slotted liners seem to become plugged more easily than wire-wrapped screens.

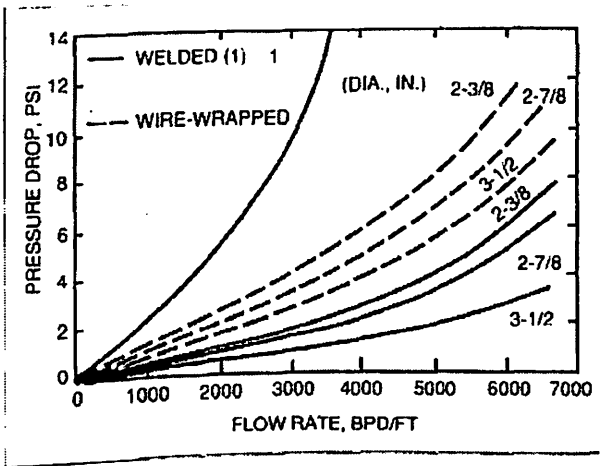


Fig. 3.3—Flow capacity of 12-gauge screens with 20/40-U.S.-mesh gravel.

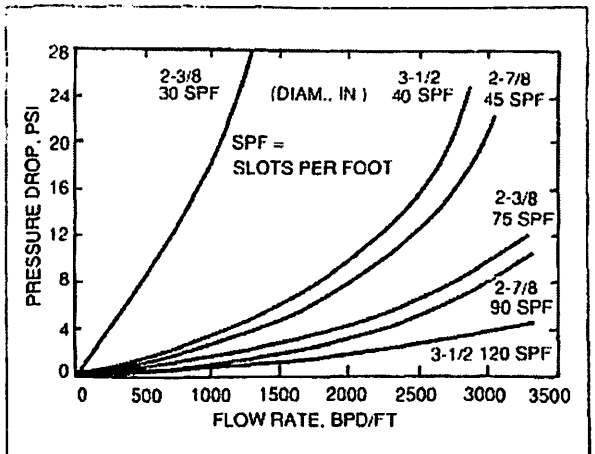


Fig. 3.4—Flow capacity of slotted liners, 0.020-in. slots, with 20/40-U.S.-mesh gravel.

Fig 3.5 shows results obtained from stimulated cased-hole gravel packs.

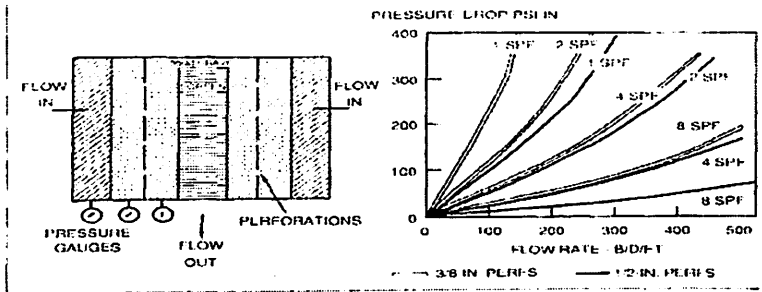


Fig. 3.5—Schematic and results of flow-capacity tests of cased-hole gravel packs.[13]

PERFORATING

Most cased-hole gravel-packed wells are perforated with jet perforators. Jet perforating consists of firing a shaped charge to generate an impingement pressure of about 5 million psi on the inner-casing wall and formation. Because this pressure is much higher than the yield strength of either the casing wall or the formation, a hole and tunnel are created with dimensions related to the charge design and the amount of explosive. Shaped charges can be designed to create either long, small-diameter perforation tunnels or short, large-diameter tunnels. The high pressures generated by the jet actually crush and compact the reservoir rock in a zone adjacent to the perforation tunnel. Fig 3.6 illustrates this Most investigations 14-16 indicate that, with conventional perforating practices, a perforation density of about 4 shots/ft with a penetration of about 6 to 8 in. results in production equal to open hole completion.(fig 3.7) Results in a productivity equivalent to that of an openhole completion. Perforating a well to be gravel-packed yields different results because, after gravel packing, the perforating tunnel is filled with gravel. At a gravel porosity of about 35 %, roughly two-thirds of the cross-sectional area open to flow contains gravel. Fig 3.6 and 3.8 shows a comparative impact of gravel filled perforations. The implications here are that higher perforation densities are necessary for gravel-packed completions than for conventional completions. Higher perforation densities are beneficial because linear flow through the gravel-filled perforation can cause high pressure losses and reduced well productivity. Large-diameter perforations are also desirable to expose more inflow area to the well. For gravel packing, large-diameter perforations are more important than perforation length, provided that the perforations effectively communicate with the formation. Perforation diameters from 0.75 in. To > 1 in. May be required for high well productivity. In evaluations of perforation charges, test results should conform to API RP 43, Standard Procedure for Evaluation of Well Perforators. To arrive at the optimum completion configuration, 17 designs of a perforating program for a gravel pack must consider the fluid flow from the reservoir, through the perforations, and from the well.

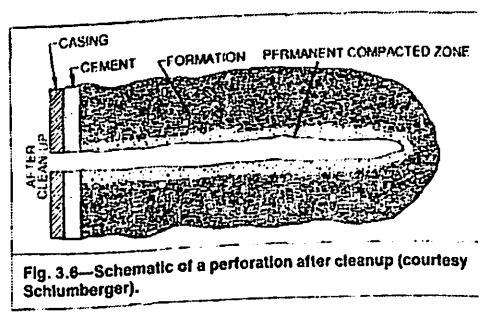


Fig. 3.6—Schematic of a perforation after cleanup (courtesy Schlumberger).

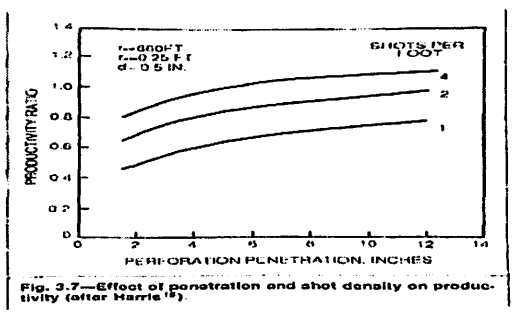


Fig. 3.7—Effect of penetration and shot density on productivity (after Harris[15]).

Some

operators have used a systems approach to gravel-pack completion design called nodal analyses that provides a reasonably sound basis for determining the tubing size and perforation requirement. For particular fields and operating conditions, however, this approach may give optimistic production forecasts if the perforations are damaged or yield small-diameter holes. The design approach is illustrated in fig 3.9. The logic used in this approach is that the difference between the well's inflow and outflow determines the amount of pressure loss that can be taken across the perforations. The inflow [PI or inflow-performance-relationship (IPR)] curves are usually calculated first on the basis of reservoir test data. The tubing capacity is then determined as a function of wellhead pressure for a given tubing size. By subtracting the tubing-capacity curve from that of the PI or IPR curve and replotting it as the pressure drop across the completion, the allowable pressure drop through the perforations is determined. The pressure drop through the perforations can then be calculated with either Eq. 2 or 3 and plotted as shown in to arrive at the proper perforation size and density configuration for that particular flow rate. The intersection of the pressure drops for the various perforation sizes and densities with the replotted curves is the highest flow rate for that perforation size and shot density. However, should the pressure drop across a perforation exceed a value known to create problems in the field, additional or larger perforations should be added.

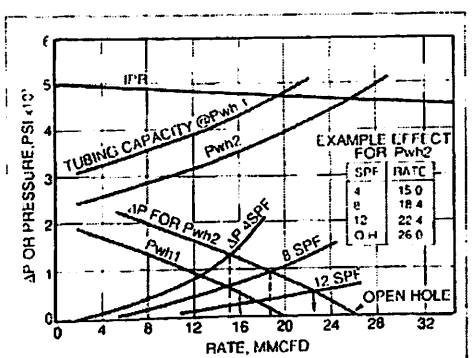


Fig. 3.9—Systems response curves to gravel-pack perforation design (after Crouch and Pack[17]).

Because the perforation tunnels can be a source of high pressure drop, particularly if formation sand enters them, it is extremely important that the proper size and number of perforations are selected. Calculations (see Eq. 2 Or 3) usually reflect ideal or optimistic projections of the pressure drop across perforations because the actual gravel permeability may be lower than that for a given mesh size owing to the generation of fines during handling. Also, the presence of gas or water saturation in the gravel, the invasion of formation fines, or the gravel being oil-wet tends to reduce its permeability. The perforation size could also be smaller than that specified. Finally, some of the perforations may not be contributing to flow because they are plugged or otherwise damaged. Hence, this procedure provides a way to determine the tubing size and the minimum perforating requirement for a gravel-packed completion but should be coupled with field experience. In many cases, the pressure drop through the tubing and the reservoir productivity are already known. The perforating program for the particular well is merely the one that provides the optimum perforation pressure drop for the projected flow rate from a cost and operational standpoint.

Equations useful in calculating the linear pressure drop through a single perforation are derived from the Forchheimer equation (Eq. 1 shows the general equation), which is usually used to describe non-Darcy (turbulent) flow:

$$\Delta Pl = \left(\frac{\mu v L}{k}\right) + \beta \rho v^2 L \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where

ΔPl = Pressure drop, psi

μ = viscosity, cp

v = Darcy superficial velocity, cm/sec,

L= length of perforation tunnel, ft,

k = permeability, Darcies,

β = turbulence factor, atm-sec^2 /g, and

ρ = density, cm3.

The first term in Eq. 1 account for the pressure drop caused by laminar flow; the second term describes the pressure drop caused by turbulence.

$$P2 = .888\left(\frac{L\mu q}{kA}\right) + 9.1 * 10^{-13}\beta l L \rho (q/\mathrm{A})\text{^}2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\

Radial Model Gravel-Pack Productivity Studies

The perforation tunnel is probably the most critical region in a cased-hole gravel pack from the standpoint of completion flow capacity. In addition to perforation diameter, the effects of gravel size, gravel/sand geometries, flow rate, and multiphase flow through gravel-filled perforations have been shown to affect well productivity and completion performance significantly. The impact of these factors on productivity and sand control has been studied in the large radial model it represented a 70° sector about a well and had a 5-ft radius. Factors that affect gravel-pack productivity could be isolated with this large model and observed in a parametric study more effectively and economically through an analysis of field results. Uniform Formation Sands. Flow test results with a uniform 5 Darcy sand with no prepack but with the perforation filled with gravel revealed a large pressure drop across the perforation. The formation sand had a uniformity coefficient of 1.5 as determined by the ratio of the 40th- and 90th-percentile diameters, d40/d90 . The four different gravel sizes used represented gravel/median-sand size ratios of 4.3, 6.9, 9.6, and 14.8. The plugging observed resulted from viscous forces causing the formation sand to migrate into the entrance of the perforation. When a prepack was used however, the pressure drop across the perforation was substantially smaller. The smallest pressure drop was associated with the largest gravel tested (7/14 U.S. Mesh).

A comparison between the two types of gravel placement -i.e., with and without Prepacking-shows that the smallest pressure drop is associated with the prepacked completions. When no prepack was used, plugging was more severe with larger gravel because the formation sand could migrate farther into the gravel in the perforation. If properly prepacked, on the other hand, formation sand was not produced at concentrations sufficient to cause plugging in the perforation, regardless of gravel size. Finally, the worst condition resulted when the perforations became completely filled with formation sand. The data also indicated that packing the perforation was not the only requirement for a successful high-rate completion, as Fig. 3.15 shows. Selecting the proper gravel size was also critical. Again, the large pressure losses were associated with the lack of Prepacking, but productivity was improved significantly by Prepacking. Fig. 3.15 also shows that, when gravel/median-sand size ratios exceed about lO, sand control becomes less effective as the gravel size increases. Testing indicated that a ratio of about 5 to 6 was optimum for effective sand control with this simulated formation sand. Under these highly controlled conditions, however, small amounts of formation sand were continually produced, regardless of the gravel size used. All data indicated that finite sand production was inherent in gravel packs. Subsequent testing with no prepack showed that such completions were more rate-sensitive than prepacked completions and that; as a result, permanent damage can result if the threshold rate was exceeded. Plugging or drainage occurred when the viscous forces were high enough to move the formation sand into the perforation. On the other hand, cased-hole prepacked gravel packs are not as severely affected by rate, they are affected by turbulent or non-Darcy flow effects. the apparent perforation-tunnel permeability

decreased as the flow rate increased. The apparent loss in permeability was the result of turbulent flow effects. Note that when the flow rate was decreased to the initial level, no permanent damage was evident. The remedy to this apparent loss in permeability is to increase the size and number of perforations.

No uniform Formation Sands. Tests with a no uniform sand (uniformity coefficient of 3.6) yielded results significantly different from those with uniform sands. The pressure dropped significantly compared with the uniform sand and that the largest drop occurred at the gravel/sand interface rather than across the perforation. However, the pressure drops across the perforation for the uniform and no uniform sands were essentially the same. In these tests, the 40/60- and 20/40-U.S.-mesh sand represented gravel/median-sand size ratios of 3.6 and 6.4. Resieving the gravel decreased the pressure drop across the interface. It also affected the sand cut. All tests with uniform sand involved gravel that was not resieved, yet the pressure drops at the gravel/sand interface were substantially lower. In this case, the sand that was not resieved contained about 10% finer-grained material, which is significantly higher than the 2 % fines allowed by API RP 58, Recommended Practices for Testing Sand Used in Gravel-Pack Operations (March 31, 1986). X-ray diffraction analysis indicated that the uniform sand contains 6.9 wt% clay and the no uniform sand contained 16.5 wt%. The additional pressure drop noted at the gravel/sand interface resulted because of the increased clay content and the wider particle-size distribution that must bridge when no uniform sands are gravel packed. Multiphase-Flow Effects. The effects of multiphase flow on gravel-pack productivity and sand production can be significant. The results of a flow test where 1O/20-U.S.-mesh gravel was used to control the uniform sand. This size represents a gravel/median-sand size ratio of about 10. The test results demonstrate that, as long as single-phase water is flowed, there is no permanent damage from perforation plugging. As shown earlier, an apparent permeability loss resulted because of turbulent flow; when the rate was decreased; however, no permanent damage was noted. When two-phase water/gas flow was initiated, permanent plugging of the perforation resulted. Gravel-pack experience under numerous conditions has shown that wells commonly decline in productivity, or begin to produce excessive amounts of sand, when water production begins. There are claims that water dissolves cementing material, and that change in capillary pressure and interfacial tension cause fines migration and sand production. The data presented here do not completely support these claims.

These data and results of other research on fines migration indicate that multi phase flow causes localized pressure disturbances because of the numerous interfaces moving through the pore structure and causing excessive fines movement. Results have also shown that, because most fines are water-wet, they do not begin to move until the water phase becomes mobile. These data indicate that, in all probability, a combination of localized disturbances and water-wet fines causes most sand production and loss of productivity in a gravel-packed region.

Gravel Pack Design

Introduction

It is important to distinguish between the production of load-bearing solids and formation fines. Formation fines also are associated with a formation but may not be part of its mechanical structure. Fines are very small particles of loose solid materials present in the pore spaces of all sandstone reservoirs. They were incorporated into the formation over geologic time. Indications are that formation fines are always produced as a result of fluid flow (see Fig. 4.1), which is beneficial. If fines are able to move, and are carried through the gravel pack by the produced fluids, they will not concentrate at pore

Restrictions and cause plugging or reduce the pack permeability. The extent to which fines move through reservoir rock is not clear. In gravel packs, however, the fines are thought to originate at the interface between the gravel pack and the near-well formation, rather than at distant places in the reservoir. The higher flow velocities near the well probably contribute to increased fines mobility in this region. The basic problem is controlling formation sand without excessively reducing well productivity. Effective control requires a good gravel-pack design and execution, including obtaining a representative sample of the formation sand, analyzing the formation grain size distribution, selecting an optimum gravel size in relation to formation sand size to control formation sand movement, and using the optimum screen slot width to retain the gravel. Other items that affect the gravel pack are proper well preparation procedures, choice of an effective placement technique, and implementation of procedures that will not impair productivity.

Formation Sampling and Sieving

Sampling The first step in the gravel-pack design process is to obtain representative samples of the formation's sand and to designthe gravel pack on the basis of the smallest representative sand stratum. The grain-size distribution often varies through a particular sand body, and usually from one zone to another. To ensure representative measurements, therefore, a number of samples are usually needed. Samples from closely spaced rubber-sleeve or conventional cores provide the best material on which to base the design. Sidewall samples are the next-best source. Bailed samples, or samples obtained from separators, can also be used but may not be representative of formations because of size segregation of the sand particles.

Information from offset wells should be used in the absence of other data. In any event, the sample sieved should be representative of the formation to be gravel packed.

Sieving In gravel packing, formation sand is controlled by properly sized gravel. For correct gravel sizing, the producing formation's The most widely used methods for assessing grain size are based on the standard screen scales, which grade the screen or sieve sizes in mesh

numbers. In this technique, representative formation sand samples are extracted, dried, weighed, and passed through screens of various sizes.

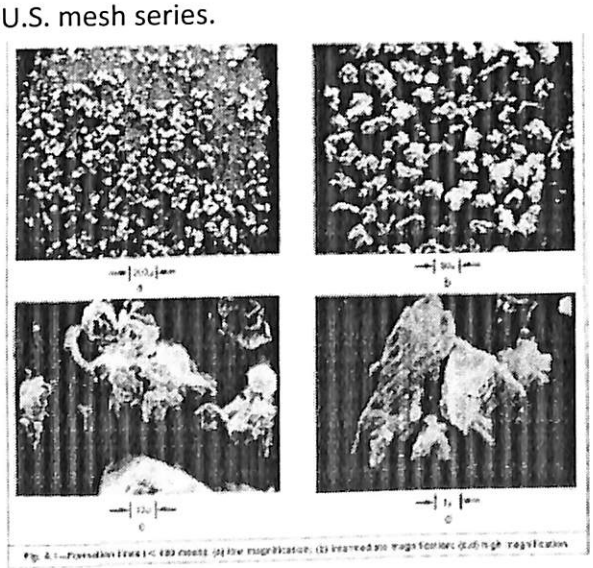
The size and distribution of the formation sand, as determined from a sieved sample of the sand formation, are important to the optimal design of gravel packs. In practice, sieving is simple. The

Disaggregated material to be sized is placed in a sieve stack and shaken until those particles smaller than the sieve openings fall through to the next-smallest sieve and so on. Separation into any number of size groups is possible if a progression of sieve sizes is used, from larger to smaller, downward from the top screen. Shaking should be done on an automatic machine for about 20 minutes (see Fig. 4.2). This length of time represents a compromise between obtaining complete' grain-size separation and avoidingsediment-particle and screen erosion. Sieving can be performed with dry, wet, or sonic techniques.

In dry sieving, all moisture must first be removed. Wet sieving, often used on formation sands having high clay content, involves flowing water over the screen in addition to shaking. This technique tends to separate the sand grains bound together by clay; the result is a representative sieve analysis. Regardless of the technique used, sieving must separate the formation sand into individual grains, and sufficient sieving time must be allowed for the sand grains to settle to the correct sieve size in relation to all particle sizes.

The theory of sieving is not quite as simple as the practice. Because most grains are not spherical, separation is not based solely on grain diameter. Grain shape also plays a part. A long, latheshaped grain theoretically could pass through a given sieve if its two smaller dimensions are less than those of the sieve opening. Despite this shortcoming, sieving is an established technique in the mechanical analysis of sediments.

Sieve analysis requires the use of a grade scale-an arbitrary, but systematic, division of sizes along a continuous scale into convenient class intervals. Several grade scales have been used. Some are arithmetic progressions; others are geometric. A geometric progression requires a fixed ratio between successive elements, such as the series 4, 2, 1, *V2,* 1fiI, Vs, where each number is half the preceding one. This is the system followed in commonly used U.S. mesh series.



The U.S. mesh series is based on a geometric progression of two. Hence, the area of the openings of each successively larger screen is increased by a factor of two and has twice the cross-sectional area (see Fig. 4.3). The diameter of grains retained on these openings thus increases geometrically by a factor of the square root of two, or 1.414. Closer grading can be achieved by including screens with openings with a progression of the fourth root of two, or 1.189. By themselves, these screens provide an offset scale that also increases by the square-root-of-two progression (see Table 4.1). Table 4.2 compares sieve sizes, and Table 4.3 lists the commonly available gravel sizes. The millimetre equivalents of these scales do not agree precisely with the Wentworth grade limits, but they are close enough to be within the U.S. Bureau of Standards limits of sieve tolerance. The square-root-of-two progression yields four U.S. mesh sieves per Wentworth grade. Fig. 4.4 shows the relationship among the Wentworth particle classification, the actual particle sizes, and the U.S. meshes series for a range that should cover most reservoir sediments. Other methods for classifying particle sizes are included for comparison. After shaking, the material retained on each sieve and the particles that fell through the finest sieve into the pan are weighed and recorded. A cumulative weight-percent distribution as a function of grain size is plotted for use in designing the gravel pack. Fig. 4.5 illustrated typical sieve analyses for several different formation sands. The tabular classification of data does not lend itself to visual illustration of grain-size distributions. Comparisons are easier when a graph of grain size (horizontal scale) is used. The use of standard statistical devices has been modified because of the peculiarities of the graphic presentation of sieve data, which are based on weight instead of number of particles and a reversed logarithmic scale of diameter. Figs. 4.6 through 4.8 are graphs of sample sieve analyses for various size distributions. Three fundamental measures of the frequency diagrams are easily obtained from sieve data. The measures of central tendencies are the averages, the median, and the mean. The measure of variation in the distribution, the standard deviation, is generally called sorting. Skewness is a measure of asymmetry in the distribution. Comparison and interpretation of the cumulative size/frequency distribution are fairly simple. If a curve maintains its form, a translation along the abscissa reflects a change in grain size (Fig. 4.6). A change in slope or steepness in the cumulative curve represents a change in the sorting of grain sizes (Fig. 4.7). Skewed distributions are asymmetrical, as shown in Fig. 4.8.

Development of Design Criteria

After representative samples of the formation sand are collected and sieved, the weights of the sieved formation sand recovered from each sieve are recorded and a sieve-analysis curve is constructed (Fig. 4.5). The slope of this sieve-analysis curve expresses the sand's uniformity. Curve A in Fig. 4.5, which is almost vertical, represents a highly uniform sand. But Curve D, which has a lower slope, suggests no uniform sand because of the wide distribution in particle

TABLE 4.1—STANDARD SCREEN SIEVES

Tyler Mesh or Tyler Number		
Progression on $(2)^{1/2}$	Progression $(2)^{1/4}$	Opening Diameter (in.)
3½	3½	0.2210
4	4	0.1850
	5	0.1560
6	6	0.1310
	7	0.1100
8	8	0.0930
	9	0.0780
10	10	0.0650
	12	0.0550
14	14	0.0460
	16	0.0390
20	20	0.0328
	24	0.0276
28	28	0.0232
	32	0.0195
35	35	0.0164
	42	0.0138
48	48	0.0116
	60	0.0097
65	65	0.0082
	80	0.0069
100	100	0.0058
	115	0.0049
150	150	0.0041
	170	0.0035
200	200	0.0029
	250	0.0024
270	270	0.0021
	325	0.0017
400	400	0.0015

Sizes compared with Curve A. A specific value of uniformity is useful in providing an approximate description of the distribution Curve. The convention has been to describe the distribution curve by the grain size at two specific percentile points, 40 and 90. The dimension of the grain size at the 40th percentile divided by that at the 90th percentile is called the uniformity coefficient, C f.'" 10 *Cil =d40 /d90* .The uniformity coefficiency is a common basis for comparing sands. The utility of the uniformity coefficient in terms of arriving at a gravel-pack design is debatable; however, some design methods use it as a basis for selecting the design point. Except for its use to differentiate between sand samples, it may be academic. Although this relationship has become the accepted method for expressing uniformity, it is somewhat confusing: highly uniform sands have low uniformity coefficients and nonuniform sands have high coefficients. As a general guideline, for *Cil* <3, the sand is considered uniform; for 3 < C *Il* < 5, the sand is considered nonuniform; and for *Cil* <5, the sand is highly nonuniform. Design Point. A gravel pack usually should be designed to restrain the load-bearing grains of the formation sand from passing into the wellbore. These grains will bridge the formation sand, controlling the entry of formation sand into the well while permitting the passage of fluids. Normally, a specific grain size is selected as a basis for the gravel-pack design. This size is used as the design point for sizing gravel, because gravel size is a multiple of the formation and size at the design point. Experience and available data show that the choice of design points has changed with time. Early packs were designed by using the 10th percentile point as the basis. Many engineers now use a higher design point, usually the 50th percentile. Some designs specify other design points; others

TABLE 4.2—STANDARD SIEVE SIZES

U.S. Mesh		Sieve Opening	
U.S. Series	Tylor Series	in.	mm
2½		0.315	8.00
	2½	0.312	7.925
3		0.265	6.73
	3	0.263	6.68
3½		0.223	5.66
	3½	0.221	5.613
4		0.187	4.76
	4	0.185	4.699
5		0.157	4.00
	5	0.156	3.962
6		0.132	3.36
	6	0.131	3.327
7		0.111	2.83
	7	0.110	2.794
8		0.0937	2.38
	8	0.093	2.362
10		0.0787	2.00
	9	0.078	1.981
12		0.0661	1.68
	10	0.065	1.651
14		0.0555	1.41
	12	0.055	1.397
16		0.0469	1.19
	14	0.046	1.168
18		0.0394	1.00
	16	0.0390	0.991
20		0.0331	0.84
	20	0.0328	0.833
25		0.0280	0.71
	24	0.0276	0.701
30	28	0.0232	0.589
35		0.0197	0.50
	32	0.0195	0.495
40		0.0165	0.42
	35	0.0164	0.417
45	42	0.0138	0.351
50		0.0117	0.297
	48	0.0116	0.295
60		0.0098	0.250
	60	0.0097	0.246
70		0.0083	0.210
	65	0.0082	0.208
80		0.0070	0.177
	80	0.0069	0.175
100		0.0059	0.149
	100	0.0058	0.147
120	115	0.0049	0.124
140	150	0.0041	0.104
170	170	0.0035	0.088
200	200	0.0029	0.074
230	250	0.0024	0.062
270	270	0.0021	0.053
325	325	0.0017	0.044
400	400	0.0015	0.037

	Permeability and Porosity of Graded Sands[9]					
U.S. Mesh	8/12 Angular	10/20 Angular	10/20 Round	10/30 Round	20/40 Round	40/60 Round
Permeability, darcies (approximately)	1,745	881	325	191	121	45
Porosity, % (approximately)	36	36	32	33	35	32

specify a design point that is dependent on the uniformity coefficient. The currently used design points are listed below and are expressed as a multiple of the formation and gravel sizes. That is, D50G is the diameter at the 50th percentile point ofthe gravel, while D50F is the diameter of the 50th percentile point for the formation.

TABLE 4.3—COMMONLY AVAILABLE GRAVEL SIZES

Gravel Size (in.)	U.S. Mesh Size	Approximate Median Diameter	
		in.	μm
0.006 × 0.017	40/100	0.012	300
0.008 × 0.017	40/70	0.013	330
0.010 × 0.017	40/60	0.014	350
0.017 × 0.033	20/40	0.025	630
0.023 × 0.047	16/30	0.035	880
0.033 × 0.066	12/20	0.050	1260
0.039 × 0.066	12/18	0.053	1340
0.033 × 0.079	10/20	0.056	1410
0.047 × 0.079	10/16	0.063	1590
0.066 × 0.094	8/12	0.080	2020
0.079 × 0.132	6/10	0.106	2670

D50G=6(D50F) .
DlOG=6(DlOF) for *Cf.t* <5,
D40G=6(D40F) for Cll > 5, and
D70G=6(D70F) for *Cf.t*> 10
D85G<4(D15F)
DlOG<10(DlOF)
Of these choices, the 50th percentile point currently seems to be common in the U.S. gulf coast, but geographical and other factors may indicate another design point.

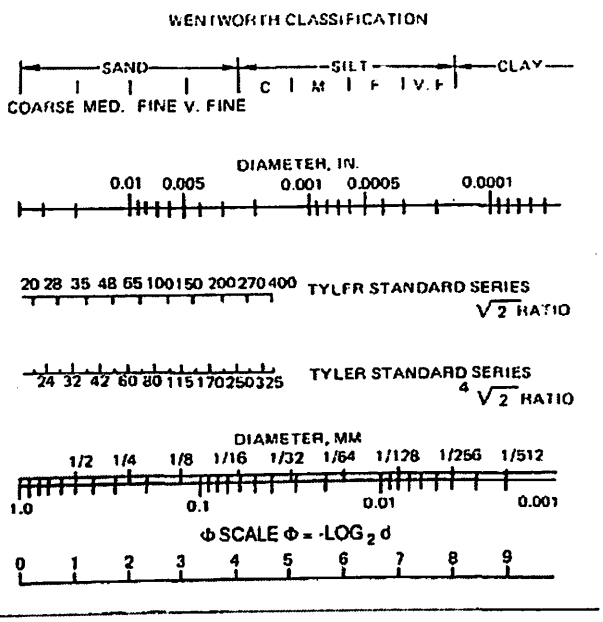


Fig. 4.4—Relationship between particle size and standard screens.

If the sands are uniform, all gravel-pack designs tend to be the same, regardless of the sizing method used, because there is little difference in grain sizes between the 10th, 50th, and 70th percentile points. For nonuniform sands, however, the designs will yield different gravel sizes, and a considerable difference in gravel sizes will exist. Hence, the selection of the appropriate design point becomes more critical for nonuniform sands. Designing a gravel pack on the 50th percentile point represents a compromise for most conditions. It will yield about the same design for uniform sand that the 10th percentile would and will provide the optimum design for nonuniform sands. In some gravel packs in certain locations, other design points yielded optimum results. Consequently, the selection of an appropriate design point should be based on the design that yields the best field results Data indicate that a gravel pack should not be designed to block all formation particles, which occurs when high design points are used. If high design points are chosen, well productivity can be severely limited by total plugging of the gravel pack by fine particles. Again, this material usually is produced through the gravel pack if it is designed to retain only the load-bearing articles. Problems arise when nonuniform sands are to be gravel packed because the range of particle sizes that must bridge is large. Under these conditions, no single design point accurately describes the entire formation and represents uniform sand. The result can be a gravel pack with good sand control, but at the expense of productivity. A gravel-pack design based on the

uniformity coefficient criterion can be greatly influenced by the way that the formation sand sample is collected. If most of the finer-grained material is lost, the sample's uniformity coefficient may register lower than it actually is, resulting in the selection of oversized gravel. Regardless of the design, point used, this example demonstrates the need for a representative sample and proper analysis.

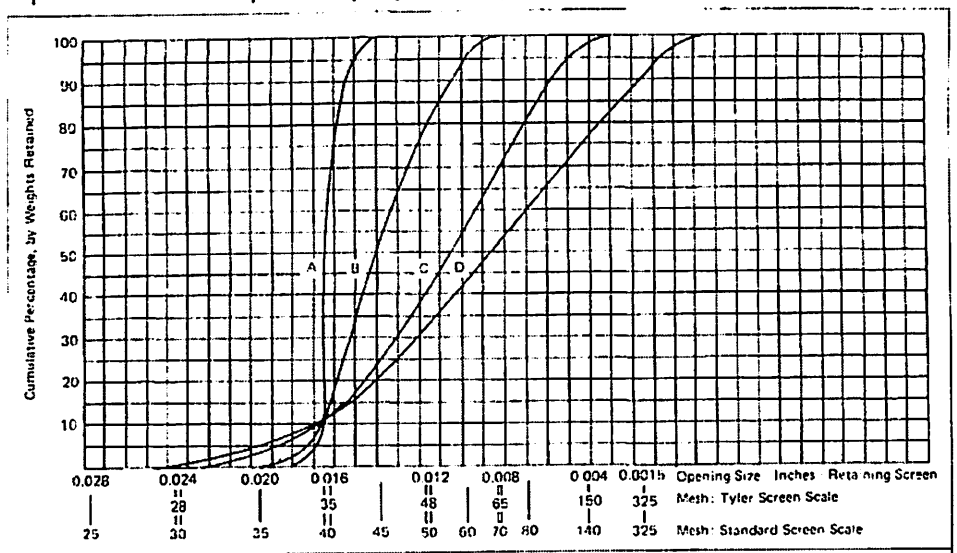


Fig. 4.5—Sieve-analysis curves constructed from the cumulative percentage of sand retained after processing through the device shown in Fig. 4.2 vs. grain size.

Gravel/Sand Ratio. The gravel/sand ratio-the ratio of the gravel grain size to the formation sand grain size at equal percentile points-is one of the most important parameters in a gravel-pack design. When the gravel/sand ratio is high, the oversized gravel is invaded by formation sand, which reduces the overall permeability of the packed zone (often to less than the native reservoir permeability) and impairs productivity. On the other hand, using undersized gravel results in excellent sand control but, in certain situations, may jeopardize productivity. The theoretically optimum range for the gravel/sand ratio is about 5 to 6, as illustrated in Fig. 4.9. Note that permeability is maximum when the gravel/sand ratios are less than or greater than 10. At a ratio of about 6, the gravel-pack permeability is at a maximum and sand is also being controlled. By contrast, at a ratio of 15, pack permeability is good but sand control is poor because the formation sand can move easily through the pack. At a ratio of 10, formation sand can move into the gravel pack but has difficulty moving through it. The result is a severe loss in gravel pack productivity. To compensate for possible optimism and to adjust for an erroneous choice of design point (caused, perhaps, by improper sampling), a gravel/sand ratio of 5 to 6 is commonly used. That is, the diameter of the gravel to be used for packing is five to six times the diameter of the formation sand at the 50th percentile design point. Given the sieve analysis in Fig. 4.10, the procedure for designing a gravel pack based on the 50th percentile design point and a gravel/sand size ratio of 6 would be as follows.

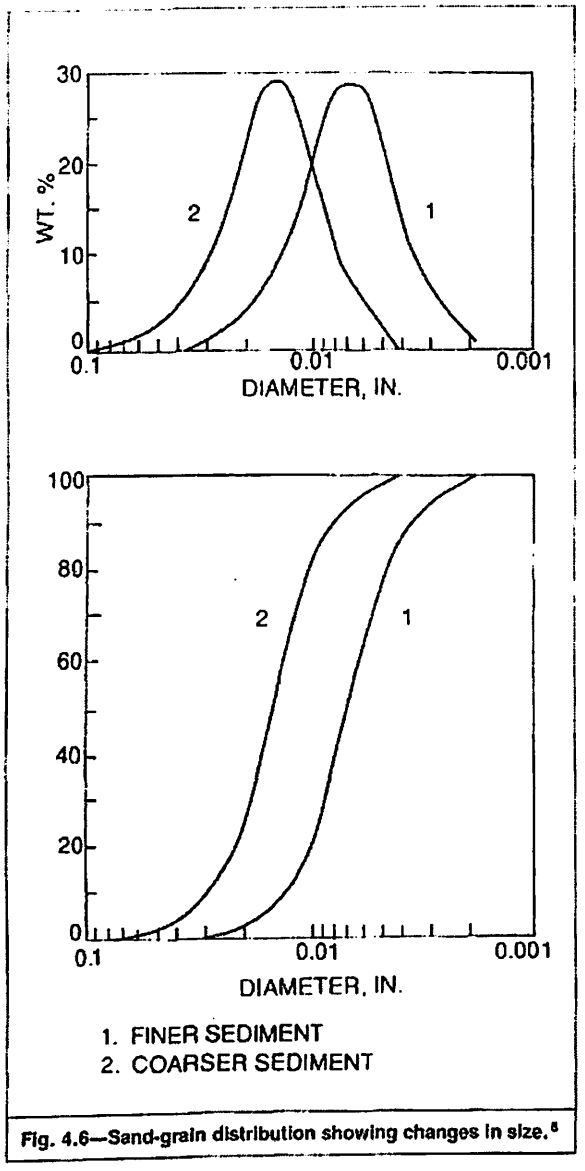


Fig. 4.6—Sand-grain distribution showing changes in size.[6]

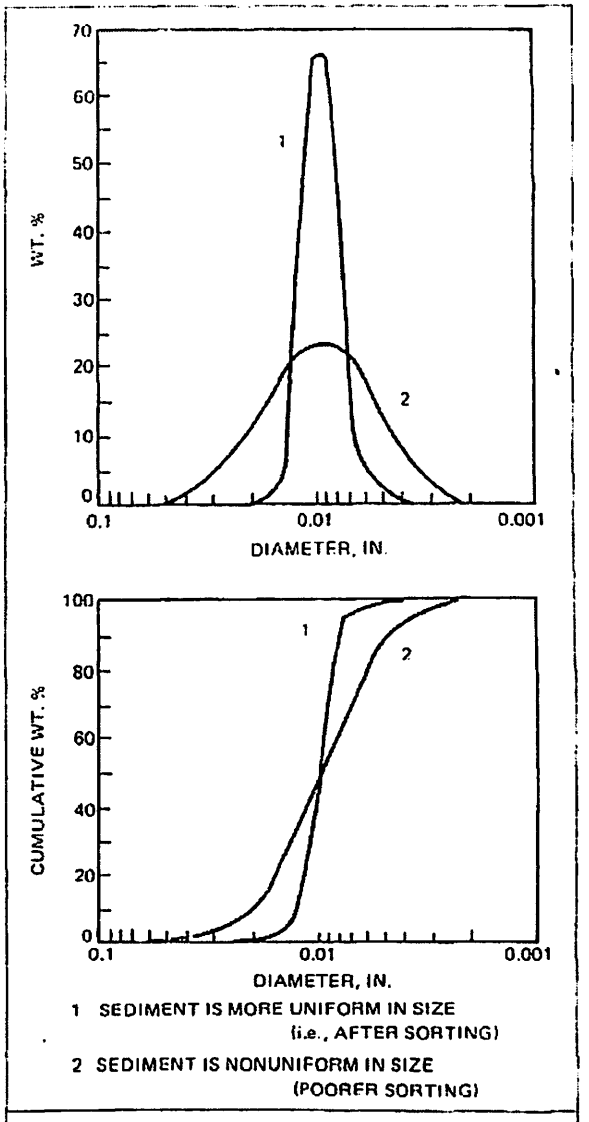


Fig. 4.7—Sand-grain distribution showing changes in sorting.[6]

1. Find the 50th percentile point.
2. Multiply this value by six.
3. Construct a gravel curve through this point-i.e *CI =1.5,* d40 /d90= 1.5,
4. Select the gravel size from the 0th and 100th percentile points (choose the closest standard gravel size at each point).
5. Select a screen slot width one-half the smallest gravel size. Fig. 4.10 shows that when the 50th percentile point is multiplied by six, that point on the gravel curve is 0.024 in. The gravel curve is then constructed so that its uniformity coefficient is 1.5. The gravel size is taken from the 0th and l00th percentile points (to the closest standard size for each). The screen-slot size is one-half the smallest gravel size. For this example, a 20/40-U.S.-mesh gravel was selected. Because 40-U.S.-mesh gravel has a diameter of 0.0165 in., the slot size should be 0.008 to 0.010 in. Other gravel-pack designs are possible by selection of different design points and gravel/sand ratios.

Screen Slot Width. Ideally, slots should be as wide as possible while retaining sand grains without restricting flow of fluids and interstitial fines. Because all the gravel must be tightly packed and retained, the screen-slot width for a gravel pack should be about one-half the smallest gravel diameter. The slot should not be wider than 70% of the smallest gravel-size diameter to avoid the production of gravel. Theoretically, a slot width greater than 70% of the smallest gravel size will retain it. However, screen manufacturing tolerances may vary, gravel sizes may not be exact, and the screen could be damaged during the completion or eroded during production. Because the flow capacities of screens and slotted liners are high, sizing the slot width on the low side will not restrict productivity and will tend to ensure that the gravel remains outside the screen.

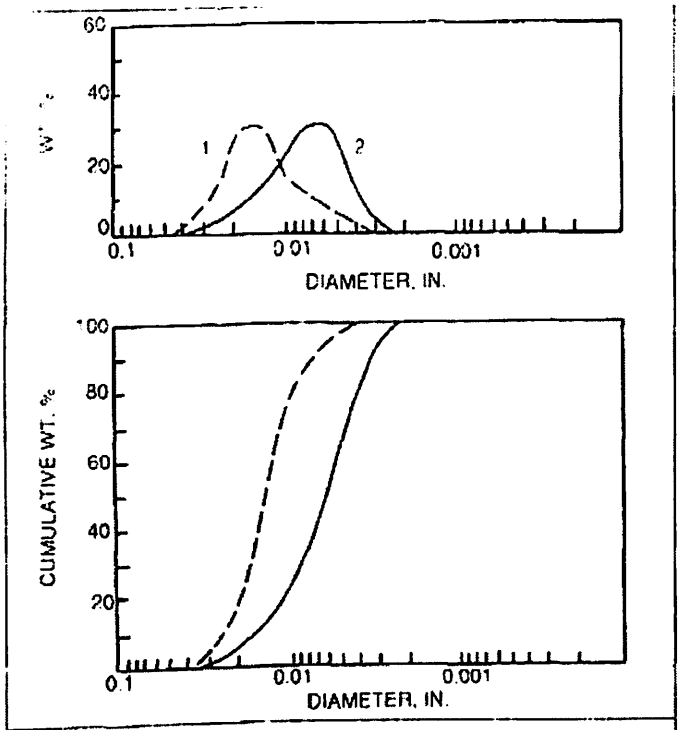


Fig. 4.8—Sand-grain distribution showing skewing.[8]

Gravel Pack Thickness. Many opinions have been expressed regarding the optimum thickness of gravel packs. Carefully controlled laboratory experiments have shown that a thickness of only 3 to 5 grain diameters is required to create a stable bridge. This conclusion, however, is based on the assumption that the bridge will sand particles with changes in differential pressures and flow velocities will no doubt occur. With each failure of a sand bridge, individual grains-particularly the finer grains-may encroach further into the gravel pack. It follows that the thicker the gravel bed, the greater the assurance that the pore spaces between gravel particles will remain unclogged with sand. Gravel-pack design should therefore place more emphasis on pack thickness than on screen diameter. However, attention must be given to well operability. Tools will have to enter the gravel-packed interval and screen removal may be necessary on occasion. Both of these requirements affect the gravel-pack thickness. Operators should be able to run the screen in the well without problems, remove it easily, and wash over it. The screen diameter should also be large enough that wireline tools, production logs, or pumps can be run inside it if needed. When all variables are considered, the following guidelines are offered for screen diameters inside various casing sizes. Hence, the clearance sets the thickness of the gravel pack.

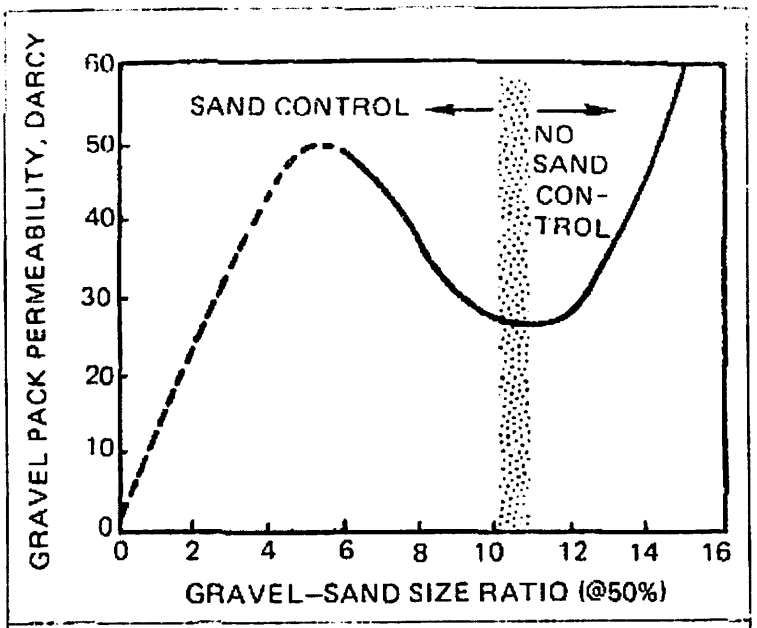


Fig. 4.9—Effect of gravel/sand size ratio on sand control and productivity.

Casing Size (in.)	Screen Size (in.)
9%	5
7%	*3.5*
7	2 to *3.5*
5.5	2
4	I

Gravel Specifications. Gravel that meets critical specifications can also affect completion success. Regardless of the gravel size required for a particular completion, recommendations are that 96 wt% of it be within the specified range. No more than 2 % should be finer than that specified. In addition to the size specification, the gravel should be rounded at its edges and spherical to minimize fines generation during handling and to provide low pack porosities.

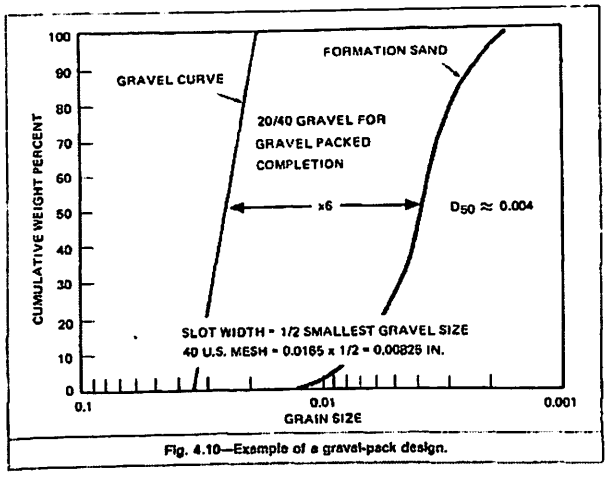


Fig. 4.10—Example of a gravel-pack design.

A roundness and sphericity of > 0.6 are suggested. The crush resistance of the gravel should be such that no more than 5 wt% fines is generated at a stress of 2,000 psi. The solubility in *12/3* % (hydrochloric and hydrofluoric acid) should not exceed 1 % when exposed for 1 hour. The low-fines content requirement of the gravel can be met by use of triple-sieving techniques offered by suppliers to meet these gravel requirements. Recommended practices for testing gravel used in gravel-packing operations are discussed in detail in API *RP 58.* While most wells are gravel-packed with silica gravel particles, other materials can be used if they meet the above specifications. Sintered bauxite and similar intermediate-strength materials have been used for gravel packing, but not as frequently as sieved gravel. They differ from ordinary gravel in that they have much higher crush resistances and higher densities. Another material available is glass beads; their use should be limited, however, to situations where no hydrofluoric acidizing is anticipated because the beads are highly add-soluble.

Gravel-Pack Well Preparation

Introduction

The proper preparation of a well for gravel packing can be the key to completion success. Careful planning, well preparation, and completion execution are required to increase completion productivity and longevity. Most gravel-pack practices are interdependent, so it is important to execute all steps properly and in the correct sequence. If a well is prepared properly, it has the best chance of being placed on production undamaged and producing sand-free. To achieve these goals, attention must be given to drilling practices, cleanliness (casing, work string, tanks, and completion fluids), completion fluids, filtration, perforating, perforation cleaning, acidizing, gravel specifications, gravel and equipment placement techniques, tool specification, and rig and service company personnel.

Drilling Practices

Drilling practices can affect a gravel pack the same way that they affect conventionally perforated wells. The well should be drilled to maintain borehole stability, and drilling fluids should be used that will not damage the formation to the point where the formation damage depth is past the perforation penetration. Drilling-fluid filtrates should be compatible with completion fluids and should not interfere with completion operations. Ideally, the drilling fluid selected should be dense enough to result in a well that is slightly overbalanced, should have low fluid loss, and should be compatible with the clays in the productive formation.

Cleaning the Casing and Work string

Cleanliness is one of the most important considerations in the implementation of gravel packs. The absence of any particulate materials can result in an undamaged completion. Particulates or other damaging material are usually, but not always, attributable to dirty work over fluids. Damaging material also can be on the inside or the outside of the work string or inside the casing string. All particulates and other potentially damaging materials should be removed before the gravel pack is performed. This step can be costly and time-consuming, but should not be taken lightly. The cleanliness of the tubular should never be ignored.

Casing

Potentially damaging materials in the casing include cement scale, rust, oxidized hydrocarbon deposits, and other debris. Removing these deposits requires bit and scraper trips for mechanical dislocation before they are circulated from the hole. The use of water, surfactants, hydrocarbon solvents, acids, and special particulate-suspending (flocculation) solutions may also be required to achieve clean casing.

Workstring

The workstring can also contain potentially damaging materials. Scale, rust, asphaltenes, and/or waxes may be present on the inner or outer surfaces. Both of these surfaces must be clean before the gravel pack is performed. These materials commonly are removed with solvents, either water or hydrocarbon-based, or weak acids, which react with nonsoluble scales or deposits. Sometimes the casing and tubing are scoured by circulation of sand slurry through them at high rates. Once the workstring has been cleaned, every effort should be made to keep it clean. During tripping out of the well before screen installation, attention to cleanliness is essential to avoid possible contamination. In particular, use of thread-lubricant compounds should be minimized because they can easily plug screens when mixed with solid particles.

Tanks and Lines

Tanks and lines should not be ignored. They should meet the same cleanliness requirements as other rig and/or well components. Such measures as scraping, jetting, and acidizing can be used for cleaning. Flocculating solutions have also been used effectively to remove sludge and particulates from lines and tanks. Where gravel packing is common, tanks should be dedicated to gravel-pack use to avoid repeated cleaning operations for drilling-mud removal.

Gravel Pack Fluids

Gravel-pack fluids can be water- or oil-based. The water-based fluids are usually considered to be more flexible. Their densities, viscosities, and formation compatibilities are more easily controlled than those of oil-based fluids. Consequently, water-based fluids are used more commonly. In certain applications, however, produced crude has been widely used as the completion fluid. Its use usually depends on the cost and availability of alternative completion fluids. Crude oil is used when it is more attractive economically, provided that it exhibits the proper physical properties and can be handled safely. The source of the completion fluid can vary. Regardless of its origin, the fluid should contain minimum particulate material and its chemistry must be compatible with the rock formation and connate water. Water that is too fresh may cause clays to swell or disperse, while the presence of some ions may cause precipitation when in contact with formation water. The most common sources are field or produced brine, seawater, bay water, or fresh water. The density of work over fluids should be controlled when possible with soluble salts such as sodium chloride, calcium chloride, calcium bromide, sodium bromide, zinc bromide, calcium nitrate, potassium chloride, and zinc chloride. All have particular advantages and disadvantages. Sometimes two or more of the brines are mixed together to achieve the desired fluid properties. Of the fluids mentioned above, the sodium and calcium chlorides and the calcium bromide are most commonly mixed together and used for gravel packing.

On the low-density side, foams have been used in certain low-bottomhole-pressure situations.

Viscosity is usually controlled with natural and synthetic polymers. Among them are guar gum and starch, XC-biopolymers (xanthangum), and hydroxyethylcellulose (HEC), carboxymethylcellulose and polyacrylamide. The amount of the polymers to be added to brine depends on the viscosity desired, the type and concentration of the salts present, and the temperature. Because of its unique combination of low residue and good viscosity yield, HEC is a popular viscosity builder for gravel packing and other completion and workover application

Foams have also been used in certain gravel-pack situations. Foam is a simple mechanical mixture of air or gas dispersed in clean fresh water or field brine containing a small amount of surfactant. Surfactant type and concentration should be selected to develop stable foam with the specific well fluids encountered. These fluids have been applied widely in shallow, low-pressure reservoirs. In wells with low fluid levels where circulation of oil- or water-based fluids is impossible, foams can be used for certain workover operations-i.e., washing out sand, drilling in, liner removal, tool recovery, and deepening.

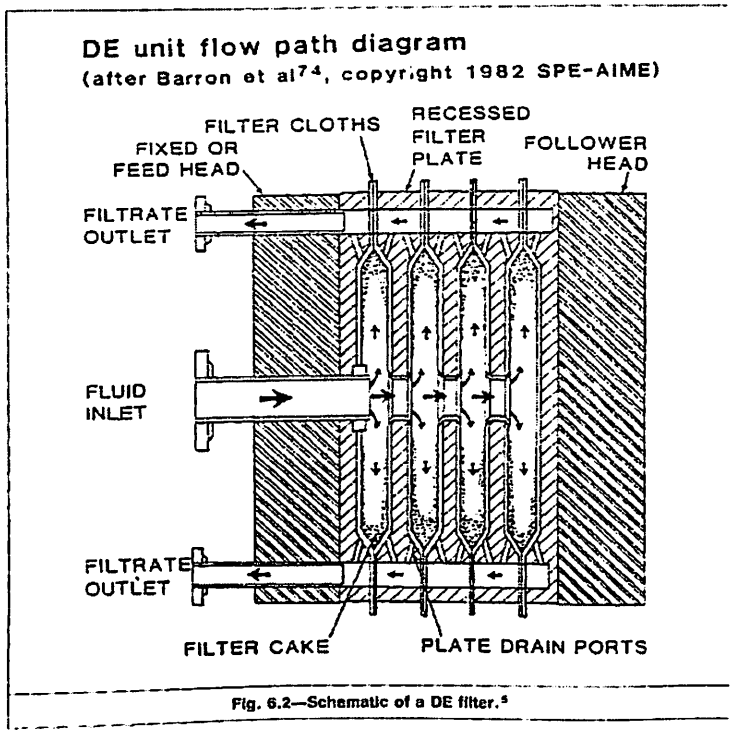


Fig. 6.2—Schematic of a DE filter.[5]

Fluid-loss control is often necessary when wells are gravel packed to prevent excessive loss of expensive or difficult-to-unload fluid or to prevent formation damage by particulate, hydro colloidal viscosity binders, or ionic species present in the workover fluid. Fluid loss should be controlled by adjustments to the completion-fluid density when possible. When fluid-loss materials are required, they should be used so that they do not adversely affect the gravel pack. Ideally, fluid loss .should be controlled at the formation face. This can be accomplished by incorporating into the workover fluid particulate materials of the proper size, shape, concentration, and particle-size distribution to form an impermeable filter cake without invading the formation. A filter cake should form quickly so that the movement of fluids and polymer in the pore space is minimized. The filter cake must be soluble or degradable in oil

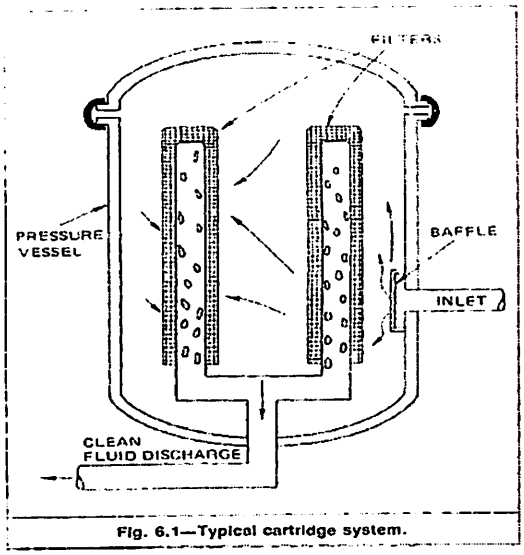


Fig. 6.1—Typical cartridge system.

or acid. To meet this requirement, calcium carbonate, graded salt, lignosulfonate, and soluble resins have been used in the completion/workover fluids to control fluid loss.

Completion-Fluid Filtration

A gravel-pack completion fluid must be sufficiently clean that suspended particles do not plug or reduce the permeability of the gravel pack or the producing formation. Filtration to 20 Um is recommended as a minimum requirement. In many situations, filtration to 1 Um is required. How the filtration is accomplished-by cartridge, diatomaceous4 earth (DE), or other techniques-is not important. The cleanliness of the fluid is the key issue. Figs. 6.1 and 6.2 show examples of a multi element cartridge filter and a DE filter unit. These units can provide clean fluids if proper procedures are followed. Current applications indicate that a completion fluid filtered by a DE filter or cartridge filter upstream in series with lower-rated cartridge filters probably is the cleanest fluid possible for many applications in terms of cost and time. 5-7 in many cases, however, only a cartridge filter is used when the completion/workover fluid is initially clean. The main advantage of the DE filter unit is its ability to filter dirty fluids at reasonably high rates compared with cartridge filter units. The cartridge filter elements are usually made from string-wound polypropylene, graded-density polyester, or phenolic-impregnated cellulose polyester. These are rated from 1 to 100 /tm or higher. The DE filter units continuously supply DE to a filter plate that acts as the filter medium to clean the fluid of impurities. The number of cartridges required for a completion depends on the' cleanliness of the workover fluid. Cartridge filter elements should be discarded once the pressure drop across them exceeds about 30 psi.

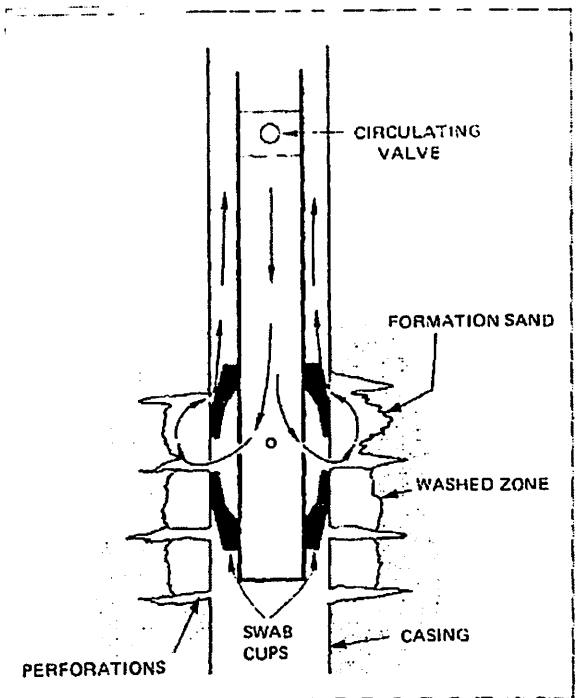


Fig. 6.5—Schematic of perforation wash tool, conventional circulation type.

Above this pressure lever: the elements tend to break down and bypass or unload debris. The general cycle times for filters are based on the pressure drop that will permit them to perform as advertised. The absolute-rated cartridge filters are a modification of the standard cartridge filter element but have pleated elements that offer about 15 times the surface area of conventional cartridges, as shown SAND CONTROL FILTER CELL FILTER CELL (i.e. 20 MICRONS) (i.e. 100 MICRONS) Fig. 6.4-Typical piping for multistage filtering unit. In Fig. 6.3. When in use, cartridge filters can be piped for either single- or multistage filtration (Fig. 6.4). Filtration should be conducted before viscosifiers are added to a workover fluid with polymers because at this point filtration tends to strip the polymers from the fluid and to plug the filters. To achieve the desired level of polymer mixing, fluids should be sheared in mixing devices that disperse the polymer uniformly in the completion fluid to eliminate un hydrated clusters, commonly called "fish eyes " Likewise, the filtration of naturally viscous fluids can be a problem because of rate and pressure-drop restrictions. In this case, the filter rating may have to be increased to achieve acceptable rates. If equipment, tanks, and time are available, a dirty completion fluid can stand overnight or longer to allow some of the particles to settle on the bottom of the tanks. Decanting the liquid from the tank allows the settled solids to be removed from the fluid.

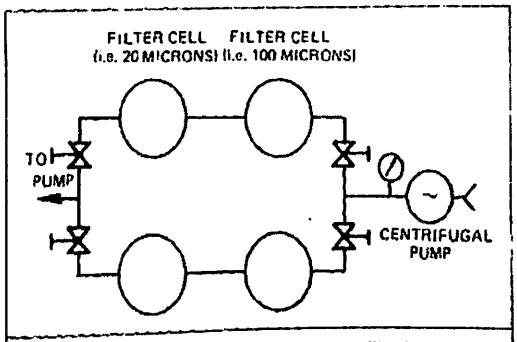


Fig. 6.4—Typical piping for multistage filtering unit.

Openhole Gravel Packs

Openhole gravel packing can result in a high-productivity completion but has the disadvantage that extraneous water and gas are difficult to isolate from the wellbore should they present a problem. Another potential problem with openhole gravel packs in the well preparation phase is the lack of hole stability. If hole stability cannot be maintained, a successful completion is doubtful. Even though openhole oil- and gas-well gravel packs are best suited for ideal reservoirs, they are often used in no ideal situations because of their high productivity when high water cuts are anticipated. . Once the decision has been made to use an openhole gravel pack in a well, the other decisions to be made relate to the casing point, total depth, and under reaming the

completion interval. Selecting the casing point is straightforward. It can usually be determined by running and correlating well logs or by analyzing sample cuttings at the surface. At all possible, the casing point should always be selected so that the overlying shale's are cased off because shale's sometimes heave or slough and adversely affect a completion by contaminating the gravel pack.

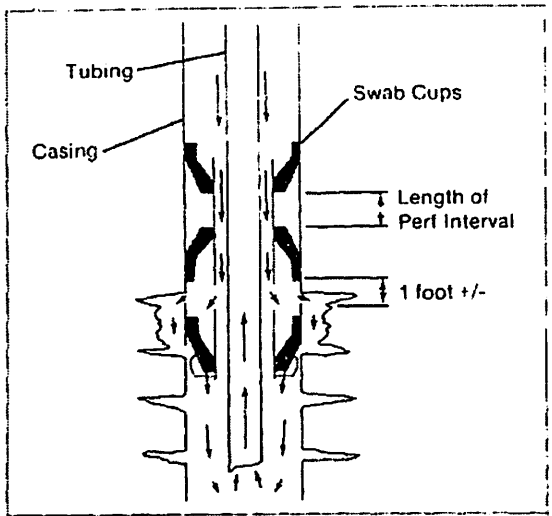


Fig. 6.6—Schematic of perforation wash tool, reverse-circulation type.

Underreaming

Underreaming is recommended in most openhole completions. The advantage of under reaming is its provision for a thicker filtering medium between the screen and the formation. Because under reaming enlarges the hole diameter, it decreases the flow resistance into the well. Decreased resistance means higher well productivity compared with an identical well that has not been under reamed. Under reamers, or hole enlargers, operate by the application of hydraulic pressure to the device, which is attached at the end of the drill string. The pressure forces the arms out against the borehole as the drillstring is rotated. This enlarges the hole diameter to a predetermined radius. When the hydraulic pressure is released, the arms return to their original position, allowing the underreamer to be removed from the well. In the absence of perforations, whole enlargement by under reaming can remove wellbore damage and mud cake from the borehole. In some isolated situations, small diameter screens are run in conventional wells. In this case, under reaming is probably not necessary because of the large annular volume around the screen. The diameter of the under reamed interval usually depends on the diameter of the production casing and the sizes of the screen and slotted liner. The screen (slotted liner) should be sized to allow it to be washed over if it must be removed from the well. The under reamed section diameter should normally be no more than 18 in. in a well with 9%-in. casing and can be decreased for smaller casing and screen sizes. In addition to providing a larger gravel-pack thickness, the under reamed interval can also be drilled with a different, non damaging fluid than that used to drill to the casing point. Formation damage is thereby minimized. Underreaming fluids used for gravel packs should have low solids content and should be non damaging to the formation. The fluids of choice usually include polymers for viscosity and incorporate fluid-loss control. HEC and other polymers have been used in many cases for viscosity control because of their reasonably low residue, which tends to minimize potential formation damage compared with clay-based fluids. During under reaming, solids must continuously be removed from the under reaming fluid with desanders and/or desilters. Where their use is feasible, brines make excellent under reaming fluids. Because of the low viscosity and potentially high fluid loss of brines,

however, their capacity to clean and remove cuttings from the hole is limited unless high fluid velocities can be achieved in the well's annulus. Calcium carbonate and lignosulfonate typically are added to under reaming fluids for fluid-loss control. Any fluid-loss-control material should be degradable or acid-soluble. Potassium chloride is used to prevent clay swelling. These fluids are available from almost all service companies that supply drilling or workover fluids. Some completion-fluid manufacturers have developed saturated-salt brines, which use salt particles to control fluid loss. After the completion interval is under reamed, caliper logs should be run over the interval to provide a basis for future gravel-volume requirements and to examine the effects of drilling rate, pump rate, fluid loss, and other variables on the openhole variable.

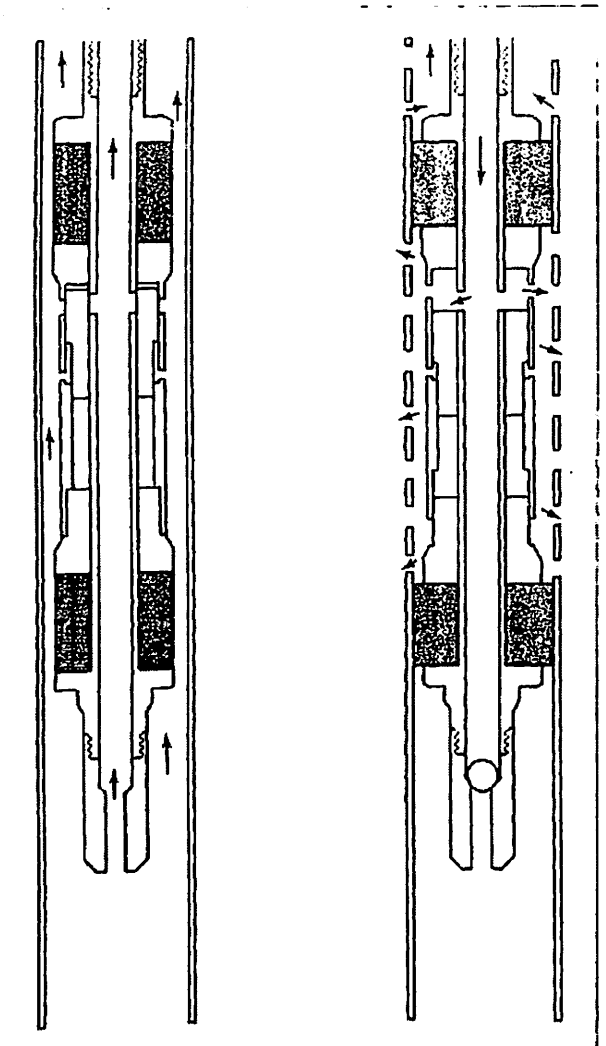


Fig. 6.7—Schematic of perforation wash tool, inflatable-packer type. (Courtesy B-J Hughes Services.)

CASED HOLE GRAVEL PACKS

Cased-hole gravel packs differ from openhole gravel packs in that the well screen is run inside perforated casing (sometimes referred to as inside gravel packs). The primary difficulty with this type of completion is its potential inhibition of well productivity of high rate wells because the gravel-filled perforations are the main restriction to flow. The design of cased-hole gravel packs should be based on fluid inflow into the well. Consequently, selecting the appropriate size and number of perforations and effectively prepacking them with gravel are critical for high-rate wells. Well cleanliness is extremely important because damage can also severely limit well productivity. The selection of perforating equipment and procedures deserves great attention before cased-hole gravel packing, not only on a new well but also on wells being worked over. Many wells are not initially gravel-packed. They may produce well, but excessive sand production may subsequently require sand control. Gravel packing at this point without re perforating could result in a low productivity well if the perforation area is inadequate for a gravel pack.

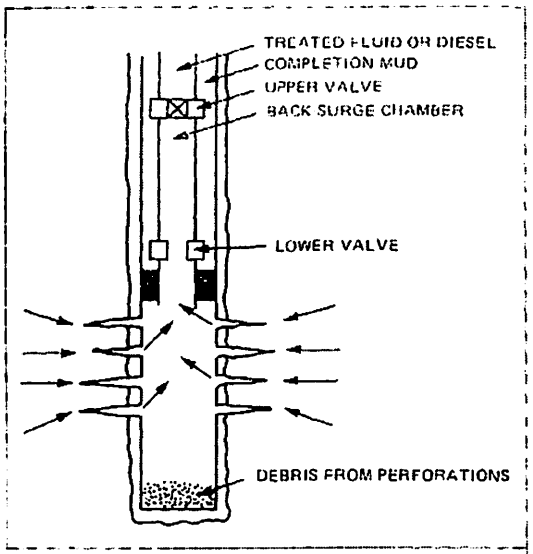


Fig. 6.8—Schematic of backsurging tool illustrating principle of the technique (after Suman *et al.*[8]).

PERFORATING PRACTICES

The charges of some gravel-pack perforating guns can create perforations with diameters well over 0.75 in. Usually, 5- or 7 -in. perforating guns shoot the large holes. Should large diameter perforations be considered necessary for a particular completion, larger casing strings than originally recommended may be necessary. Once the perforation size and density have been determined, perforation phasing should be considered. Phasing can be 0, 90, 120, or 180°; however, most 3.5-in. and larger guns are phased at 90°. There are some indications that 90° phasing is the most effective. The perforation size as it relates to gravel packing is most important. The size controls not only the amount of formation sand exposed to the well but also how effectively gravel-pack material can be placed through the perforations. In both cases, large-diameter perforations are desirable because the perforation area through the casing and cement sheath is more important than penetration as long as the formation is in communication with the well. As a general guideline, select perforating guns that yield the largest-diameter perforations yet allow adequate communication between the well and the producing formation. The perforation density necessary to produce a well at the desired rate is also critical. Perforation densities are typically between 8 and 12 shots/ft for cased-hole gravel packs. In selecting both the number and size of the perforations. Underbalanced perforating is the recommended practice. 8-12 How much underbalance is necessary depends on the formation and the fluid properties. One general guideline is to perforate oil wells 500 psi and gas wells 1,000 psi underbalanced, although specific situations may dictate different procedures. The underbalance pressure should not exceed the collapse strength of the casing or cause excessive formation failure that prevents the removal of the guns from the well. Some operators 11 advocate flowing the well for several tubing volumes to facilitate perforation cleaning. Both wireline and tubing-conveyed perforating practices are amenable to gravel-packed completions. While both have advantages and disadvantages, the tubing-conveyed guns are attractive in that they can perforate an entire interval underbalanced. In long intervals, the tubing-conveyed guns may also be less expensive than wireline guns. Regardless of which perforating technique is used, a cased-hole gravel pack should not be completion-limited by insufficient perforation area. Each gravel pack should be perforated from the standpoint of the production rate anticipated.

PERFORATION CLEANING

Perforation cleaning is critical to gravelpacked completions to ensure that formation damage is minimized and that the condition of the perforation tunnels and the region outside the perforations will allow gravel packing. Chap. 3 discusses the effect of packing the perforation tunnels with gravel on productivity. Methods for cleaning perforations include perforating washing, surging, underbalanced perforating, and in some cases producing the well for a period of time before gravel packing. These techniques should remove formation sand from all perforations so that high-permeability gravel can be pumped into them to maximize productivity and completion longevity. Perforation washing!3-16 is performed by pumping a wash fluid through the perforations over a short interval (usually about 1 ft or less) to remove formation sand from the perforations and possibly from the region outside the perforations before prepacking with gravel. The amount of material removed varies, depending on the strength of the formation. More formation sand can be removed by washing in low-compressive-strength formations than in highcompressive strength areas. How much formation material is removed can also be related to perforation wash techniques and procedures. Fig. 6.5 shows a conventional circulation-type perforation wash tool. Several different designs allow normal and reverse circulation washing. Some tools have opposed swab cups and inflatable elements. Fig. 6.6 illustrates a reverse-circulation tool; Fig. 6.7 shows an inflatable-packer-type tool. Perforation washing is an art that requires attention to detail. The following procedures should be followed to achieve effective perforation cleaning and well control during washing operations.

I. Run and retrieve swab-cup perforation wash tools slowly. Running or retrieving them at rates exceeding about 1,000 ft/hr risks either breaking the formation down or swabbing the well in.

2. Check the fluid level in the workstring every few stands when running or retrieving operations are in progress.

3. Select a wash-fluid density considered to be the minimum for well control.

4. Use clear brine as the wash fluid, do not use viscosity building additives because they can create filter cake buildup and reduce formation sand removal.

5. Space the wash cups (elements) as close as possible (6 in.).

6. Wash from the bottom perforated interval up.

8. Use a wash volume of 10 bbl or until a pressure break is observed. Clean fluids that are compatible with the formation should always be used when perforations are washed. Also, the density of the wash fluid should correspond to the minimum acceptable overbalance pressure. Both conditions are important to minimize the risk of damaging the formation

with particulates or workover fluids. The loss of workover fluids during perforation washing operations can be a serious problem. When loss of workover fluids cannot be controlled, perforation cleaning with surge tools may be a viable alternative.

Perforation surging is another way to clean perforations and remove plugging material. The tool is no more than a cylindrical chamber that can be sealed at the surface so that the air inside the chamber is at atmospheric pressure. Fig. 6.8 is a schematic of the tool. After the tool is run in the well, it is opened to expose the perforations to atmospheric pressure. The pressure change forces a limited volume of perforation debris, mud, formation sand, and reservoir fluid from the perforation. Compared with a wash tool, the surge tool requires tripping the work string for each surge run. Because flow through the tool is limited when the tool is opened, several trips may be required for long intervals. In some situations, the surge volume in the tool can be changed to create larger surge volumes. Tests 14 have shown that surging does not remove formation sand as uniformly as perforation washing, but wells that have been surged show excellent productivity. When perforation washing is not used, surging may be a viable alternative to cleaning perforations.

ACIDIZING

Acidizing can be used several different ways to enhance the success of a gravel-pack completion. Acid treatments can be performed either before or after the gravel pack using the design shown. When acidizing is performed before the gravel pack, the treatment is run as it would be in a normal well. If acidizing is considered necessary to completion success, it should be performed before gravel packing. A well is typically treated with acid after the gravel pack if it is not producing at an acceptable rate. These treatments should be pumped at rates and pressures that will ensure that the formation will not be broken down.

GRAVEL-PACK PLACEMENT

Introduction

Gravel placement involves those operations required to transport gravel from the surface to the completion interval to form a downhole filter that will permit the flow of fluids into the well but will prevent the entry of formation sand. The gravel pack must be placed so that a uniform pack with a porosity of 38 to 39 % or lower results. The gravel should also be placed so that the pack is not damaged to the point that well productivity is restricted. Low- or high-viscosity fluids can be used with several placement techniques to transport the gravel to the completion interval. The fluid and technique selected depend on well conditions, the probability of success, and the cost.

Choice of Fluids

Selecting a gravel-placement technique for completing a well usually involves choosing fluids to transport the gravel slurry to the completion interval. Water- and oil-based fluids, emulsions, and foams are commonly used. Clean fluid is essential. Depending on well pressures, high-density, solids-free soluble salt solutions may be required to maintain well control. These fluids have densities as high as about 18 lbm/gal. The use of the high-density brines involves significantly higher completion-materials costs and requires handling procedures that necessitate additional rig time. Table 8.1 lists some fluids used to gravel-pack wells. Most of these fluids can be further viscosified by adding polymers (see Fig. 7.10). The viscosities of the brine solutions also depend on the salt concentration and temperature. In many situations, brines are combined to achieve a given density at a reduced cost. The implication of the wide viscosity range is that higher-viscosity fluids have a greater ability to suspend gravel particles. Low-viscosity fluids can transport only about 1.0 lbm/gal (1.0 lbm of gravel in 1 gal of fluid- i e.,the total volume is greater than 1 gal) of gravel at normal pumping rates; the very-high-viscosity fluids, particularly cross linked polymer solutions, can transport gravel at concentrations exceeding 15 lbm/gal. A thorough understanding of the properties and capabilities of these fluids can be critical to completion success.

There are two techniques for placing gravel around a screen. With conventional packing techniques, the gravel is placed at concentrations less than 2 lbm/gal by use of low-viscosity fluids. In slurry packing, high-viscosity fluids containing high gravel concentrations are used (4 to 15 lbm/gal). The delineation between the two is not always as simple as low vs. high viscosity because their uses overlap considerably. Different gravel-placement procedures are required when these two fluid systems are pumped. In some cases, gravel slurries are pumped by modified conventional practices to place the gravel. But because slurry-pack fluids have high viscosities, they can also suspend gravel and squeeze it through perforations so that the prepack and the gravel pack can be performed simultaneously.

This option does not ordinarily apply to gravel placement with low-viscosity fluids. Here, perforation prepacking is commonly performed before the screen is run in the well. Regardless of the fluid chosen as the transport fluid, gravel placement ideally progresses from the bottom of the completion interval upward. Because of the well deviation and the fluid viscosity, this progression does not always occur. Thus, a thorough understanding of the gravel-placement mechanics of each fluid system is important in achieving the desired result a sand-free, high-productivity completion.

Choice of the gravel-transport fluid is in many cases not the important issue. Conventional and slurry packing methods can produce completions with excellent productivity, provided that the proper method is selected for the particular application and that the gravel is packed properly in the perforations and around the screen. Regardless of the fluid system chosen, the materials, equipment, and placement techniques should be selected that will yield a sandfree completion with the desired productivity.

Conventional Packing

Conventional packing, sometimes called circulation gravel packing, normally involves the placement of gravel suspended in a low viscosity transport fluid pumped at low gravel concentrations. Circulation packing is usually conducted after the perforations have been prepacked with gravel or in an open hole. Typically, the transport fluid is filtered brine with the gravel added at a concentration of 0.5 to 1.0 lbm/gal. The gravel is commonly mixed into the fluid through a gravel injector (shown later) while pumping at rates from about 0.5 to 3.0 bbl/min. Conventional packing is compatible with essentially all the placement techniques that are discussed later. Fig. 8.1 is a schematic of gravel placement with conventional packing techniques and crossover equipment at well deviations between 0 and 450 from vertical that shows that, within this range of well deviation, the final result is the same. Gravel is transported into the annulus between the screen and casing (or open hole) where it is packed into position from the bottom of the completion interval upward. The transport fluid then returns to the annulus through the wash pipe inside the screen that is connected to the workstring. The when the gravel level reaches the tell tale screen. No further gravel placement is required above this point in the well. Telltale screens range from about 5ft in length for short completion intervals to 30 ft when long intervals are gravel packed. Slot densities in telltale screens may be less than that of the gravel-pack screen. Some operators do not use upper telltale screens and extend the screen higher in the well. The amount of blank tubing between the screen and the telltale (see Fig. 8.1) is called the gravel reserve. Its purpose is to replace gravel in the gravel pack that may be lost owing to settling over the life of the completion. When low-viscosity fluids are used, the Gravel-pack reserve volume is usually equal to that opposite the screen but may vary depending on well conditions and the length of the completion interval; ie .short intervals usually have a larger gravel reserve than long intervals. Conventional gravel packing has both advantages and disadvantages over slurry packs

TABLE 8.1—PROPERTIES OF GRAVEL-PACK FLUIDS

Fluid	Approximate Density (lbm/gal)	Approximate Viscosity (cp at 60°)
Fresh water	8.33	1
NaCl brine	8.33 to 9.6	1 to 3
$CaCl_2$ brine	8.33 to 11.6	1 to 20
KCl brine	8.33 to 9.8	1 to 2
$CaBr_2$ brine	8.33 to 15.1	1 to 30
$NaBr_2$ brine	8.33 to 12.7	1 to 20
$ZnBr_2$ brine	8.33 to 19.0	1 to 20
Oil	7.0	1 to 100
Emulsions	8.33 to 11.0	5 to 100
Foams	0.3 to 4.0	1 to 50

ADVANTAGES

- Positive indication of gravel level at gravel-pack completion.
- No mixing of complex fluids
- Low gravel concentrations
- Minimum settling after placement
- Better suited for long intervals and high-angle wells

DISADVANTAGES

- Long placement time may be required in long intervals.
- Possibility of screen erosion during placement.
- Requirement of a prepack if water is used as the carrier fluid.
- Possibility of gravel-size segregation.
- High fluid loss in certain situations.

Slurry Packing

Slurry packing involves pumping gravel at high concentrations in a viscous transport fluid. The slurry is usually mixed in a blender or paddle tank before it is pumped. Although the fluid can be either water- or oilbased, hydroxyethyl cellulose-viscosified brine is the usual choice. The typical polymer loading is 60 lbm/1, 000 gal.In some situations, carboxymethyl hydroxyethylcellulose fluid is cross linked to create very high viscosities. The concentrations of gravel usually pumped with slurry-pack fluids is about 10 lbm/gal.In certain situations, however,concentrations have ranged from much less than 10 to more than 18lbmJgal. When these high-density fluids are pumped, the fluid and gravel tend to move as a mass. Compared with the low-density conventional gravel-pack fluid, these slurry systems have significantly greater gravel-suspending capabilities. Pump rates normally range from Ih to 5 or 6 bbl/min when gravel is placed around the screen and depends on well conditions. Fig. 8.2 also shows the gravel sequence with a viscous fluid at well deviations between 0 and 45° from vertical.

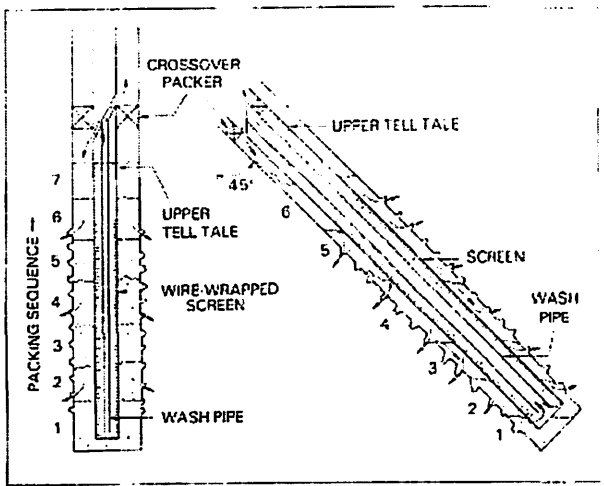


Fig. 8.1—Conventional packing techniques, crossover equipment.

Slurry-pack gravel placement is also compatible with most gravel-pack equipment and techniques. When high-viscosity fluids are used to transport gravel into the completion interval, a reserve volume should also be specified It usually is higher than required for low-viscosity fluids to allow for subsequent settling. Well conditions affect the gravel reserve volume when viscous fluids are used. Before the gravel is pumped, calculations should be made to determine the theoretical amount of gravel required to pack the annulus around the screen in addition to the gravel reserve. The placement should be about 100% under ideal conditions .Depending on the additional gravel placed through the perforations, possible bridging in the tubulars, or pumping conditions, the amount of gravel placed could differ from the theoretical volume. If it is considerably less, premature bridging probably has occurred and measures should be taken to settle the gravel around the screen and to pump addition al gravel before the well is placed on production. When high-viscosity fluids are used to circulate gravel around the screen, care should be exercised to pump at a low rate so that the viscous-drag forces do not exceed the gravitational forces on the gravel once the slurry has reached the completion interval.

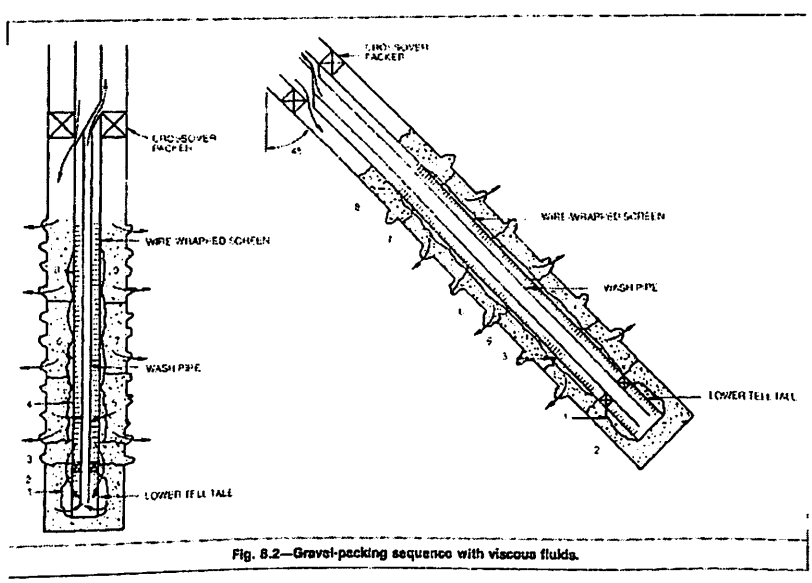


Fig. 8.2—Gravel-packing sequence with viscous fluids.

Should the viscous forces dominate, the gravel will be drawn into the screen rather than settling to the bottom of the well, as Fig. 8.2 illustrates. This causes the gravel to pack radially outward from the screen to the point that there may be premature indications of a completed gravel pack. This type of packing geometry and sequence is not desirable because, for the best packs, the gravel should dehydrate from the bottom of the completion interval upward. The potential for nonuniform packing is one of the disadvantages of slurry packs. Again, attention should be given to comparing the actual volume of gravel pumped to the theoretical volume. I f the pumped gravel volume is much

less than the theoretical volume when high viscosity fluids are used, pumping should be stopped until the gravel settles before additional gravel is pumped to complete the gravel pack. The use of an upper telltale is discouraged when high-viscosity fluids are used to circulate gravel to avoid bridging. The reason is that a gravel screenoff on the upper telltale is highly probable when higher-viscosity fluids are used. This screenoff could prevent gravel placement over the main completion interval. Recommendations are to extend the screen or slotted liner above the completion interval before blank tubing is added to achieve a gravel reserve when no upper telltale is used. Because of gravel settling, a portion of the gravel reserve volume will be filled provided that well deviations do not exceed about 60°.A lower telltale screen is sometimes used with slurry packing; however, some operators do not use a lower or upper telltale with this fluid system but tube the wash pipe to the bottom of the screen section. Although the benefits of a lower telltale may be limited and it use complicates field operations, many operators use it. If a lower telltale is used, the wash pipe can initially be packed of f above the lower telltale when crossover equipment is used (see Fig.8.2).

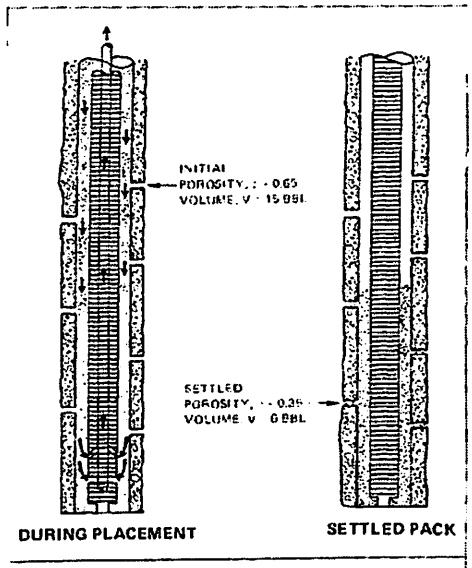


Fig. 8.3—Displacement process when first significant amount of slurry reaches bottom.

The lower telltale is claimed to ensure that gravel is initially packed in the rathole. Hence,it is preferred that the screen be set as close as possible to the plugback total depth to avoid a large rathole interval. Because of the high fluid viscosity, the gravel settles slowly in slurries. Consequently, placing the gravel initially in the rathole region will avoid subsequent disruption of the gravel pack after placement by settling. After the rathole is filled, gravel can be squeezed into the perforations. When the wash pipe is removed from the packoff, circulation can be continued through the wash pipe above the packoff to complete the gravel pack around the screen. Hence, the entire prepack and gravel pack can be completed in a single operation. Also, because high gravel concentrations are used, the gravel pack can be performed quickly compared with low-viscosity conventional packs. Viscous fluids provide excellent gravel transport into the entrance of the perforations when the gravel descends down the well compared with water because the drag forces on the gravel are high. The perforation-packing efficiency in the perforation tunnels is high once the gravel enters the perforation, regardless of the fluid used.

However, there must be fluid loss for high perforation-packing efficiency, as mentioned previously. When slurries are pumped, it is important to know the approximate viscosity of the fluid at downhole conditions to enhance placement efficiency. Viscous slurries are sometimes difficult to dehydrate if premature bridging occurs in the completion interval.The

result is that voids may form in the gravel pack- eg.adjacent to blank sections,couplings, and other locations in the gravel pack -particularly in long or long, deviated intervals, and will remain unless the bridges break down with time and allow the gravel to settle. Another disadvantage of slurry packs is the potential for nonuniform packs that initially contain voids that may not be removed by settling.

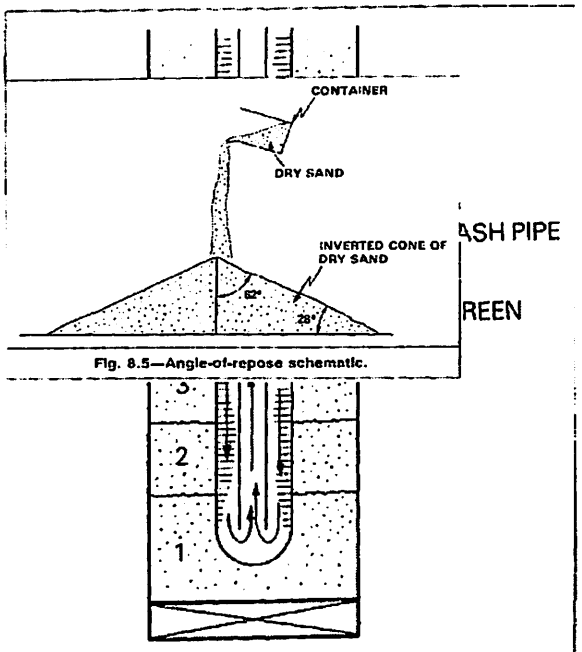


Fig. 8.5—Angle-of-repose schematic.

Fig. 8.4—Void formation opposite blank sections caused by viscous fluids.

This occurrence is uncommon when water is used as the placement fluid. Desirable, complete dehydration of the gravel slurry may not be essential when low-deviation wells are slurry packed. Viscosity break and subsequent settling can also create a gravel pack as Fig. 8.3 shows. However, sufficient gravel volume must 'be available in the gravel reserve to obtain a settled pack without exposing some of the completion interval to the screen. The settled volume of gravel whenslurries are pumped is related to gravel concentration. The settled bulk gravel volume of 10 lbm of gravel in 1 gal of neat slurry is about 0.45 gal; 15 lbm of gravel in 1 galof neat slurry settles to a bulk volume of about 0.65 gal. If settling is relied upon to complete the gravel pack, large gravel reserve volumes may be required compared with conventional packing. In short intervals, a gravel reserve several times the completion interval is not uncommon when slurries are pumped. After settling, about one half this volumes will contain gravel. To accelerate settling after placement, polymer-viscosified fluids should always be accompanied by a breaker to reduce the fluid viscosity by 90% or more after a few hours at the formation temperature. While not preferred over dehydration during placement, settling is an alternative, but it probably results in higher pa ck porosities. Before the well is produced, however, complete viscosity break is essential to provide a low porosity gravel pack. Attention should be given to the screen assembly so that no blank sections are included. Blank sections can cause voids in the pack these intervals when viscous fluids are used. The void is the consequence of the viscous forces dominating the gravitational forces. This results in voids opposite the blank sections as a consequence of bridges that form at the top of the blank section. Hence, blank sections should be avoided when gravel packs are conducted with viscous fluids. A problem that must be contended with is slurry roping in the tubing caused by its high density compared with those of the fluids in the tubing. This difference in density causes the gravel to settle in mass ahead of the transport fluid. This condition exists only at low pump rates or when a low-viscosity fluid is ahead of the slurry.

When it occurs, it could lead to premature indications of gravel arrival at key locations in the well. To minimize roping, a lead pad of gravel-pack fluid can be pumped ahead of the slurry. Also, pumping the slurry at velocities of about 500 ft/min while the slurry is in the tubing will minimize roping. When the slurry arrives at the completion interval, pump rates usually should be reduced when gravel is placed around the screen to reduce premature bridging of the gravel high in the completion interval.

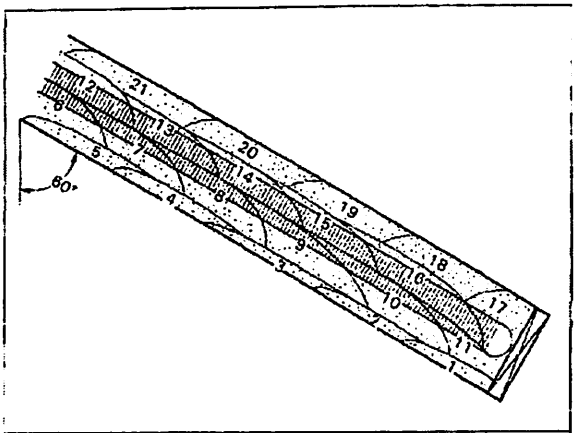


Fig. 8.6—Gravel-packing sequence at a well deviation of 60°.

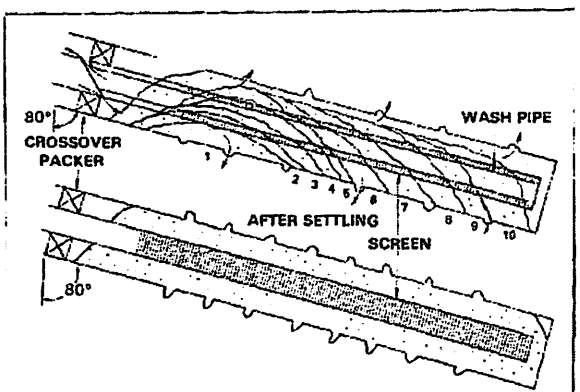


Fig. 8.7—Gravel-packing sequence in an 80° deviated well with large-diameter washpipe (ID/OD ratio = 0.8).

Use of slurry packs has both advantages and disadvantages.

Advantages

- Shorter pumping time.
- Low fluid-volume requirements (and tankage).
- Reduced pumping time because of high sand concentrations.
- Simultaneous Prepacking and gravel packing.
- Minimum returns through the screen, which may reduce erosion.

Disadvantages

- No positive indication of the gravel level around the screen when placement is ended.
- Nonuniform gravel packs.
- Several joints of blank pipe to allow for uncertainties in placement; the gravel reserve is sometimes well over 100%.
- Requirement of complex fluids.
- Potential bridging in blank sections of the screen.
- Problems with gravel dehydration owing to slow gravel settling.
- Not well suited for long, highly deviated completion intervals

With low-viscosity transport fluids (see Gravel Placement in Deviated Wells).Probably the most attractive feature of slurry packing is that it can be performed very quickly owing to high gravel concentrations. Another principal advantage is that prepacking and gravel packing the completion interval can be performed simultaneously, saving thousands of dollars in rig costs. Slurry packing does have limitations, however. Dehydration problems occur with slurries. Also, their use in highly deviated wells may be ineffective i f the pack is not effectively dehydrated during placement and pack settling creates voids. Gravel Placement in Deviated Wells Model studies have indicated that effective gravel placement in deviated wells can be achieved with a rather wide range of fluid viscosities but requires special placement-design considerations. But regardless of the fluid viscosity and placement

techniques used, the slurry must be dehydrated so that a low-porosity gravel pack exists upon cessation of pumping operations. Changes in gravel transport begin when the well deviation exceeds about 45° but become critical at deviations above 55 to60°.The reason is that gravel's angle of repose is about 25 to 28 and represents the angle between the horizontal and a stable inverted cone of gravel that is in equilibrium with a flat surface. The angle of repose is the complement of the well deviation. Fig. 8.5 illustrates this concept. The implication of this information is that effective gravel packs should be possible up to well deviations of 62 to 65°

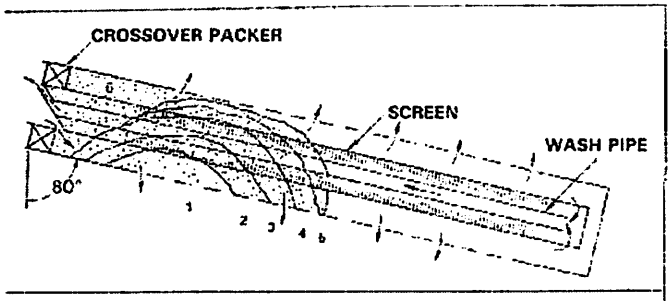


Fig. 8.8—Stalled gravel pack caused by fluid diversion into the screen/washpipe annulus (ID/OD ratio = 0.5).

Without special designs; however, this analysis does not take into account boundary effects from the casing and screen. Hence, gravel packs at well deviations greater than 60° will settle to form a void over the top of the pack unless dehydration is complete and the gravel is at its lowest possible porosity when pumping is completed. Fig. 8.6 shows the gravel-packing sequence at a well deviation of 60° and illustrates the complexity of the placement because the gravel deposition is taking place at about the angle of repose. Conventional Packing. Properly executed gravel placement in deviated wells (greater than 60°) with low-viscosity fluids initially results in gravel-dune formation on the low side of the well high in the completion interval. As additional gravel enters the screen annulus, the dune height increases to an equilibrium height controlled by the pump rate. Any subsequent gravel transport occurs over the top of the dune with deposition on the back side. Thus, the gravel dune lengthens until it reaches the lower portion of the screen or rathole.

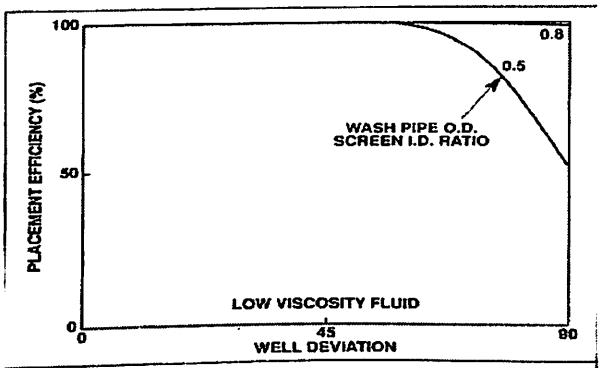


Fig. 8.9—Gravel-pack efficiency as a function of well deviation and wash-pipe size.

At this point, the channel over the top of the settled gravel is packed. Fig. 8.7 illustrate this packing sequence. For gravel to be packed effectively at the high angles (60° or more), the gravel-pack equipment and procedures must be analyzed critically. One of the main problems during low-viscosity placement is that the gravel dune tends to divert fluid into the well screen. If too much fluid is diverted, there is insufficient flow in the outerscreen annulus and the gravel bank ceases to proceed downward.A sandout high in the completion interval and insufficient gravel placed around the screen results. Fig. 8.8 also shows this packing situation. Two techniques have been used to avoid this occurrence using cups on the washpipe or increasing the wash-pipe diameter. Both techniques divert flow to the screen/casing annulus, resulting in superior gravel

placement. For operational reasons, increasing the wash-pipe diameter is the preferred technique because it increases the resistance to flow between the screen ID and the washpipe OD.

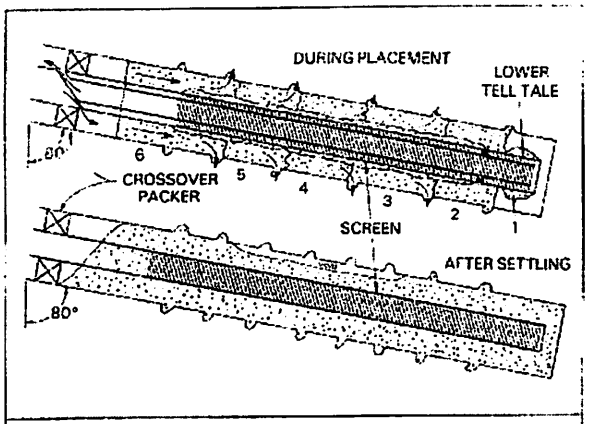


Fig. 8.10—Gravel-packing sequence with viscous fluids and void formation after settling.

This diverts fluid to the outer-screen annulus to transport the gravel down the well. Although the wash-pipe-OD/screen-ID ratio should be 0.8 or higher for the best results, because of clearance problems in the well, wash pipe with a ratio of about 0.8 seems to be the largest-diameter pipe that most operating personal are willing to run. While these high diameter ratios are necessary for high-angle wells, they also assist in packing vertical wells. Fig. 8.9 compares the placement for two different wash-pipe sizes and shows that the use of a large-diameter wash pipe maintains high placement efficiency. High-angle wells have been successfully gravel packed with the large-diameter wash-pipe approach when only water was used as the transport fluid. Increasing only the wash-pipe diameter does not ensure effective placement. Maintaining a high pump rate is also quite important for efficient placement in deviated wells. Unlike gravel placement in vertical wells, gravel packing in highly deviated wells depends on the pump rate when low-viscosity fluids are used. Pump rates should be as high as possible as long as excessive bottomhole pressures are not generated. For effective placement, the superficial velocity (ratio of the pump rate to the annulus area around the screen) should be at least 1 ft/sec to avoid the formation of a premature bridge high in the completion interval. Gravel packing highly deviated wells with conventional gravel pack equipment does not pack the rathole very well. When circulation-type equipment is used, the gravel-pack assembly should be placed as low in the well as possible to pack the rathole. Also, the use of an upper telltale screen has no benefit and can even prevent effective gravel placement if well angles exceed 45° they should be omitted in these situations. An advantage of using low-viscosity fluids for highly deviated wells is that, after the completion interval has been effectively packed, little or no settling occurs. Also, no attempt should be made to settle the gravel in high-angle completions Voids can form across the top of the pack and may lead to gravel-pack failure. Some operators advocate perforating the low side of the well only in these situations.

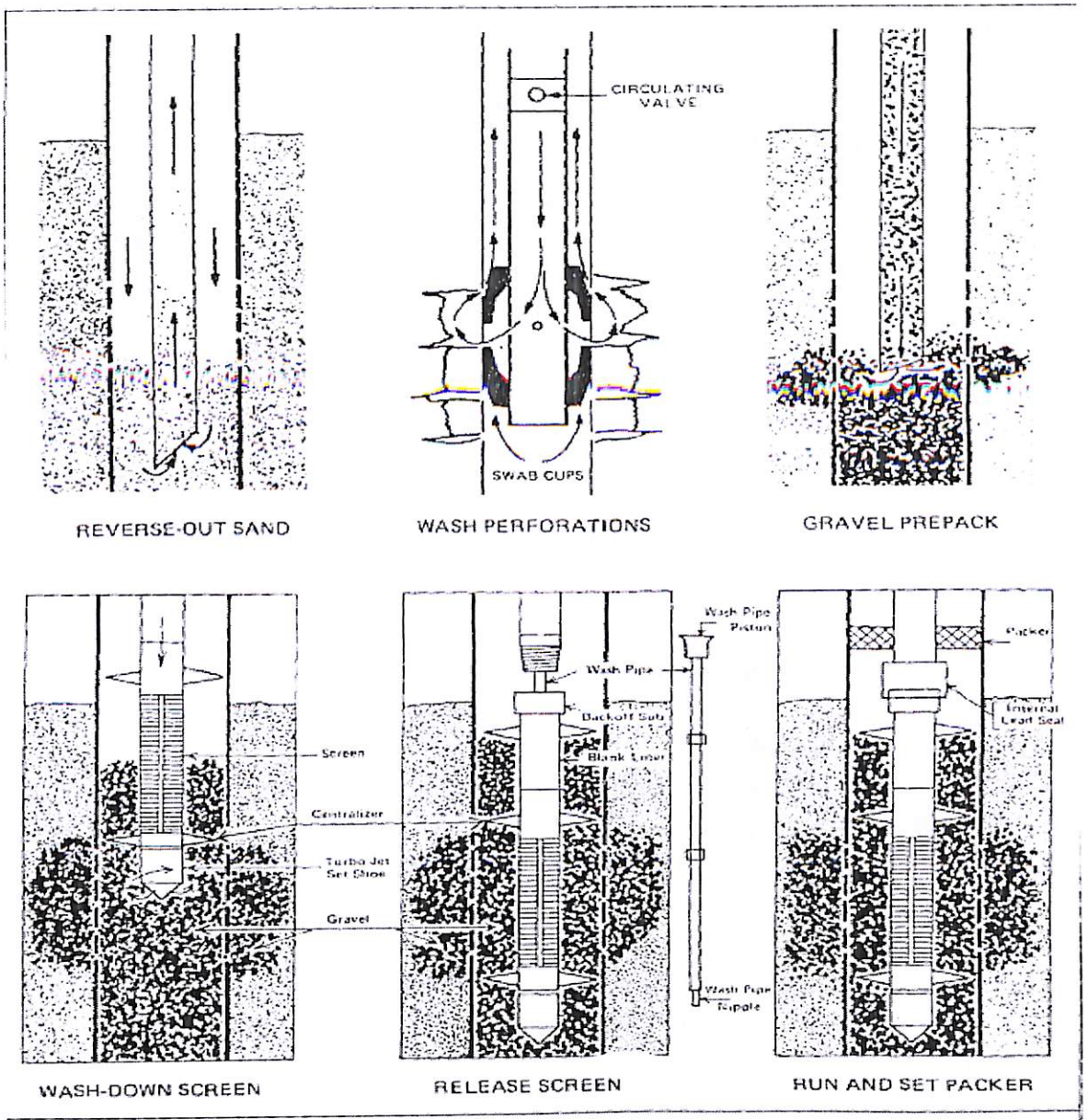


Fig. 8.11—Wash-down method (courtesy Howard Smith Screen Co.).

Slurry Packing In highly deviated wells, gravel is transported with viscous fluids completely differently than with low-viscosity carrier fluids. In this case, higher gravel concentrations (about 10 lbm/gal or more) are usually used in fluids that contain polymer loadings of 60 to 80 lbm/ l ,000 gal as are used in pumping slurries in vertical wells. These fluids provide excellent proppant transport. Gravel tends to be transported in mass along the low side of the well because of the high gravel concentration and the high fluid viscosity. When viscous fluids are pumped with crossover gravel-pack equipment, a lower telltale assembly is usually used. In fact, an upper telltale is not recommended and may cause a premature bridge at that location. The initial flow of fluid is through the lower telltale, causing gravel to be packed around it. Once packing is completed across the telltale, the gravel-pack equipment should be manipulated to squeeze fluid through the perforations to prepack

them before diverting returns through the wash pipe in the upper circulating position to gravel pack around the screen.

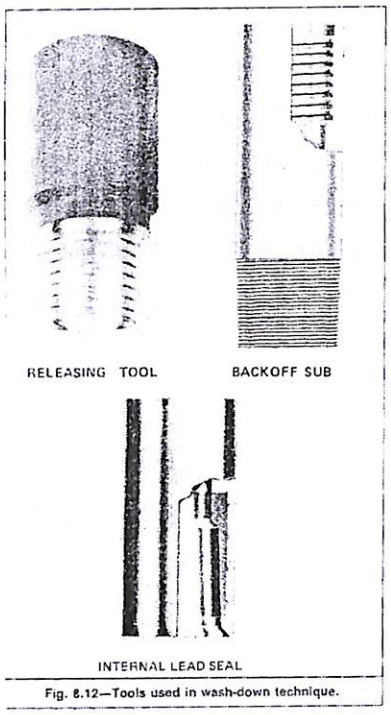


Fig. 8.12—Tools used in wash-down technique.

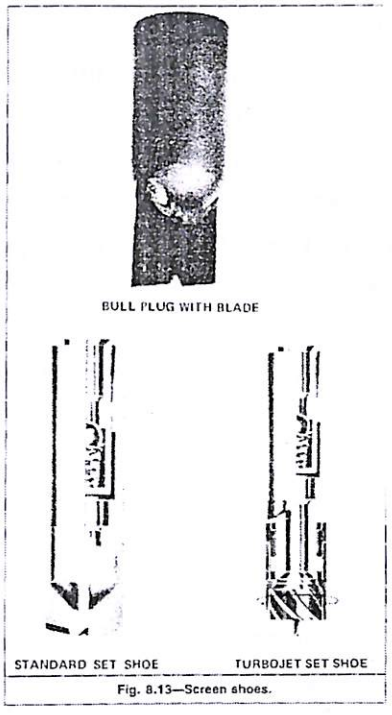


Fig. 8.13—Screen shoes.

Unlike the low-viscosity fluids, high-viscosity fluids move gravel from the lower telltale screen upward. Gravel dehydration in wells deviated more than 55 to 600 becomes more difficult with slurries than with low-viscosity fluids. Studies have shown that dehydration usually is good at the lower and upper portions of the gravel-packed interval but that a void exists along the top of the middle of the pack (see Fig. 8.10). this void is created because the viscous forces dominate the gravitational forces. Consequently, the gravel bridges prematurely at the top of the interval before the middle of the gravel pack have time to dehydrate. Thus, dehydration is good at the top and bottom of the gravel pack, but voids exist at the top of the pack in the intermediate locations. Hence, gravel packs performed with slurry-pack techniques require special attention to achieve acceptable placement and dehydration in highly deviated wells. For the best pack efficiency with slurries, the gravel pack should also be conducted with a wash-pipe-OD/screen-ID ratio of 0.8.This practice has benefits even in vertical wells. Pumping at a high rate is not as critical for effective placement with viscous fluids as with low-viscosity fluids. Dehydration can be significantly improved when slurries are pumped by reducing the gravel concentration to about 3 lbm/gal or less. Techniques and Equipment for Gravel Placement Several techniques and types of equipment are available for gravel packing wells. Each technique has advantages and limitations. The most successful gravel-pack techniques are the wash-down, reverse circulation, and crossover-placement methods. Most of the other placement methods are modifications of these techniques. Service companies may also use slightly different equipment and procedures to achieve the desired gravel placement. All these placement techniques can be used for either open or cased holes.

Wash-Down Method

The wash-down method (Fig. 8.11) is a simple completion technique but is performed quite differently from the placement methods described previously. As in all cased-hole gravel-pack operations, it is necessary to clean the wellbore and the perforations and then pack the perforations with gravel. The completion sequence is as follows. Once the perforation prepack is completed, gravel is left inside the casing at some predetermined height. The screen is run to the top of the gravel, and circulation is initiated through the bottom of the screen. Fig. 8.12 shows several devices that allow sufficient circulation to fluidize the gravel. The screen is washed into place, circulation is stopped, and the gravel is allowed to settle around the top of the screen or slotted liner section. The working string is released from the screen with a backoff sub and is raised a few feet. Reverse circulation is initiated up the wash pipe to ensure that, the inside of the screen is clean. When necessary, a second trip is made to put a packer device on top of the screen assembly. The major disadvantage of this method is that the length of screen that can be washed down successfully is limited. Discontinuing circulation to make a connection can cause gravel to settle around the screen and may prevent further screen movement.

As a result, the maximum screen setting is usually no more than one joint of tubing if the rig can handle single strings only. If a larger rig is available, the length of the screen setting is limited to the length of a stand of pipe. Either low- or high-viscosity fluids can be used with this technique. The only requirement is that the gravel be sufficiently fluidized so that the screen can be washed into position. Tools like those in Fig. 8.13(and Fig. 8.12) are needed for this type of installation. The releasing tool and back-off sub have left hand Acme threads, which allow right-hand rotation for releasing from the top of the screen. The back-off sub is screwed on top of the screen assembly, and the releasing tool is part of the workstring. Fig. 8.12 show an internal lead seal device that is run below a conventional packer and affixed to the top of the back-off sub to provide a seal between the two. The bull plug with a welded blade on the end in Fig. 8.13 provides some capability of washing down or rotating the pipe when necessary. Pipe rotation usually is not recommended because the screens are not designed to withstand high torque forces. The turbojet and standard check-valve shoes often are used in wash-down operations. Theoretically, the turbojet shoe is an improvement over the standard jet shoe for wash-down techniques because the lower blade assembly creates greater turbulence as the circulating fluid exits from the end of the wash-pipe assembly.

Reverse-Circulation Method

This method of gravel placement (see Fig. 8.14) requires wellbore preparation similar to that needed for the wash-down method, except all gravel is washed from the wellbore after the perforation prepack. The screen is then run and set in position, and the carrier fluid and gravel are reverse circulated to deposit the gravel around the outside of the screen. This method usually is used in conjunction with low-viscosity fluids, but high-viscosity fluids are acceptable when pumped at slower rates. The releasing tool, back-off sub, and lead seal (Fig. 8.13) used in this technique are essentially the same as those used in the washdown

method. The primary disadvantage of this technique is that the tubing and casing string may be contaminated with debris that could interfere with the gravel-pack permeability. Hence, cleanliness is a major concern. Crossover Method. In the crossover gravel-pack method (Fig. 8.15), a workstring pumps gravel slurry around the screen. With this equipment, the slurry is crossed over between the screen and the casing at the top of the screen section. The gravel is then placed in the screen annulus while fluid returns to the surface through the well's annulus. This technique is preferred for most situations. Crossover gravel placement has several advantages over wash-down and reversecirculation techniques.

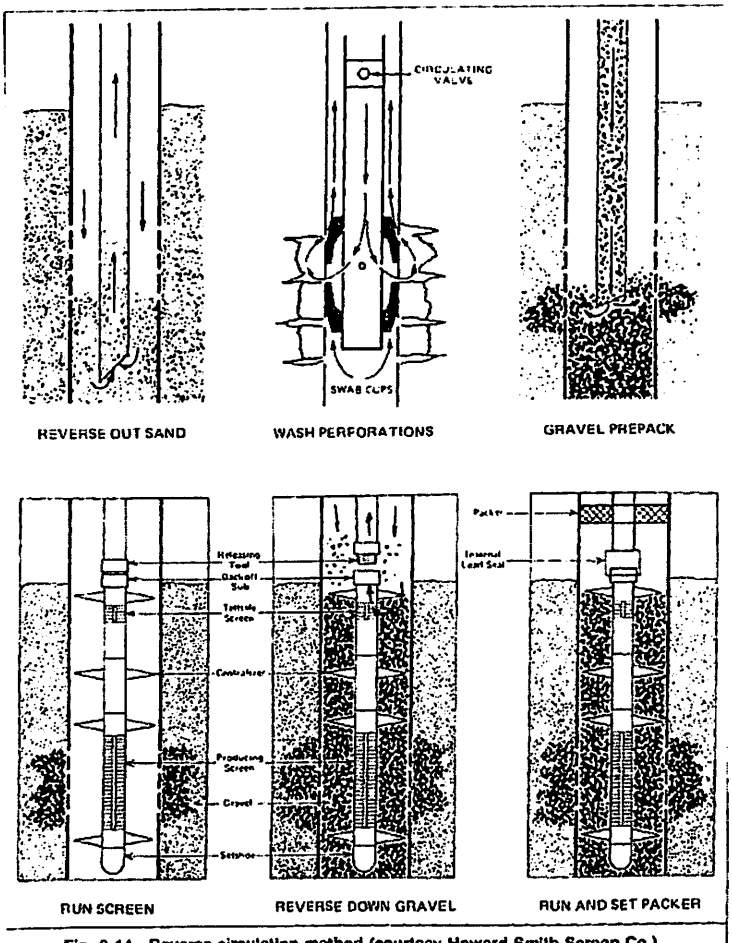


Fig. 8.14—Reverse-circulation method (courtesy Howard Smith Screen Co.).

- The gravel slurry will not scour mud, rust, pipe dope, or scale from the casing. Thus, the risk of depositing debris in the perforations or on the screen is reduced.
- The Work string volume is smaller than that of the Workstring casing annulus. At equal pumping rates, the higher fluid velocity inside the workstring decreases placement time and the possibility of bridging or gravel segregation.
- Control of both fluid and gravel location within the workstring is more precise.
- Additional trips to run the lead seal as described for the previous techniques are circumvented because the packer provides a positive seal for the screen (only when crossover packers are used). A disadvantage of the crossover method is that it is more expensive and may result in an expensive workover if the packer cannot be easily removed. Crossover-type gravel placement can be accomplished with a liner hanger (Fig. 8.16), a cup-type crossover tool (Figs. 8.17 and 8.18) or a crossover gravel-pack packer (Fig. 8.19). With the cup-type equipment, the crossover tool is part of the Workstring and consistes of a dual swab-cup assembly and crossover device.

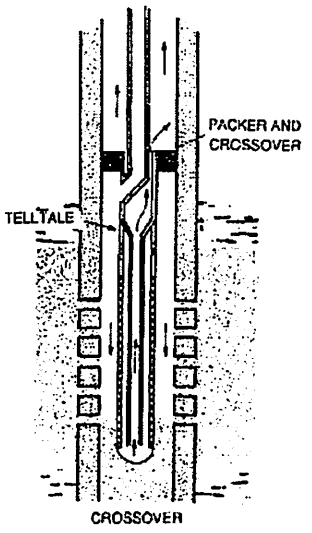


Fig. 8.15—Crossover gravel-pack technique.

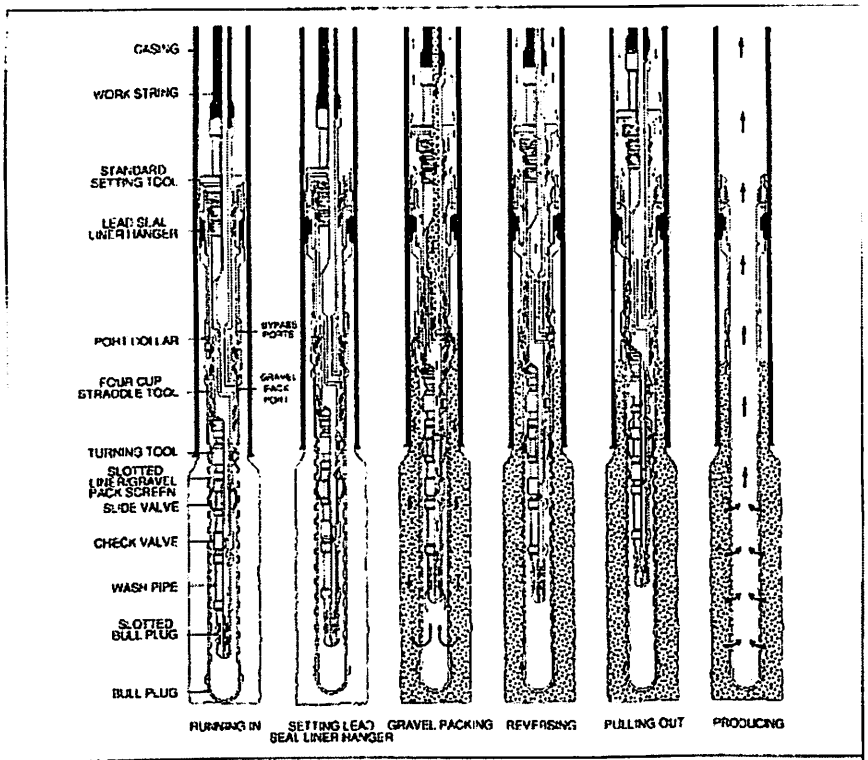


Fig. 8.16—Schematic of a linear hanger/crossover gravel pack (openhole) (courtesy Baker Sand Control).

It is re-moved from the well after gravel packing is completed. A second trip is required to set a packer or seal on top of the screen assembly. Several service companies offer a crossover gravel-pack tool for use with one or more of their standard completion packers (Fig. 8.19). They generally use a ported extension with a crossover assembly attached to the production packer and extending through the ported extension. Additional equipment (such as wash pipe inside the screen with a backpressure valve) may also be added to the assembly.

The packer/crossover assembly has five major functions.

1. A means for setting and testing the packer.
2. A flow path for the sand slurry to be pumped down the workstring and out through the ports in the ported extension below the packer.
3. The capability either to circulate fluids through the screen and out the workstring/casing annulus (circulating position) or to bullhead the fluids into the formation (squeeze position).
4. A means to release the crossover tool assembly from the packer.
5. The capability to reverse circulates and cleans out the workstring after releasing from the packer. Before selecting a supplier of such tools and services, the operator should consider the following factors that affect the success of gravel-pack placement.

• Wellbore fluids should not be allowed to flow through the screen during tripping in the hole. Problems with screen plugging can easily occur in open holes, especially in old wells.

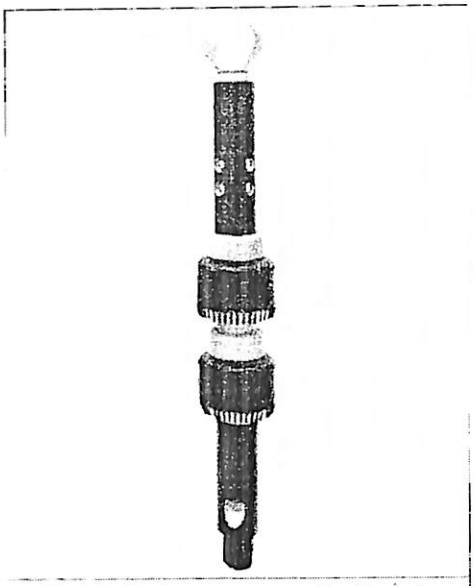


Fig. 8.17—Cup-type crossover gravel-packing tool.

• The ports on the crossover-tool outlet and ported extension should be large and should overlap. These features are especially important when large gravel or high-sand-concentration slurries are pumped.

• Some means must be provided to close or pack of across the ported extension after completion of the pack.

• A positive indication of the tool position, such as squeeze or circulation, should be available. For example, a sudden increase in pickup weight may be a clear indicator of a correct position. (A collet is commonly used for this purpose.)

• There should be flexibility for use with either an upper-telltale or packed-off lower-telltale screen assembly.

• A squeeze position should be maintained without excessive tubing weight. The various operations possible with crossover/packer assemblies are shown in Fig. 8.19. Neither an upper nor a lower telltale screen is illustrated. Fig. 8.19 do illustrate the use of a sump packer in combination with a gravel pack. The sump packer serves as a base for the screen and makes the rathole available for the settled solids in the well's flow stream. An alternative to the use of a sump packer is a bridge or cement plug as a base.

Rathole annular volume below the screen should be the minimum possible, as mentioned previously. This is particularly important for good gravel placement in deviated wells and when viscous fluids are used. While the bottom of the screen assembly should be as close to the bridge or cement plug as possible, it should be positioned so that the screen is not in compression. The normal procedure for locating the screen in the well is to set the packer so that the screen bottom is less than 0.5 ft above the plug. If a sump packer is used, the screen is usually located in a collet that requires several thousand pounds of upward pull before it can be removed. After latching into the collet, the screen assembly is sealed at the top by setting the gravel-pack packer. The stress state of the screen at this point should be essentially neutral.

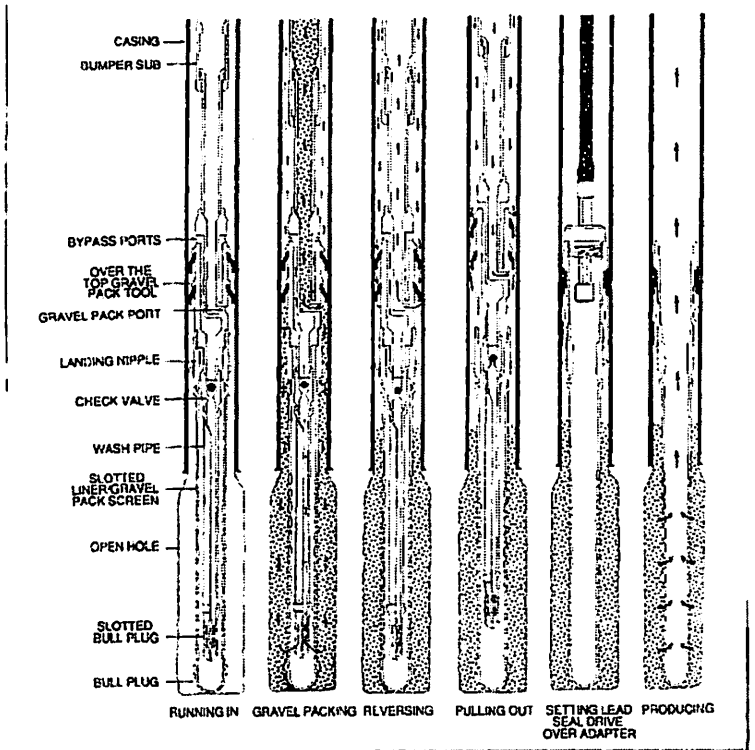


Fig. 8.18—Schematic of a cup-type crossover gravel pack (openhole) (courtesy Baker Sand Control).

Centralization

In the installation of any gravel pack, regardless of the completion technique, the screen should be centralized so that gravel can be uniformly packed around it. Spring, weld-on, aluminum, and plastic centralizers are available (Fig. 8.20). The weld-on model, sometimes called a guide, is the most commonly used centralizer in cased-hole gravel packs. Some companies prefer not to weld to pipe and therefore choose clamp-on centralizers available in aluminum and plastic. Solid devices offer the best support for centralizing the screen inside the casing. The spring centralizers are usually run for centralization in openhole gravel packs. Centralizer spacing usually is between the screen sections at the coupling. In vertical wells, one centralizer every 30 ft is sufficient. In deviated wells, centralizer spacing becomes more critical. In wells where deviations exceed 60°, a 20-ft or closer centralizer spacing is advisable.

Other Gravel-Pack Equipment

In addition to filters and pumps, some means of mixing the gravel with the carrier fluid is necessary before it can be transported into the well. Gravel injectors, blenders, and paddle tanks are commonly used. Gravel injectors (Fig. 8.21) can inject the gravel downstream of the pumps. An advantage of their use is that the sand is not flowed through the pumps, which is claimed to reduce crushing. Gravel injectors are usually used with very-low-viscosity transport fluids (water). Two limitations of their use are that regulating the gravel SAND CONTROL concentration over sustained periods of time is difficult and that they can be used only for low gravel concentrations. The gravel concentrations that can be sustained are about 0.5 to 1.5 lbm/gal. Auger-type sand injectors sometimes called gravel infusers (Fig.8.22), provide a means of conveying gravel into the flow stream over a wide range of gravel concentrations, regardless of the viscosity of the fluids pumped. The infusers control the gravel concentration with an auger that conveys the gravel into the suction of the pumping unit at a uniform rate controlled by their rotational speed.

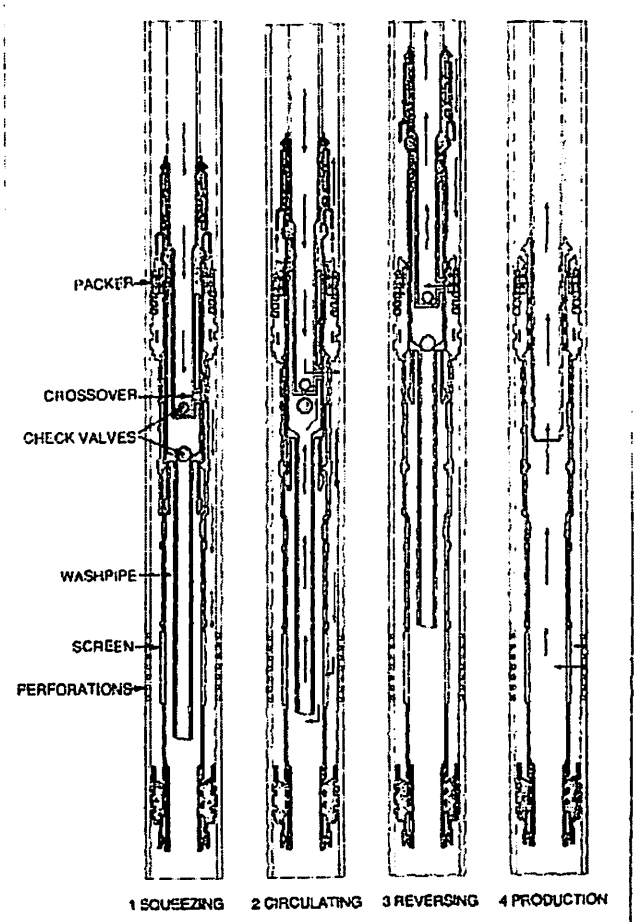


Fig. 8.19—Schematic of a crossover-type gravel pack with sump packer (cased hole).

The primary advantage of the infuser is that the gravel concentration can be conveyed more uniformly and precisely than conventional pot-type sand injectors, yet they have the flexibility to operate over a wide range of gravel concentrations. They also can handle bulk quantities of gravel, an impossible job for pot-type injectors because of their limited capacities. Paddle tanks (Fig. 8.23) are commonly used for mixing slurries. These tanks have either hydraulic or mechanical (or both) mixing capabilities. The mixing can be on either a continuous or a batch basis. Paddle tanks are usually used for mixing slurry-pack fluids. After the fluid is prepared, the gravel is added. Gravel is suspended in the fluid by constant mechanical and/or hydraulic agitation, complemented by the high fluid viscosity. Depending on the fluid viscosity, gravel concentrations in excess of 15 lbm/gal can be mixed in these tanks. A disadvantage of premixing the gravel slurry is that the gravel must be conveyed through pumps before it is transported to the well. This increases the possibility of some disintegration. However, disintegration is not usually a problem. Blenders are modifications of paddle tanks and provide a means of mixing gravel in a fluid stream and pumping it from the tank in a continuous operation despite the small blender volume (5 to 10 bbl). With this capability, premixing of gravel and fluid is not required, but the fluid may require mixing before it is inducted into the blender.

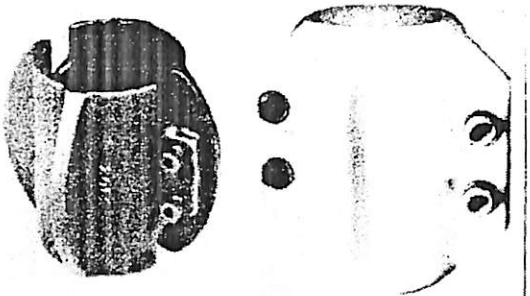
Completion Execution

Gravel-pack execution requires attention to details by personnel knowledgeable in all phases of the operation. This is a key requirement for a properly executed gravel pack. Remember that a gravel pack is nothing more than the installation of a downhole filter. Any operation that prevents or limits the gravel pack's ability to filter fluids effectively or restricts well productivity hampers an effective completion. Before any gravel-pack equipment is run into the well, the completion engineer should be satisfied that the casing

and Workstring are clean; that clean, non damaging workover fluids have been used; and that proper perforating or underreaming practices have been applied.



WELD-ON CENTRALIZERS



ALUMINUM CENTRALIZERS

PLASTIC CENTRALIZERS

Fig. 8.20—Screen centralizers.

Considerable care should be taken during the handling of all gravel-pack equipment. The screens should not be uncared until they are on the rig floor. They should be thoroughly inspected to ensure that they are undamaged and that all specifications have been met. When the screen is being "made up," the operator shoulde careful to avoid damage, particularly allowing the screen to contact the' 'spider," blowout preventers, or other objects on or near the rig floor. The screen should contain centralizers to minimize damage when it is run in the hole and to center it in the completion interval. The entire gravel-pack assembly should meet specific well conditions and should be spaced properly. The screen should overlap the completion interval by a minimum of 5 to 10 ft. The screen and gravel-pack equipment should be run in the well slowly, with the gravel-pack packer set to prevent flow through the screen. This is usually the squeeze position on a crossover-type gravel-pack packer. Excess pipe dope is a source of potential formation damage when combined with particulates. Connections on the workstring do not require pipe dope for the trip to run the screen. If pipe dope is considered absolutely necessary, only the pins should be doped, and those sparingly. Similarly, no equipment run with the gravel-pack assembly should be painted because the paint could peel and cause contamination. Attention to rate and pressure schedules is important during gravel packing. The gravel volumes pumped into the well (and reversed out) should be compared with theoretical volumes. Actual pumped gravel volumes that exceed 100% of the theoretical volume are not uncommon. Gravel volumes significantly lower than the theoretical volume, however, probably indicate ineffective gravel placement,

Usually voids in the gravel pack or settling problems. In these situations, measures should be taken to correct the discrepancy. Sometimes this will require only the cessation of pumping to allow the gravel to settle in the completion interval. In other cases, more sophisticated measures may be required to settle the gravel. Gravelpack washing should not be used to settle gravel or to eliminate voids. This practice is believed to promote gravel/formation-sand mixing.

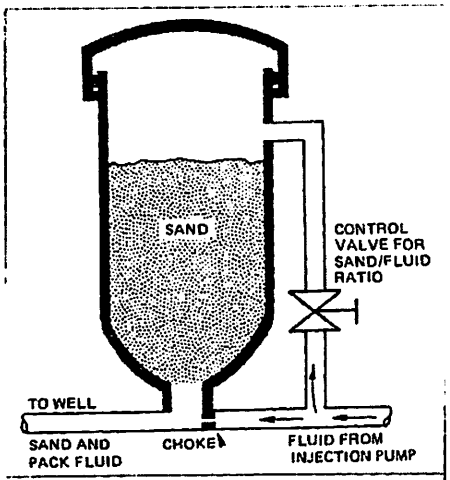


Fig. 8.21—Downstream gravel injection.

Gravel-Pack Evaluation

Several logging techniques have been used to measure the degree of packing in the annular space around the screen. These logging tools are capable of determining the porosity or density of the gravel pack. When they are run after a gravel pack, voids that could lead to completion failure can be identified. If voids are detected, the pack should be settled before the well is produced. In some cases, time will settle the pack, but the effects of gravity and time should not be relied upon. Wireline devices will settle the pack. After repair, the well should be logged again to confirm that the gravel pack has been settled successfully before it is placed on production.

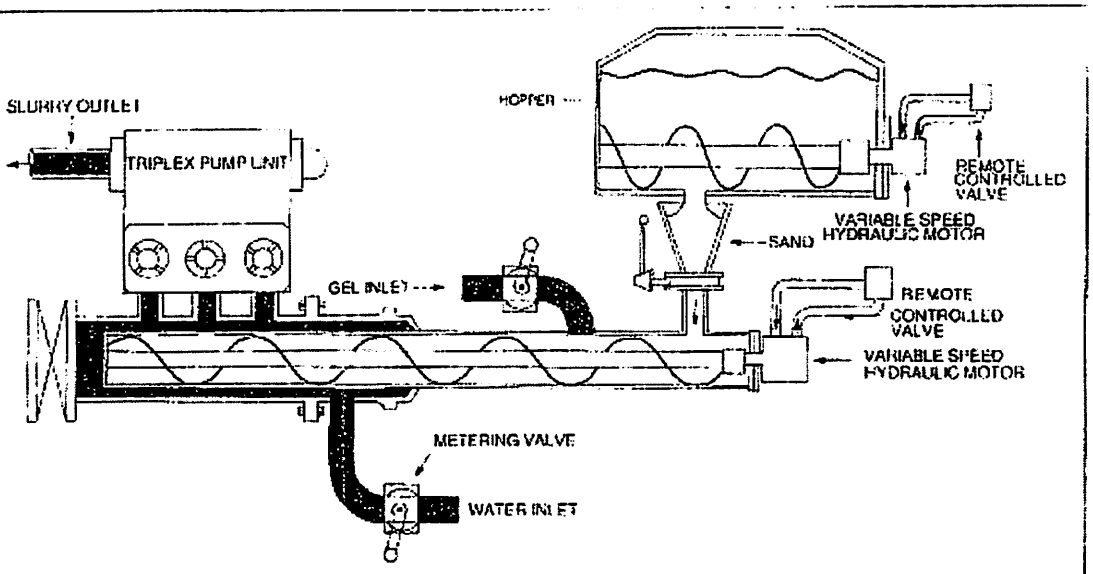


Fig. 8.22—Auger-type gravel injector (courtesy Baker Sand Control).

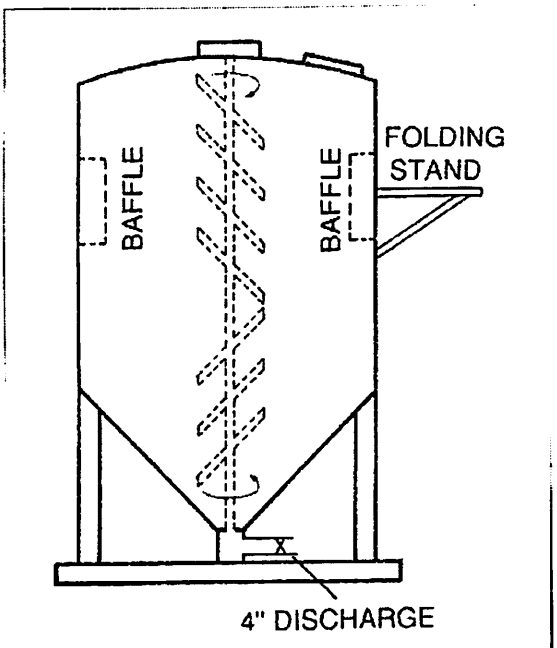


Fig. 8.23—Paddle tank.

Gravel-Pack Vibration

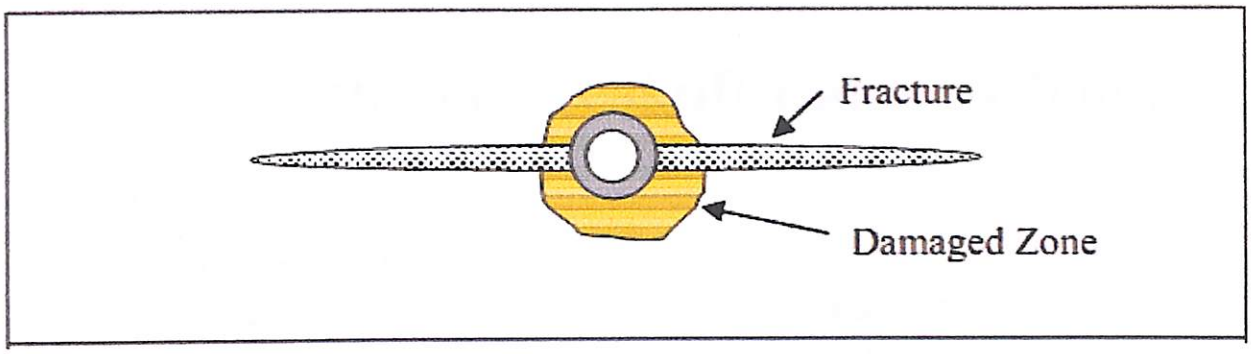
Techniques are available that are claimed to be capable of vibrating the gravel pack to create low pack porosity. These methods impart mechanical energy to the screen or slotted liner during the packing process to rearrange the gravel grains. Gravel-pack vibration is believed to be highly desirable if it can be accomplished under field conditions. Field-scale laboratory tests have demonstrated that low-viscosity fluids pack at a porosity of about 39 to 40%. Vibrating these 20-ft-long gravel packs reduced the porosity to about 35 %. Tests with slurry-pack fluids indicated that they pack at a porosity of 41 to 42 %. Pack vibration before the viscosity was broken indicated that pack settling was slow and that the porosity could not be reduced to a low level without breaking or removing the viscous fluid before vibrating.

TIP SCREEN OUT (TSO)

As was previously mentioned cased-hole gravel packs are one of the most common methods for controlling the production of formation sand in oil and gas wells. While prepacking the perforations helps reduce damage inside the perforation, it does not help with damage outside the perforation. One of the main detriments to Prepacking below fracture pressure is that gravel can only be placed into spaces created during the perforating and perforation cleanup operations. If this amount of penetration into the formation does not extend completely through the near-wellbore damaged zone, restricted well productivity will result. To overcome this difficulty it becomes necessary to remove the damage with acid or bypass the zone in some other manner. Removal of damage by acid is not always possible. Therefore, several techniques have been developed to bypass the damaged zone rather than to attempt to remove it. This is accomplished by hydraulically inducing a fracture through the damaged zone.

In high permeability formation the goal of a hydraulic fracturing treatment is typically to create a short, wide, highly, conductive fracture in order to bypass near well bore damage done in drilling or in completion to ensure good communication between the rock and wellbore and to increase the surface area available for fluids to flow into the wellbore. The most common method of creating short wide fractures is to initiate a tip screen out during the pumping operation. In a TSO the solid concentration becomes so high due to fluid leak off into the formation that the slurry is no longer mobile. The concentrated proppant slurry plugs the fracture and prevents additional fracture growth. Additional pumping of the proppant into the formation after the screen out causes the fracture to grow wider and large conc. of proppant per surface area r placed in the fracture.

FracPack is a general term given to a process that is both a stimulation technique and a sand control method. The term fracpack generally refers to completions that combine a "tip screen out" (TSO) hydraulic fracture stimulation, which is now usually pumped with a gravel pack (GP) screen and packer assembly in place. The TSO creates a short, highly conductive fracture that is designed to by-pass near wellbore damage, and provides a small degree of stimulation.



Thus the gravel pack sand also functions as a proppant. The fractures are normally in the 25- to 50-ft range in length. The pump rates are typically in the range of 15 – 25 bpm and proppant loading is ramped from very low concentrations up to 12 to 15 ppa. The total amount of gravel pumped is typically in excess of 900 lbs/ft.

There were very few fracpacks conducted before 1990, but this is now a very common completion technique for unconsolidated sands worldwide. There were still only about 200 fracpacks placed worldwide in 1993.

FracPacks were initially developed as a method of achieving sand control, while reducing the amount of skin damage usually associated with a conventional gravel pack. Typical gravel pack completions in cased wells usually have skins in the order of 8 to 25, especially when placed with a gel carrier fluid. This means that the well productivity is reduced by more than a factor of two. Even open-hole gravel packs usually exhibit positive skins, as do cased wells pumped with high-rate water packs. Thus, short fractures placed in the wells are a method to improve productivity and longevity compared with other types of conventional gravel packs.

Since fracpacks are placed in unconsolidated sands with a TSO design, the fractures are much wider than conventional hard rock fractures. Fracture widths range from a few tenths of an inch to a few inches wide at the wellbore. The increase in effective wellbore radius effectively bypasses any positive skin. Thus, the fracture also simultaneously furnishes a degree of stimulation, with some operators reporting as much as a five-fold increase in average production compared to gravel-packed wells. Another very important aspect of this completion method is that the fracpack also reduces the problem of fines migration because of the reduced flow velocities across the formation/gravel interface.

Unfortunately, placing a fracpack is much more difficult than placing a conventional gravel pack. A fracturing simulator must be used to design the application, and even then it is necessary to make refinements for subsequent wells after the data is obtained from the first well to be fracpacked in a new zone.

Figure 1.2

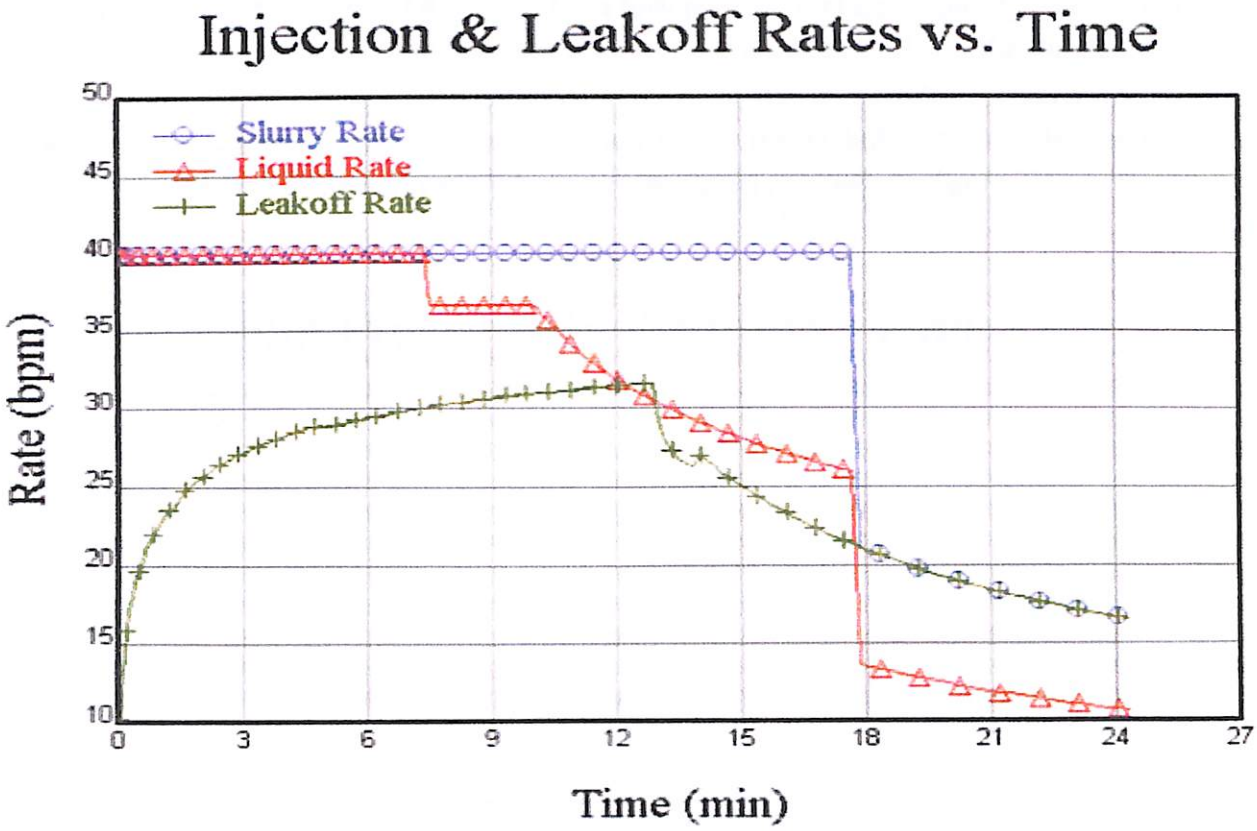
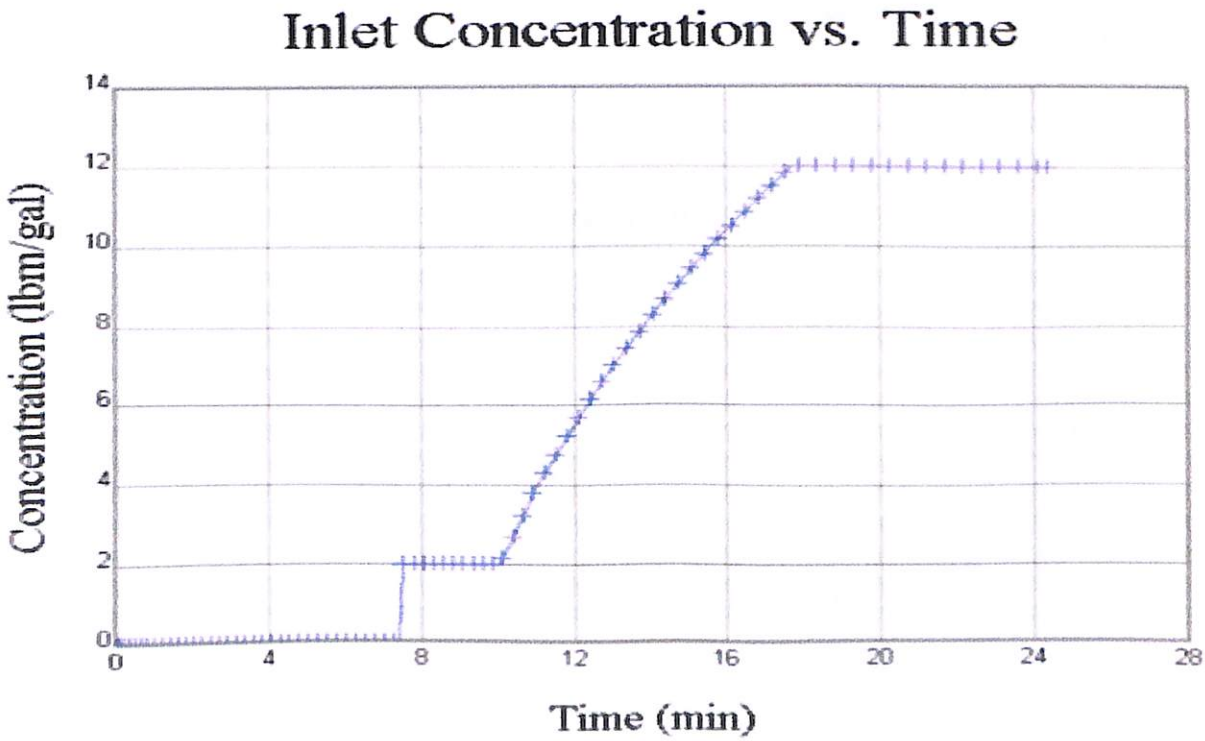


Figure 1.3



Once the design fracture length is achieved at about 13 minutes fracture extension (length and height) stops as a result of the tip screen-out condition (Figure 1.4). The fracture

continues to balloon from 13 to 17.5 minutes to a width of about 1.3 in. (Figure I.5) to meet the design concentration/area of 9 lbm/ft^2 for a fully packed fracture. Figure I.2 shows that once the fracture stops propagating the leakoff rate decreases. Also, the liquid rate decreases with increasing inlet sand concentration. After the slurry rate decreases to the leakoff rate at tc_{max} the liquid injection rate falls below the leakoff rate. The higher the maximum allowable inlet concentration the lower the liquid rate wills be figure

Figure 1.4

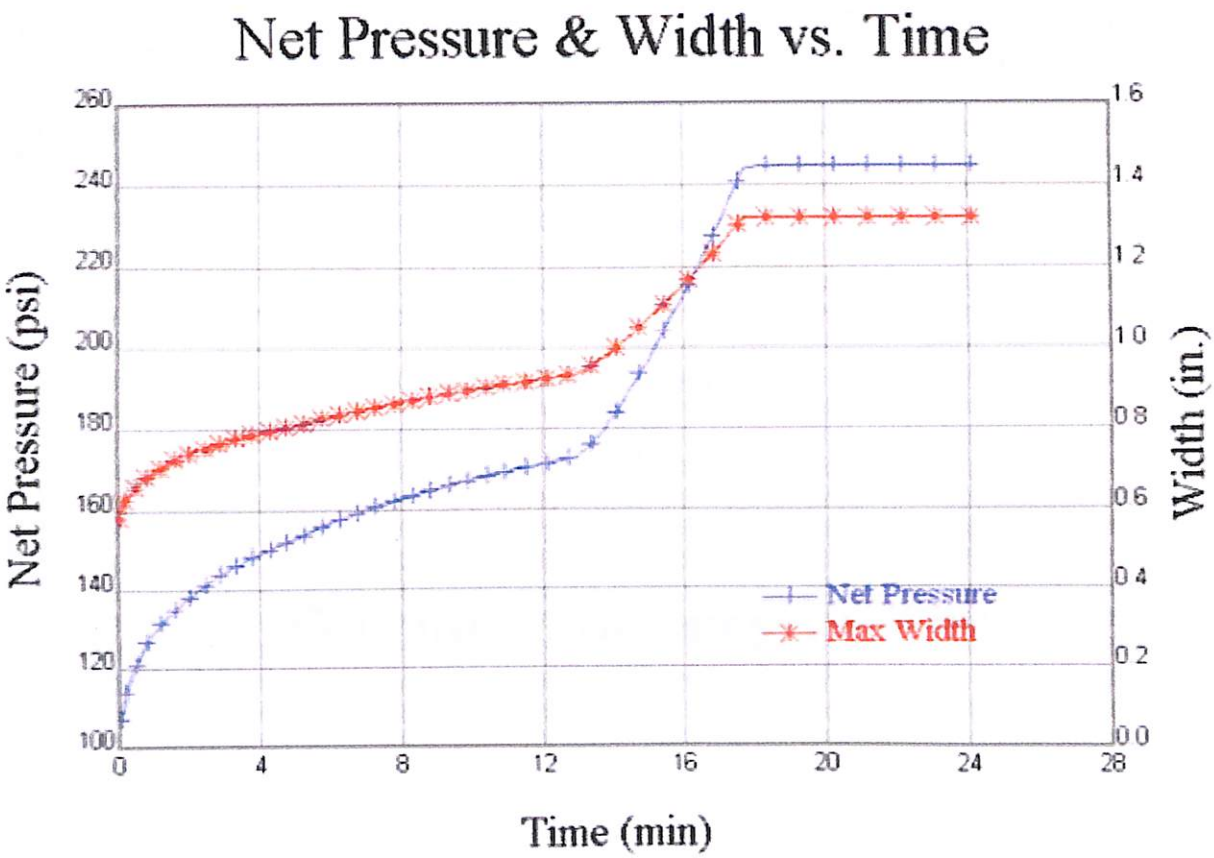


Figure 1.5

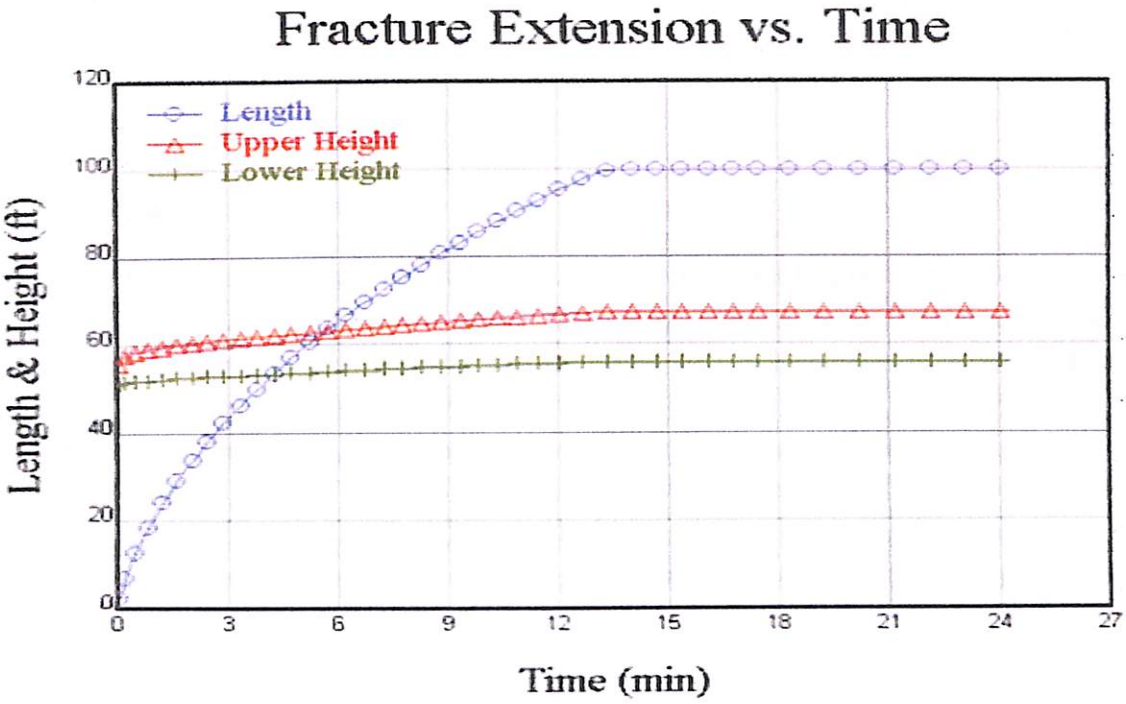


Figure 1.6

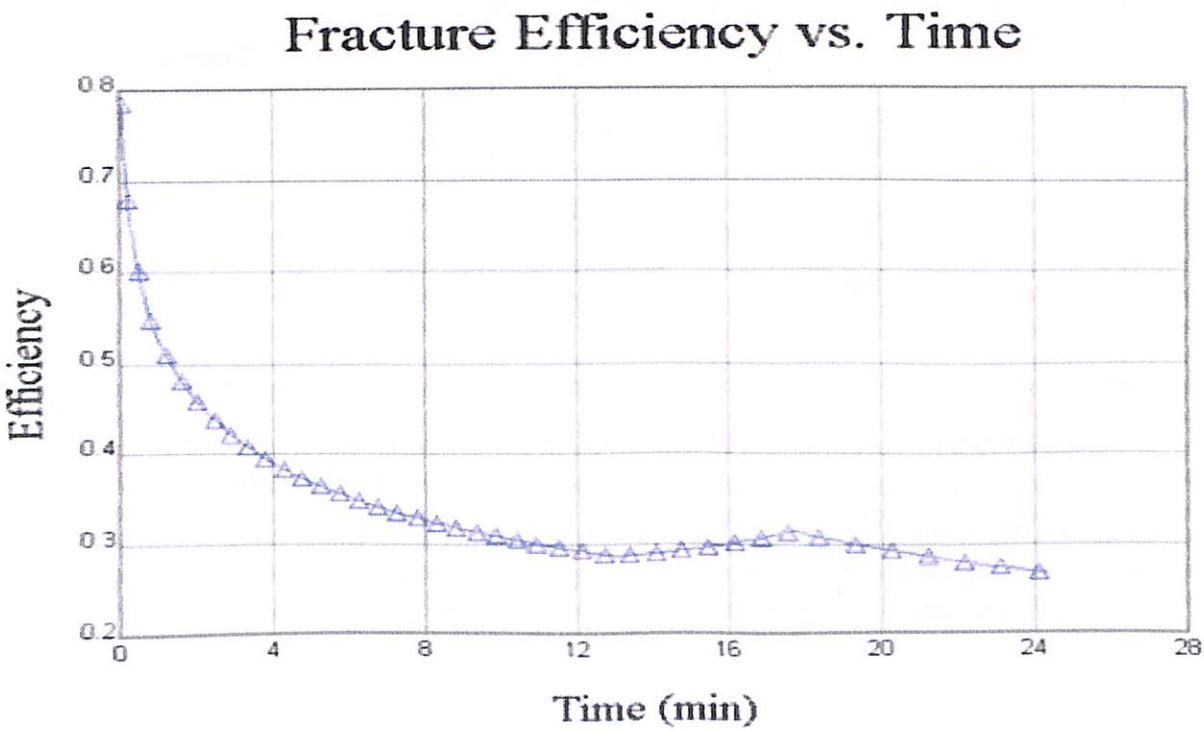
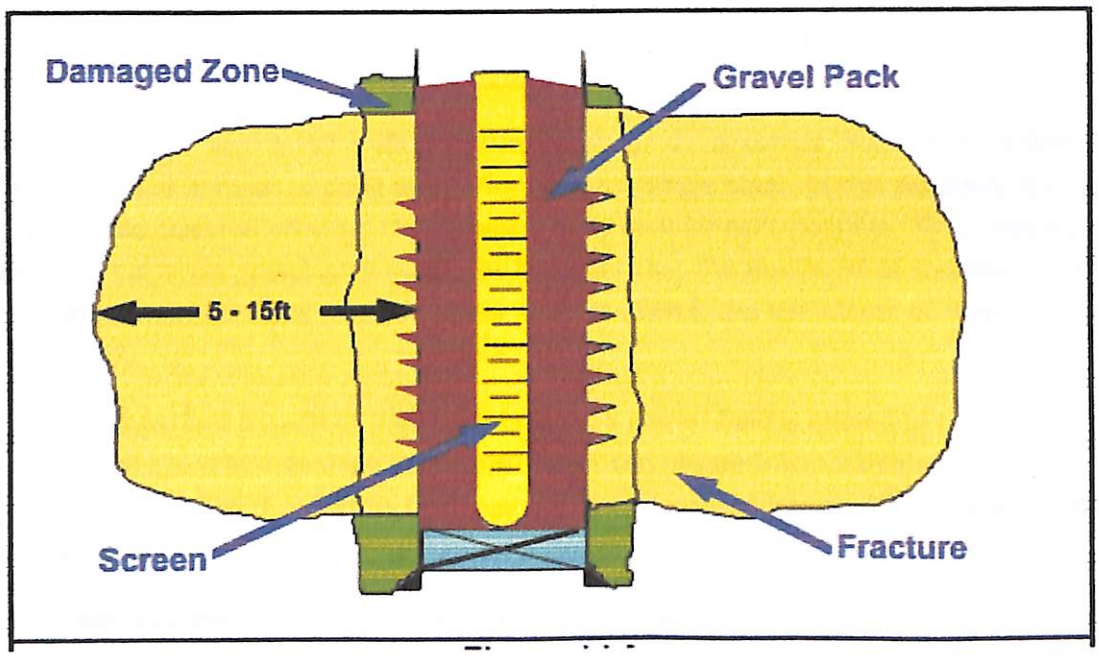


Figure 1.6 shows the behavior of fracture efficiency as a function of time. After the propagation rate diminishes at 13 minutes the efficiency rises as a result of the decreased leakoff rate. However, once the injection rate decreases to the leakoff rate the fracture

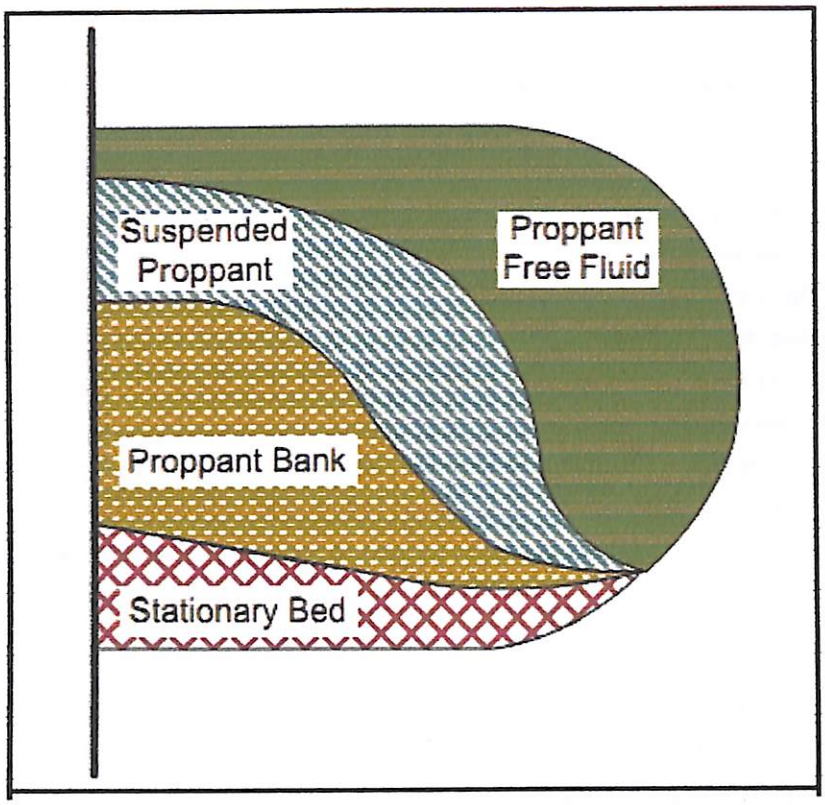
volume remains approximately constant (i.e., the compliance factor may, however, change slightly with time) and the efficiency will continue decreasing until the fracture is fully packed. The fracture efficiency at closure represents the fraction of propped volume to total injected slurry volume

WATER FRAC

Another technique that is similar to a conventional fracpack is a technique developed by Baker Oil Tools, and is called the H2O-FRAQ process. This is similar to a fracpack, but is placed with clear brine instead of a gel. A fracture with a length between 5 and 15 ft is created with a low-viscosity (brine) carrier fluid. Pump rates are higher than conventional gravel packing operations, but usually lower than for a frac-pack. Typical pump rates are in the range of 8 to 12 bpm. Proppant loading is held constant between 1 and 2 ppa, and total job size is typically from 100 to 150 lbs/ft. These treatments can be multi-staged to further enhance the ability to effectively treat several sand subintervals with a single treatment



Water as a Carrier Fluid -In conjunction with creating a short fracture, it is also necessary to place the proppant close to the wellbore, and not carry it deeply into the fracture. A good method to accomplish this is to use a low-viscosity fluid, such as water, to carry the proppant. The lack of viscosity causes the proppant to be deposited by the formation of an equilibrium bank, thus resulting in most of the proppant being concentrated very close to the wellbore.



Another benefit associated with the use of water as a carrier fluid arises when the prepacking and annular packing are performed as a single step. In this situation, it is vital that the fluid selected provides the highest quality annular pack possible. Since research in the Baker Oil Tools gravel pack simulator indicates that the likelihood of creating a void is much greater when using a viscous fluid to carry gravel, the usefulness of water is again highlighted.

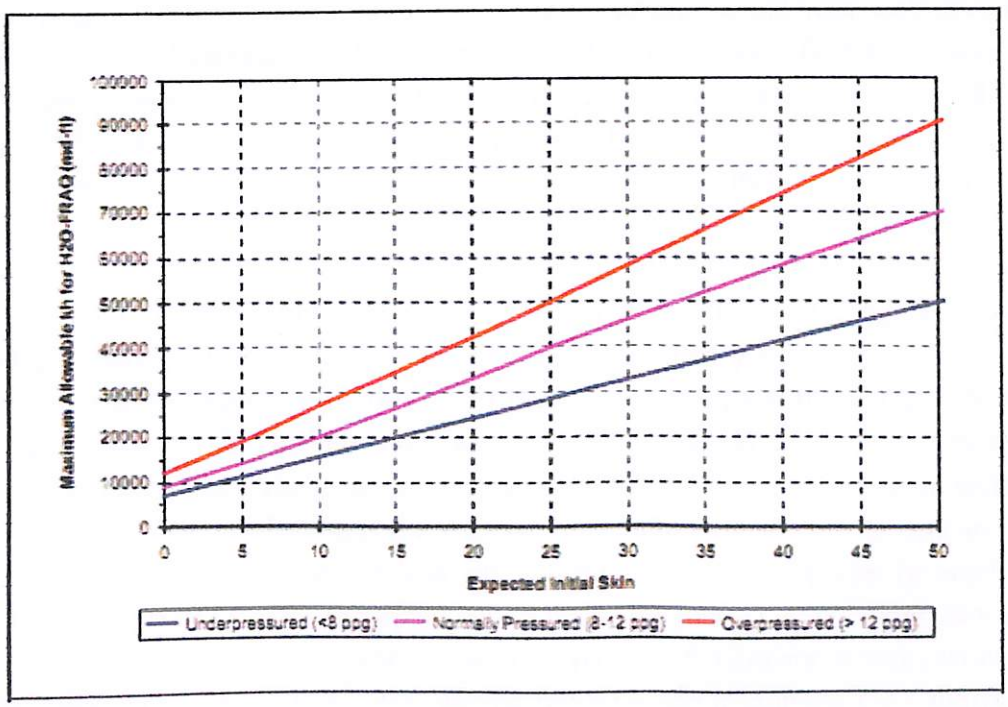
The third important benefit of the use of brine as a carrier fluid is related to the elimination of several of the major damage mechanisms that can plague frac-pack completions. Wong et. al have identified four factors that may lead to a damaged frac-pack completion. These four factors are:

- The fracture skin (related to fracture conductivity)
- Perforation skin (related to the proppant permeability as well as the total area available for flow)
- The choked fracture skin (related to a reduction of fracture width in the immediate near-wellbore area)
- The fluid leak off skin (related to the formation damage imposed due to the leak off of the high-viscosity fracturing fluids).

Of these four damage mechanisms, use of brine as a carrier fluid can eliminate (or significantly reduce) the fracture skin, the choked fracture skin, and fluid leak off damage.

Fracture skin is eliminated by avoiding proppant permeability reductions caused by gel residue. The lack of gels also greatly reduces the formation damage along the fracture face. Finally, the elimination of the choked fracture effect relates to how frac-pack treatments are often pumped. Since frac-packs are usually pumped with the gravel pack assembly in place, it is critical that no voids remain in the screen/casing annulus at the end of pumping. However the use of gelled fluids results in a high probability that voids will be created. To remedy these voids, the pressure is rapidly bled off of the annulus at the conclusion of pumping; in hopes of bring proppant into the wellbore from the fracture to fills voids. For this to occur, the fracture width in the near-wellbore vicinity must be reduced, thus leading to a choked fracture. When brine is used as a carrier fluid, the risk of creating voids in the screen/casing annulus is virtually eliminated. Therefore, there is no need to surge proppant into the wellbore from the fracture. In addition, the equilibrium bank transport mechanism present with low-viscosity carrier fluids concentrates the proppant close to the wellbore, further reducing the choking effect.

Another issue that must be addressed when determining where an H2O-FRAQ treatment is applicable is the ability to fracture the formation with brine at an injection rate available with rig-based pumping equipment. Factors controlling our ability to fracture the formation with brine include: formation permeability, interval length, degree of formation damage, reservoir pore pressure, and reservoir fluid viscosity and compressibility.



(Maximum Allowable kh For Each Sand Subinterval that can be Fractured at 10 BPM at a given Value for Estimated Initial Skin)

Findings based on the results presented in figure above are

1. If the kh of the formation (or the kh of any single sand layer in an interval consisting of multiple sands) is less than 15,000 md-ft, a fracture can easily be created with brine. Therefore, any near-wellbore formation damage can be bypassed equally well with either a H2O-FRAQ or a frac-pack.

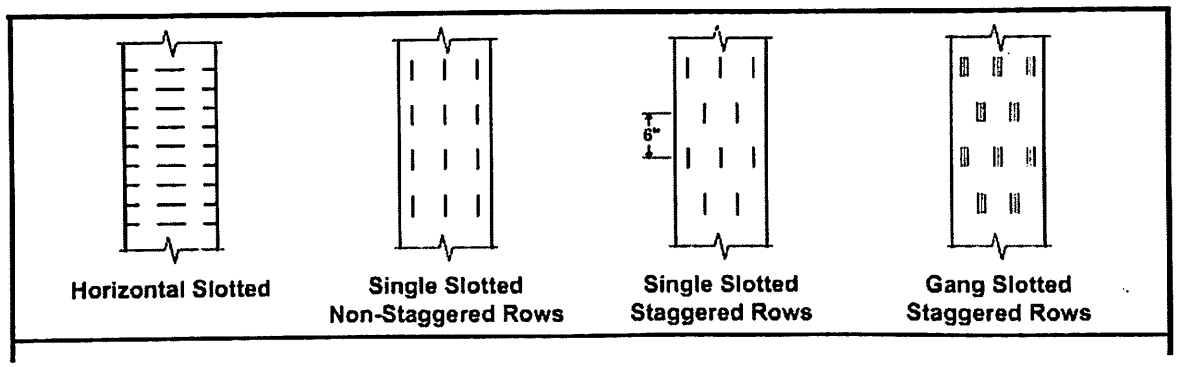
2. If the formation kh increases to a value between 15,000 md-ft and 40,000 md-ft, it begins to become more difficult to fracture the formation with brine. For formations of this conductivity the H2O-FRAQ will still be applicable as long as a skin of at least 5 to 25 is present. This moderate level of formation damage might be expected if the well is a new completion drilled with a conventional drilling fluid. If reservoir kh exceeds 15,000 md-ft, and the formation is relatively undamaged (skin less than 5, as would be typical for a well drilled with a specially selected drill-in fluid), this formation would not be able to be fractured with brine. However, because of the low amount of formation damage, the need for any type of fracture to bypass this damage is questionable. Therefore, it is recommended that an H2O-PAQ, possibly preceded by an acid prepack (either non-diverted, or using foam or sand as the diversion material) should be successful at removing the small amount of damage that may be present, thus resulting in a highly-efficient completion.

3. If formation kh exceeds 40,000 md-ft, the well will need to be highly damaged to allow fracturing with brine. Therefore, for the situation where an old well with severe near wellbore formation damage is to be worked over, either an H2O-FRAQ or a frac-pack should successfully bypass this damage. For the H2O-FRAQ, the reduced permeability will provide the leak off control while the fracture is propagating through the damaged zone. Once the fracture extends beyond the damage, the leak off rate will increase, and fracture propagation will cease. Therefore, an H2O-FRAQ should be successful at placing gravel pack sand through the damage zone, but not too far beyond. However, for a highly permeable formation, this would be sufficient. If a high kh formation is to be completed, which is expected to have only a moderate amount of damage, it may prove difficult to create a fracture with brine. However, there would still be a need to bypass this damage; therefore, a frac-pack would be the recommended treatment. Formation kh and skin are not the only factors that control the ability to fracture a formation with brine. Another factor that affects the leak off rate of brine is the viscosity and compressibility of the reservoir fluids. For high-viscosity crudes, natural leak off control is provided by the reservoir fluids themselves. Therefore, even for very high kh wells, H2O-FRAQ completions can be very successful in situations where the reservoir fluids have an API gravity of approximately 20º or less. Again, benefits of H2O-FRAQ will be strengthened if multiple sand subzones are present in the overall interval.

EXPANDABLE SAND SCREENS

Slotted Liners

Slotted liners are used in gravel packed completions to prevent the production of gravel pack sand or can be used in stand-alone service when the formation grain size is uniform and large. Slot widths are often referred to in terms of "gage" or "gauge". Slot or screen gage is simply the width of the opening in inches multiplied by a 1,000. For instance, a 12-gage screen has openings of 0.012 inches. Slotted liners are manufactured by machining slot openings through oil-field tubulars with small rotary saws. Slotted liners are fabricated in a variety of patterns. The minimum slot width that can be achieved is about 0.012 inches; however, slot widths cut below 0.030-inches involve higher costs because of excessive machine down time to replace broken saw blades that become overheated, warped and break. While the slotted liners are usually less costly than wire-wrapped screens, they usually have a smaller inflow area and will therefore experience higher pressure drops during production. Slotted liners also plug more readily than screens. They are normally used where well productivity is low and economics cannot support the use of screens.



Slotted liner geometries

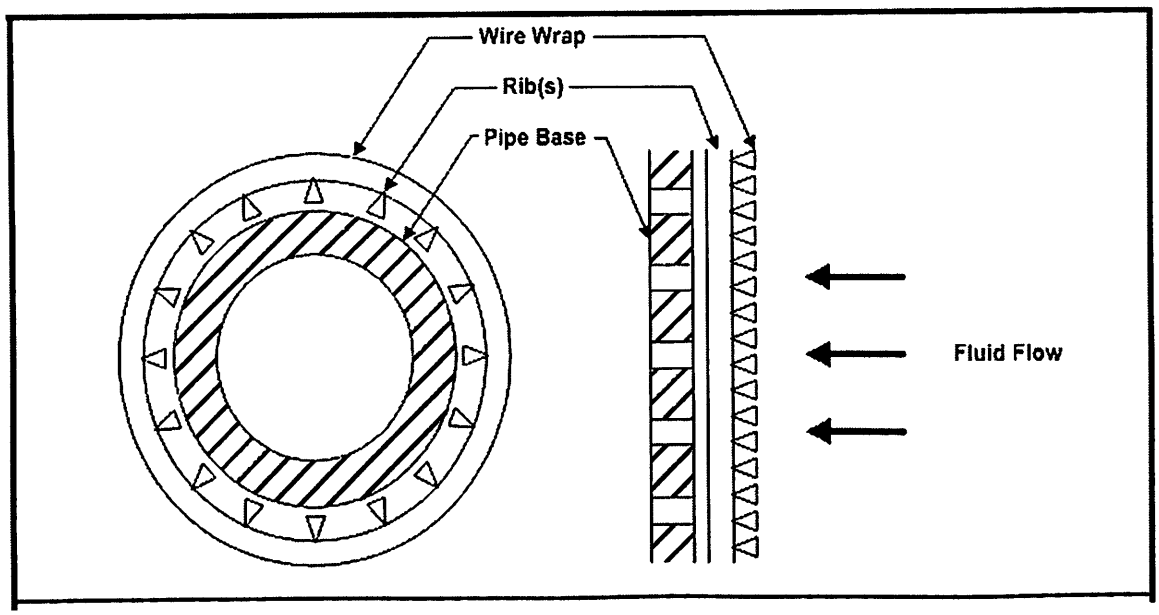
The length of the individual slots is gauged on the ID of the pipe. Usual practice dictates 1½ inch long slots for slot widths 0.030" and under, 2 inch long slots for slot widths between 0.030 to 0.060 inches and 2½ inch long slots for slot widths 0.060 inches and larger.The primary advantage of slotted liners over wire-wrapped screens is usually cost; however, certain slotting geometries may cost almost as much as wire-wrapped screens. The disadvantages of slotted liners are limited flow area (creating a low tolerance to plugging) and minimum available slot size (approximately 0.012 inches). The practical minimum slot size is about 0.020-inch widths compared to 0.006 inches for wire-wrapped screen. In slot sizes less than 0.020 inches, the saw blades are thin and blade breakage increases. Increased blade breakage adds time and cost to the manufacturing process. The broken blades often wedge in the slot interfering with the available flow area. Another potential problem with slot widths less than 0.020 inches cut in standard carbon steel pipe grades is

that corrosion products that may close the slots. Also, in some cases, corrosion opens the slot width so that the liner does not control sand.

SCREENS

Wire wrapped screens

Wire-wrapped screens offer another alternative for retaining the gravel in an annular ring between the screen and the formation. The advantage of a wire-wrapped screen over a slotted liner is substantially more inflow area. The screen consists of an outer jacket that is fabricated on special wrapping machines that resemble a lathe. The wire wrap is simultaneously wrapped and welded to longitudinal rods to form a single helical slot. The jacket is subsequently placed over and welded at each end to a supporting pipe base (containing drilled holes) to provide structural support. This standard design is generic and is manufactured by several companies.

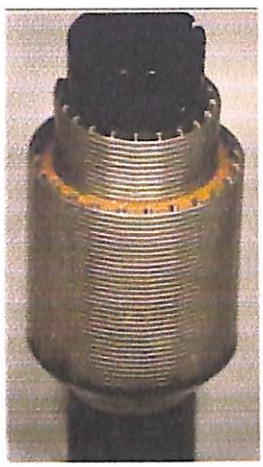


Rod based screen

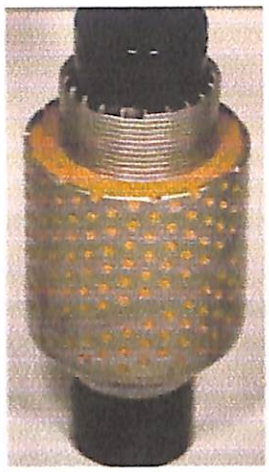
A version of the wire-wrapped screen is the rod-based screen which consists of the jacket only however, rod-based screens may have additional, heavier rods and a heavier wire wrap than the jackets used on pipe base screens to provide additional strength. Rod-based screens are commonly used in shallow water-well completions that typically range from a few hundred to maybe a thousand feet in depth. Water wells are almost always drilled vertically. Hence, they do not require the strength that is gained by installing the screen jacket over a pipe base.

Prepacked screens

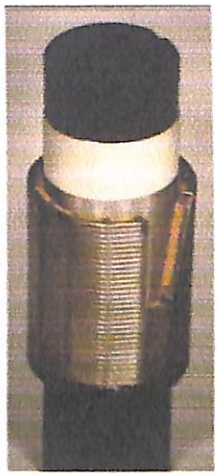
Prepacked screens are a modification of existing wire-wrapped screens and represent a modular gravel pack. They consist of a standard screen assembly with a layer of resin-coated gravel (consolidated) placed around it which is contained in an annular ring supported by a second screen (dual-screen prepack) or outer shroud (single-screen prepack). The thickness of the gravel layer can be varied to meet special needs. The screens with the lowest profiles are those which contain an annular pack between the jacket and the pipe base which has a thin lattice screen wrapped around it to prevent gravel from flowing through the drill holes in the pipe base prior to consolidation (SLIM-PAK™). They have been used in conjunction with gravel packs instead of a wire-wrapped screen in addition to being used as standalone applications in horizontal wells.



Dual-Screen Prepack



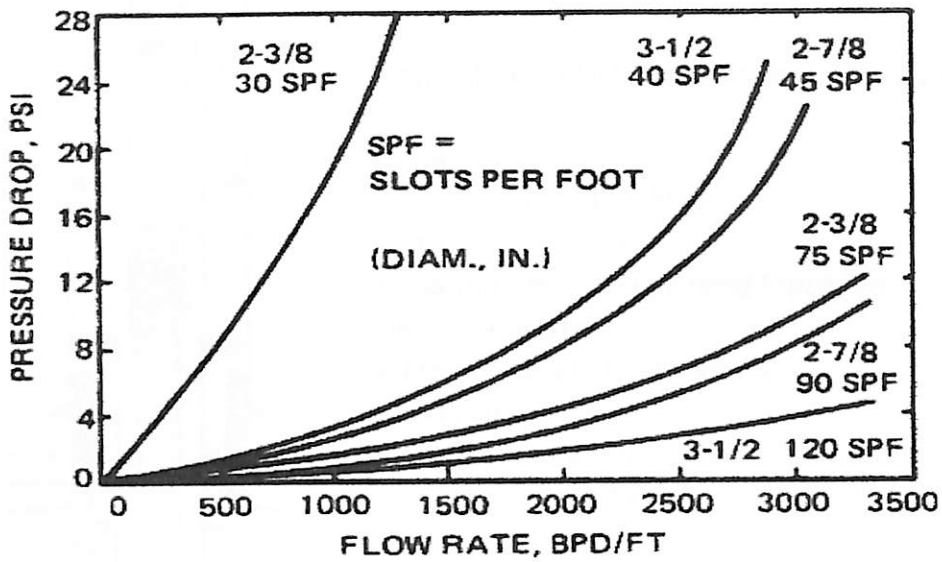
Single-Screen Prepack



SLIM-PAK™

Flow capacity of screen and liners

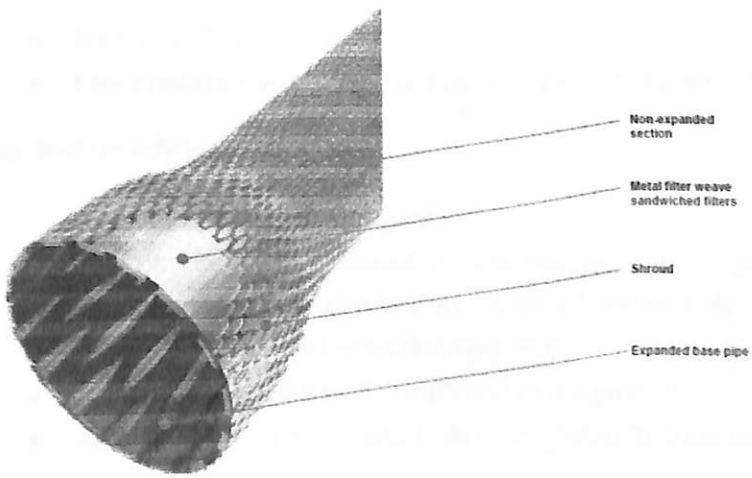
The flow capacity tests were performed using water containing no plugging material. The data indicate that all screens have exceptionally high flow capacities. Flow testing with slotted liners revealed that their flow capacity was related to the slot density rather than the screen diameter . Note that the flow rates were measured in increments of barrel/day/ft of screen or slotted liner. For flow rates that are typical of most wells, the pressure loss through the screen is negligible provided that they do not plug. Testing has demonstrated that slotted liners are more easily plugged than wire-wrapped screens since the slots are usually cut parallel. On the other hand wire-wrapped screens are fabricated with keystone-shaped wire that allows a particle to pass through the screen if it can traverse the minimum restriction at the OD of the screen.

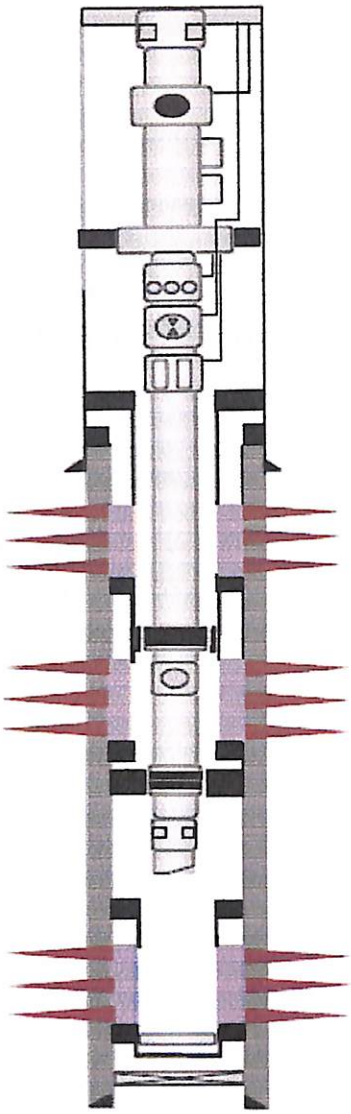


EXPANDABLES SAND SCREENS (ESS)

ESS is an alternative sand control solution to gravel packing because it eliminates the open annular between the wellbore and the screens and hence the need to gravel pack. This removes the risk of not achieving a complete a gravel pack. It also eliminates the cross flow along the open annulus, which may lead to hot spots and erosion. The ESS also provides wellbore stabilization due to the post expansion ESS directly support the wellbore. The properly sized filter media will retain the formation sand particle form production.

In comparison with wells completed with OHGP's, ESS installation show more uniform downward and inflow profiles. Consequently ESS installations are less prone to coning problems at the heel, and improve reservoir drainage through better flow contribution at the toe of the well.





A typical Expandable Sand Screen assembly comprises of the
Following:

1. ESS Deployment Packer
2. Space-Out Blank pipe
3. ESS Top Sub X-Over (housing Expansion Cone Assembly)
4. ESS Expandable Top Connector
5. ESS Joints
6. ESS Expandable Bottom Connector
7. ESS Bottom Sub X-Over
8. Blank Bull Nose or Landing Nipple

ESS ADVANTAGES AND DISADVANTAGES

The expandable sand control system is an alternative sand control method, which can be used for vertical, deviated, horizontal, and multi-lateral well installations. Generally the ess has the following advantages and disadvantages.

WELL PERFORMANCE ADVANTAGES

- Improve the well production rate and productivity.
- Reduce the well drawdown and postpone the early water/gas coning.
- Enhance the hydrocarbon recovery and reservoir management.
- Eliminate the annulus flow and maintain wellbore stability
- No ESS moke/up losses
- More resistance to plugging due to larger open area to flow.

Application Advantages:

- Allow deeper and chaper wells.
- Allow wells to be reduced in size without loss in productivity. Smaller wells are generally less expensive to drill, construct and complete.
- Be compatible with both OBM and WBM
- Allow more flexible well design and management.
- Allow both open and cased hole in single/multi-zone completions.

Operational Advantages:

- Posses operational simplicity
- Larger ID gives fullbore access to lower reservoir zones.
- Better workover / interventions due to large base pipe ID after expansion.
- Tolerates variable gauge hole.

ESS Disadvantages:

- ESS in not designed for high torque which means no rotation is recommended while running ESS string to the depth.
- Minimum weight on bit is required for the expansion and thus heavy weight drill pipe / drill collars may be required for some ESS installations

SOUTH KADI FIELD SAND CONTROL MEASURES

Description of South Kadi Field

South Kadi field is located about 50 KM North West of Ahmedabad town in alluvial plains of Gujarat State and in Mehsana – Ahmedabad block of Cambay basin. It belongs to Area-III of Asset. It was discovered in Feb'68 and was put on regular production (@ 58m3/day through well SK#4 at reservoir pressure 362.5 kg/ cm2) in Aug '68. The permeability of these sands is in medium to high range. The crude oil is light in nature with bottom hole temperature varies from 90 to 115 degree. The oil has viscosity at reservoir conditions 0.9- 1.1 cp , specific gravity of 31-39 degree API.

SAND PRODUCTION HISTORY

The beginning & extent of sand production from the individual wells in South Kadi field is difficult to judge as no record of sand production is available. it is believed that sand in traces might have been producing since early production life of the field, which went unreported and the sand cut could be realized only when its production becomes severe. The first reported case was in early in 1988. Sand had been cleaned in several wells from well bottom during work over. A good number of wells resulted in poor influx due to sand incursion and thereafter the wells were put on SRP.

Probable Reasons of Sand Incursion in South Kadi are given below:

- Partially consolidated sand
- Injection water break through
- High withdrawal rate

The reservoir rock matrix in south kadi field is partially consolidated .The sandstone is possessing low percentage of cementing agent which is mainly constituted of carbonaceous and calcareous matters. Chlorite is the predominant clay mineral with low concentration of Kaolinite & Illite. All these clays are migratory in nature and with increase in water encroachment the clay matrix gets loosened and disintegrated thereby making sand & clay mobile.

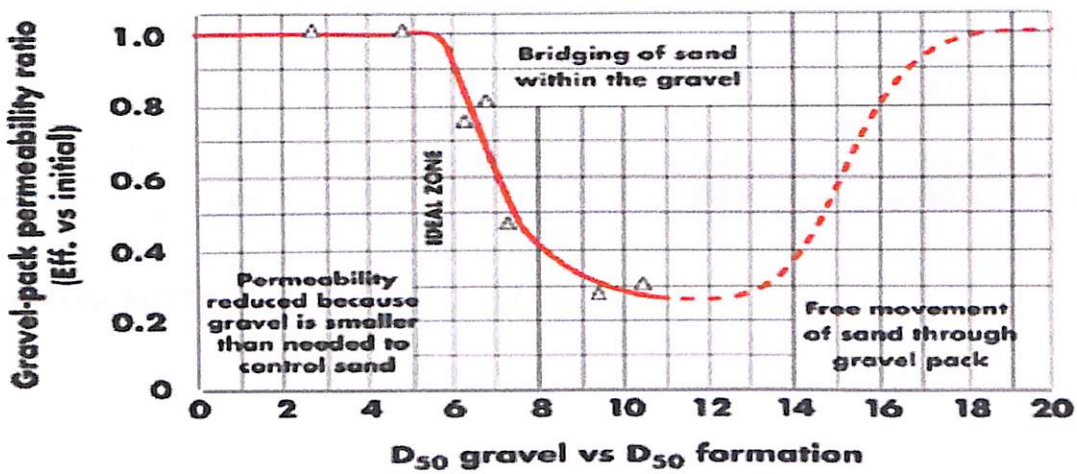
The Primary objectives of any sand control job are:

- Preventing formation sand production
- Achieving high productivity
- Providing completion longevity

CASE STUDIES ON GRAVEL PACK

In 1998, the Gravel packing was employed as a standard means of sand control in South Kadi Field. High and low density slurry packs with Gravel have been used. As on date, a total of 09 wells were gravel packed. The well SK#147 landed in complication after G.P. completion in May, 2009 as the well did not produce on SRP and just after 2 days of operation , SRP was stuck up. Finally the GP assembly was retrieved in July 2009 and repacked. The other wells which were gravel packed after the sand problem are also facing problems. It is anticipated that lot of sand might have already produced from these wells making cavities / channel behind casing. Initially, the gravel pack completion has sustained the liquid rate without any sand production for several years.

SELECTION OF GRAVEL SIZE



Graph-1: Effect of Gravel-Sand ratio on gravel-pack permeability.

The D50 is multiplied by a factor of 4 to obtain the smallest size of gravel and by 8 to obtain the largest size of the gravel. The size selected on this basis will provide good pack permeability and stop the movement of formation particle.

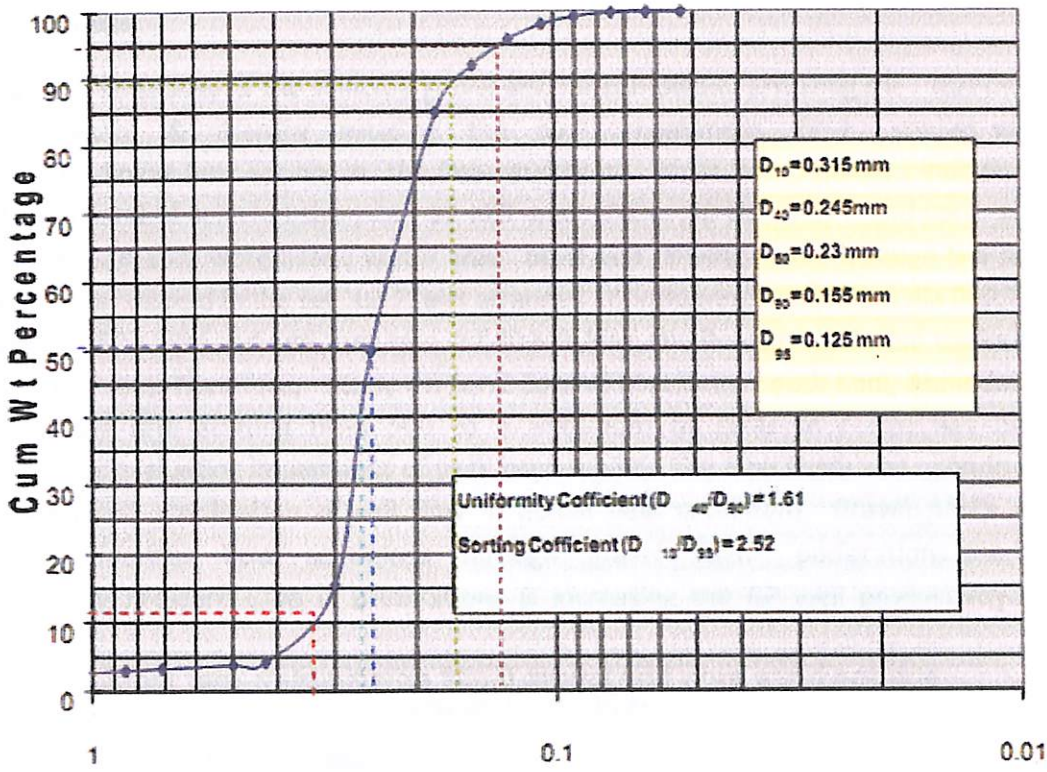
SIEVE ANALYSIS

IOGPT has carried out the sand grain analysis of the produced sand from SK#147 and core sand sample from SK#102 by dry sieve analysis to select commercially available gravel. 100 grams of sample is analyzed for sand grain size distribution by dry sieving technique using standard set of test sieves. The sieves are stacked coarser to finer from top to bottom with pan at bottom on 3-D imported sieve shaker.

Sl. No	ASTM sieve NO.	Equivalent mesh size in micron	% Retention (w/w)	Cumulative weight percentage
1	16	1180	2.55	2.55
2	20	850	0.41	2.96
3	25	710	0.32	3.26
4	35	500	0.50	3.78
5	40	425	0.42	4.20
6	50	300	11.32	15.52
7	60	250	34.09	49.61
8	80	180	35.31	84.92
9	100	150	6.92	91.84
10	120	125	3.88	95.72
11	140	106	2.26	97.98
12	170	90	1.18	99.16
13	200	75	0.57	99.73
14	230	63	0.11	99.84
15	270	53	0.03	99.87
16	325	45	0.13	100.00
17	pan	--	0.00	100.0

Table : Sieve analysis of produced sand from SK well # 122

SIEVE ANALYSIS OF PRODUCED SAND OF SK#122



As per above saucier Graph, D/50: 0.23 mm

Minimum gravel size (D/50X4): 0.92 mm

Maximum gravel size (D/50 X8): 1.84 mm

Corresponding gravel size: -14 +20 US mesh

Commercial gravel size: -12 +20 US mesh

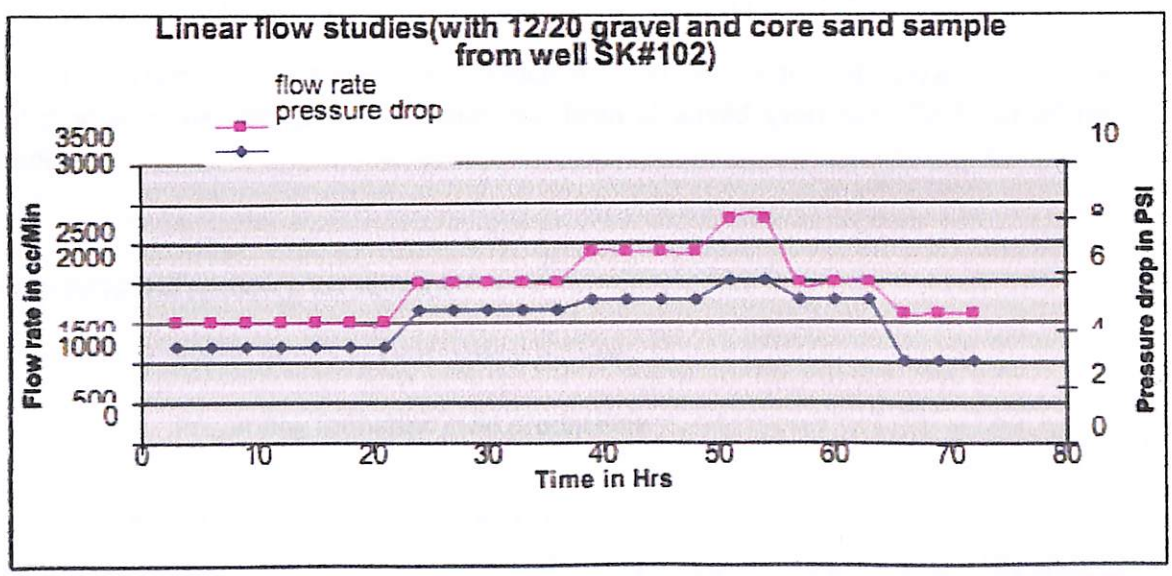
From these sieve analysis of produced sand samples, the D10, D50 Sorting and Uniformity Co-efficient etc. were determined. It is also observed that there is negligible fine content (sand size below 100 µm is almost nil). However, in actual condition there is every possibility of the presence of fines and clays in the reservoir core sands. Collected sample / test report may not be true representative of the sand size distribution of the reservoir sand.

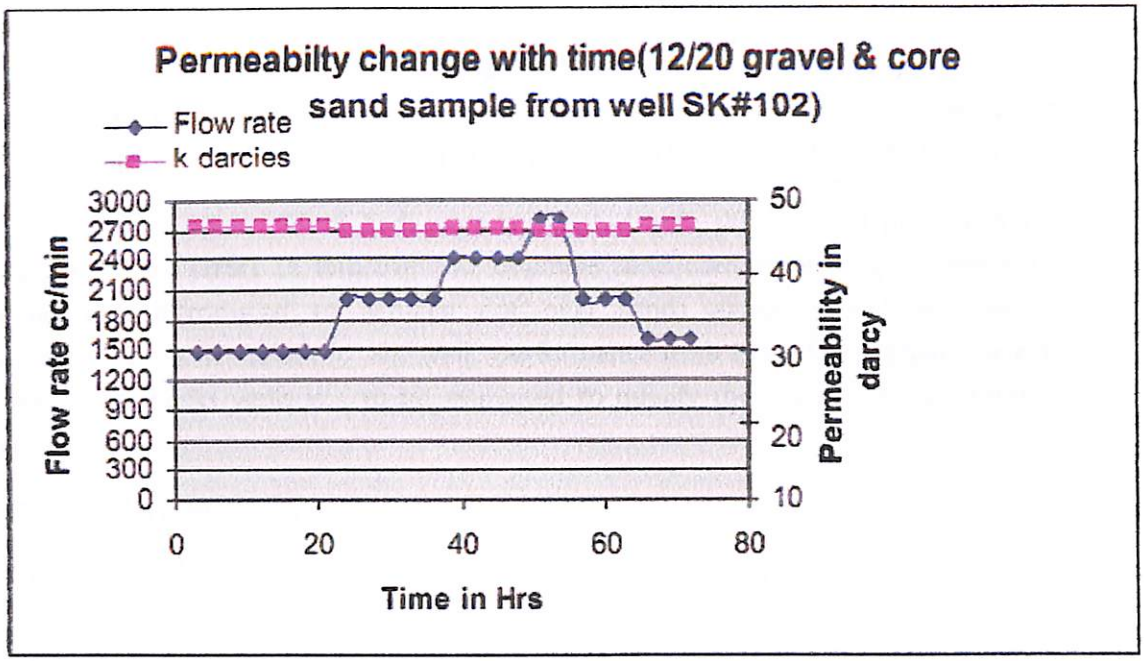
Conclusion

Considering all the aspects, gravel pack seems to be the right choice for sand control in South Kadi Field. The experience of gravel packs in earlier 9 wells in the South Kadi field is also evident of the technical feasibility of the technique in the field.. The results of sieve analysis show that 12 / 20 gravel is suitable for arresting sand. The produced sand samples

are not true representative samples and during washing of sand sample low clay content was observed. Hence, it is recommended to go for GP with 12/20 US mesh gravel and 24 gauge screen size.

To ensure the suitability of the selected gravel size for completely arresting the formation sand movement & thereby avoiding the pack impairment, flow studies were conducted in linear flow set up. In the flow studies on linear flow model , indigenous natural silica sand of selected size , i.e. -12 +20 and -20 + 40 U.S. mesh and core sand sample from SK# 102 were used.. Water was used as a flowing media through the pack The Sample was packed in the set up & was arranged. Considering perforation dia 0f 0.75", shot density of 36 SPM and well flow rate of 40 M3 /day, the flow per cm2 area works out to be 140 cc / min. Therefore, Study On Sand Control Measures, South Kadi, Ahmedabad Asset36 flow rate starting from 500 to a maximum of 2800 cc / min has been maintained for evaluating impairment of pack permeability. The flow study was continued for 72 hrs (until stabilization of well flow in actual field condition). Gravel packs aim to achieve laminar flow conditions through gravel filled perforations thereby minimizing the pressure drop in perforations & increasing the GP well productivity.





Graphs have been plotted to show pack permeability behavior with time.

In the graphs, no permeability reduction , in the pack of 12/20 and 20.40 indigenous gravel with formation sand, has been observed even after 72 hours of flow studies.

HIGH RATE WATER PACK TECHNIQUE

The Primary objectives of any sand control job are:

- Preventing formation sand production
- Achieving high productivity
- Providing completion longevity

Gravel pack procedures were developed in the mid 1930's and subsequently optimized to increase the well productivity. More recently, high rate pressure packing techniques have been employed because some operators were disappointed with the productivity and the high skins of the conventionally gravel packed wells. This method has been utilized to reduce the damage effect by placing sand outside the perforation. However, this technique is limited in its ability to eliminate the effect of reservoir damage beyond the well bore. Its advantage over typical gravel pack operations is probably due to reduced skin within the perforation tunnel & around well bore. Skins of +2 to +5 are reported for this process as compared to skin values of +15 to + 40 for conventional internal gravel pack completions.

High Rate Water Pack (HRWP) was introduced first time in ONGC in Rudrasagar field w.e.f. June, 96, by packing the cavities created by sand production. Not even a single well has been packed with HRWP technique in South Kadi field up to the end of 2008.

Historically, most wells in South Kadi were completed with slurry gravel pack with good success rate. In an effort to improve and optimize sand control techniques, the HRWP technique was introduced to achieve not only sand exclusion but also provide additional reservoir stimulation. The well performance from these Slurry gravel pack and high rate water packs wells is to be evaluated to qualify the benefit of this improved technique.

The HRWP job is preferred in:

- Pay zones where competent shale barriers above and below the perforation interval do not exists.
- Pay zone that is near to water or gas.
- Where Pay zone mobility (kh /μ) is lesser than 4000 md ft / cp.

Tentative job plan for HRWP

- Subdue the well.
- Clear the bottom with open end tubing
- Re-perforate @ 36 SPM, 0.75 EHD, 1200 phasing.
- Scrap the casing.
- Set bridge plug just below perforation.
- Casing tubing clean out job.
- Back-surge perforation.
- Circulate out sand and perforation debris.
- Carry out thermo gel job.
- Position gravel packs assembly with packer & multi-position gravel pack tool (MPT).
- Establish circulation with MPT in circulating position.
- Test injectivity in squeeze position.
- Acidization job if required.
- Position GP assembly in squeeze position and carry out High Rate Water Pack followed by high density slurry pack in circulation position. Usually pumping rate 6-10 bpm with 1-2 ppg slurry of 10 cp and High density (10-15 ppg) slurry of 40-50cp pack in low rate of 1- 2 bpm .
- Reverse out excess gravel by pumping down annulus with MPT in reverse circulating position.
- Pull out MPT
- Install tubing along with artificial lift equipment & well head.
- Activate the well.

CONCLUSIONS

- Produced sand samples from wells SK well # 122, 143 ,147 and one core sand sample from well SK #102 (available in IOGPT) were analysed in the lab.
- SAS(standalone screens) is the right choice for uniformity co-efficient <5. It is only a filtering medium. There is possibility of plugging the screen by fine sand and silt. . Moreover, there is possibility of mechanical failure of the SAS due to high velocity of fluid passing through it.
- There is negligible fine content available in produced sand samples. Samples were collected during bottom clearing by CTU. These samples may not be true representatives of the reservoir sand.
- No remarkable impairment of pack permeability was observed with 12/20 and 20/40 US mesh size gravel even after 72 hours of flow studies.
- Gravel pack seems to be the right choice for sand control in South Kadi field.
- Earlier gravel packing with viscous slurry technique was being followed with 20/40 mesh silica sand.
- 11 gravel pack jobs were carried out in South Kadi till date. 9 wells by slurry squeeze and 2 wells by HRWP method (results awaited.) Except one all are successful and long lasting.
- HRWP technique offers better well flow management in reservoirs having mobility less than 4000 md ft /cp, good permeability and zones that are near oil and gas without competent shale barriers.
- Recently high rate water packs with around 10 cp carrier fluids and 2.2ppg slurries are being done by the Asset.

RECOMMENDATION

- High Rate Water Pack with proper job design and execution using 12/20 US mesh gravel and 24 gauge (0.025 inch) slot opening screen is recommended.
- Wells should be prepared with perforation density @ 36SPM, perforation diameter (EHD) of 0.75 , and Perforation phasing of 1200.
- Sintered Bauxite or Light weight ceramic gravel of API specification in place of natural gravel may be used for improved results.
- Completion and carrier fluids should contain less than 10 ppm solids larger than that the median pores size of the formation.
- All surface equipments, flow lines, tanks etc. that are in fluid contact should be clean.

Tatipaka Asset Sand Production case history

Introduction

The tatipaka is the main gas producing fields of Rajahmundry asset. Through most of the wells are producing sand free production but four of the wells are facing the problem of sand production. It has been observed that there was gradual reduction in the productivity followed by closure of the wells. These sands are hydrocarbon bearing and the average porosity of the reservoir sand is 14.22% and the permeability ranges from 2 to 25 md.

Analysis of the problem:

Sand cut id most likely to occur in the fields of tatipaka (onshore). The main reason for sand cut in these fields is the presence of clay coating in the entire reservoir facies in the field, poorly consolidated formation, low shot density and high water cut. The clay coated reservoir rocks generally lack other cementing materials and make it more susceptible to damage. Also due to low salinity of formation water, these clays tend to swell and grain bond is weakened /destroyed and formation sand may be produced.

The other factor influencing sand cut mostly in the wells of tatipaka field is attributed to high water cut. The onset of water production seriously affects the cementing materials and increase in water oil ratio causes excessive stresses on weakly consolidated formations which in turn may exceed the ability of the cementing material to bound sand together

Laboratory calculations

Soxhelation process: In this process sand was washed thoroughly with the mixture of benzene, toluene and xylene to remove ant traces

The sand samples were analysed using 3-D sieving machine. A set of 16 sieves ranging from 10 US mesh to 325 US mesh were used for sieving the samples. 100 gms of sample was sieved and particles retained on each sieve was collected and weighed. A graph between the cumulative weight retained and the mesh sizes is made in order to compute the design point.

S.NO	US mesh	Mesh Size(mm)	Weight retained (gms)	Cum.Wt retained(gms)	%cumwt retained
1	10	2	.7381	0.7381	0.7485
2	14	1.4	1.8446	2.5827	2.6192
3	20	0.85	1.6036	4.1863	4.2455
4	30	0.6	3.8397	8.0260	8.1395
5	40	0.425	6.949	14.9750	15.1868
6	50	0.3	12.1454	27.1204	27.5040
7	60	0.25	5.1173	32.2377	32.6937
8	70	0.212	5.5407	37.7784	38.3128
9	80	0.18	3.97	41.7484	42.3389
10	100	0.15	15.5067	57.2551	58.0650
11	120	0.125	15.1621	72.4172	73.4416
12	140	0.106	6.4056	78.8228	79.9378
13	170	0.09	13.5022	92.3250	93.6310
14	200	0.075	2.3079	94.6329	95.9715
15	230	0.063	2.596	97.2289	98.6042
16	270	0.053	1.0469	98.2758	99.6659
17	325	0.044	0.3124	98.5882	99.9828
18	PAN	0.031	0.017	98.6052	100

From the graph

GRAVEL SELECTION

(1) Uniformity Coefficient= D40/D90 = .2/.099

Uniformity Coefficient= 2.02 (sand is uniform)

Uniformity Coefficient varying between

- 1-3 indicates "sand is uniform"
- 3-5 indicates "sand is non uniform in character"
- >5 indicates highly non uniform sand

(2) Design Point

From the graph we have calculated 50 percentile point = 0.1597 mm

Smallest gravel size = 4*(50 percentile point)

= 0.6388 mm

Largest gravel size = 8*(50 percentile point)

= 1.2776 mm

Selected gravel size= 14/30 US mesh

(3) Gravel Size

Sizing Method	Application
Saucier: D_{g50} = 6 to 8D_{s50}	Most widely used method. Loss of fines or coarse particles does not affect result as much as with other methods.
Schwartz: $D_{g10} = 6D_{s10}$ for $C_u < 3$ (uniform sands) $D_{g40} = 6D_{s40}$ for $5 < C_u < 10$ (nonuniform sands) $D_{g70} = 6D_{s70}$ for $C_u > 10$ (very nonuniform sands)	Gravel sized using design points selected on uniformity.
Stein: $D_{g65} < 4D_{s15}$	Best applied to formations with uniform particle size.
Coberly: $D_{g10} < 10\text{-}13D_{s10}$	Based on the largest 10th percentile. Valid only for uniform sands.
D_g = diameter of the gravel D_s = diameter of the formation sand C_u = uniformity coefficient. D40/D90. For all methods: $D_s x$ = formation sand X-percentile point. i.e., the grain diameter at X cumulative percent of a sample by weight when plotted on a semi-logarithmic scale. $D_g y$ = gravel Y-percentile point.	

According to the saucier design method

GRAVEL SIZE = 6* 0.1597

= 0.9582 mm

(4) SCREEN –SLOT WIDTH

Since all the gravel must be tightly placed and retained ,the screen–slot width must be one half of the smallest gravel size

Since US 14/30 mesh was selected , 30 US mesh gravel has a diameter of 0.589 mm . therefore the screen slot size would be = 0.5* 0.589

= 0.2945 mm

(5) Fines percentage

The difference of percent cumulative mass retained on the pan and the last sieve is the measure of fines and clays.

Mass retained on the pan = 100 gms

Mass retained on the last sieve = 99.9828 gms

Fines percentage = 100-99.9828

= 0.0172 gms

Conclusion and recommendations

Gravel packing is one of the most successful method of sand control and can be used in greater variety of wells than any other techniques. It is used in most wells including wells with shale zones.

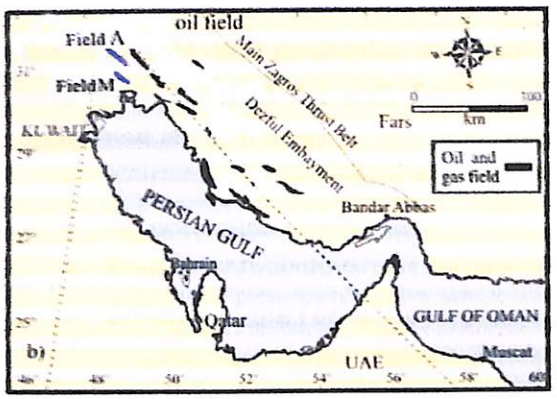
GRAVEL SPECIFICATION

1. Roundness and Sphericity of >0.6 are suggested
2. The crush resistance of the gravel should be no more than 5 wt% fines is generated at a stress of 2000 psi.
3. The solubility in 12/3 % (HCL+HF) should not exceed 1% when exposed to 1 hour.
4. Silica gravel particles are generally used; however Sintered Bauxite can also be used if higher crush resistance is needed.

Case Study on ESS

INTRODUCTION

Iran is one of the countries which have the largest oil and gas fields in the world. More than 80 percent of Iran oil reservoirs are carbonate and about 20 percent are sandstone. The main sandstone reservoir layers in Iran fields are in Asmari, an Oligo- Miocene formation. The Asmari oil fields of Iran are truly giant, most of them having recoverable reserves greater than 1 billion bbl each, and many having much more. Asmari reservoir is limestone of Oligo-Miocene age and mostly consists of shallow-water, with a significant sandstone member in the northwest part of the area.



Field and Reservoir Characteristics

Overview of field A

Field A is one of the major oil reservoirs in Dezful Embayment, north of Persian Gulf which is discovered in 1958 when the presence of two oil producing formations were established: the Asmari and Bangestan reservoirs. Field A sandstones were cemented by dolomites and its sandstones in subsurface sections have loose grain. There have been reports of sand production problems at Asmari reservoir since 1940. Recently, to control sand production, Expandable Sand Screen (ESS) has been installed in 4 wells of this field that has serious sand production problem. Analyzing the performance of these ESS systems is discussed in the subsequent sections.

Over view of field M

Field M was discovered in 1962 and consequent drilling has been confirmed in two reservoirs (Asmari and Bangestan). It was put on production in 1974. A total of more than 60 wells have now been drilled in the field. The Asmari formation is recognized as a regionally extensive geological unit, and it is known to contain a number of large oil accumulations.

In 1978 Shir Mohammadi reviewed this reservoir and separated it into 8 zones. Zones 1, 6 and 8 were mainly carbonate whereas zones 2, 3, 4 and 5 were mainly sandstone, and zone 7 was locally sandy shale. Based on the petrophysical evaluations zone 2 (by more than 80 percent sandstone) is the best pay zone and has the most values of net thickness, net to gross ratio and oil column and oil saturation. Due to unconsolidated sandstones in Asmari formation and high oil flow rates, sand grains will go upward with fluid and cause problems. To prevent sand production, in 9 wells of this field ESS system is installed

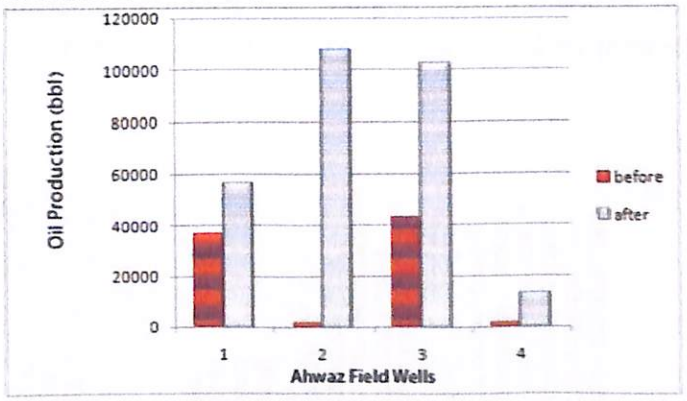
Sand Production Consequences

The effects of sand production are nearly always detrimental to the short and/or long term productivity of the well. Some problems that are happened as a result of sand production are as follows:

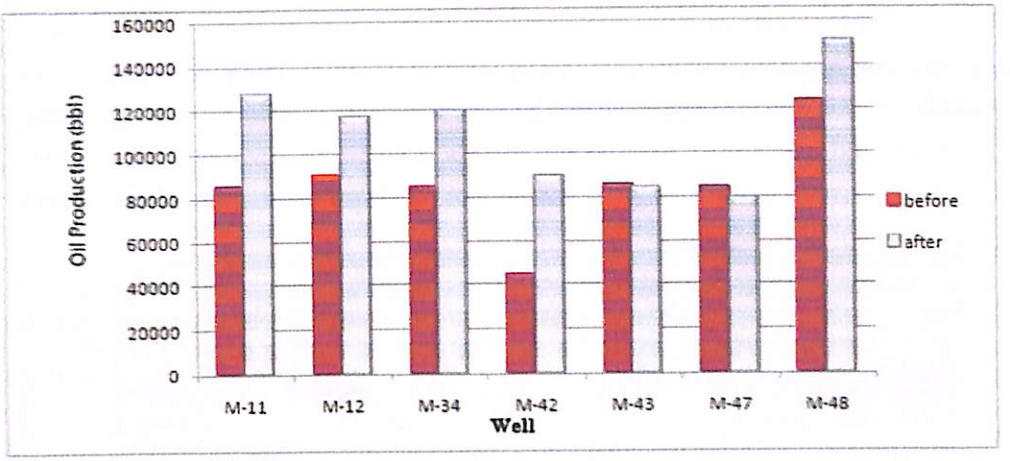
- Accumulation in Surface Equipment
- Accumulation Downhole
- Erosion of Downhole and Surface Equipment
- Collapse of the Formation

Production Results

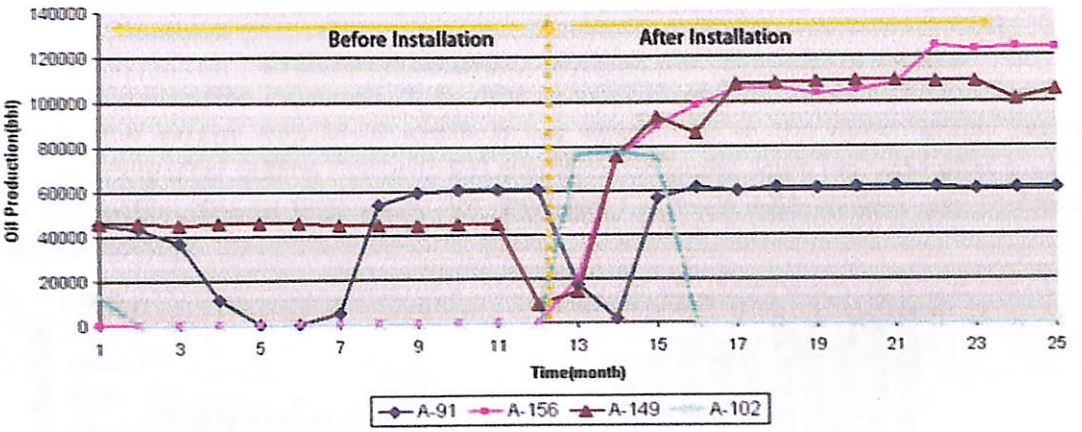
In this work, 4 wells from field A and 8 wells from field M have been studied. According to the oil production history of these wells which were completed with ESS in both fields, a comparison was performed in oil production before and after installation of ESS. Firstly for each well, oil production during one year before and after installation of ESS is selected and a monthly oil production average has been calculated. Fig.3 and Fig.4 show the results of this comparison in A and M fields.



Average oil production of each well in field A before and after ESS installation

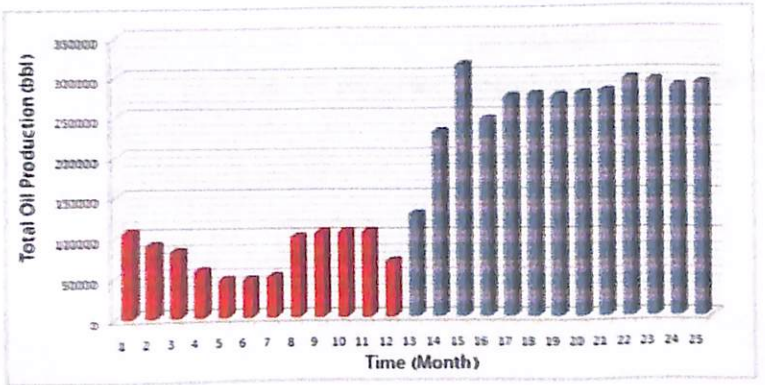


Above graph shows oil production history of wells in field A during one year before ESS installation and one year after ESS has been installed.



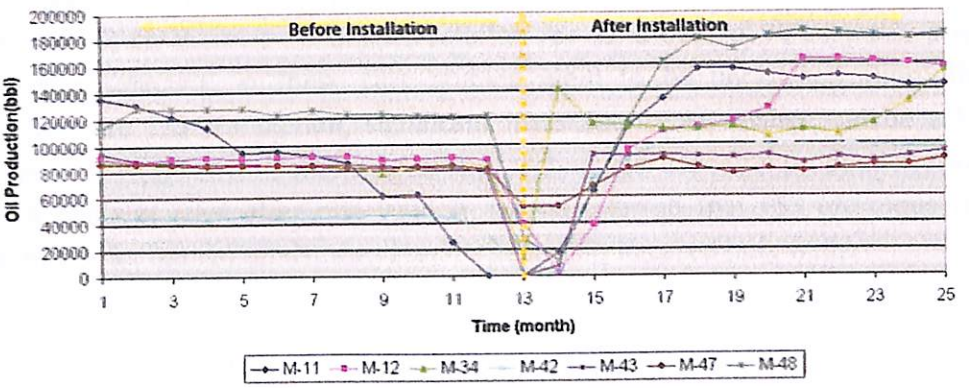
Oil production comparison before and after ESS installation in field A

The cumulative oil production in the year after installation of ESS is more than the time well was producing without ESS completion. Total oil production increased 247 % after installation of ESS



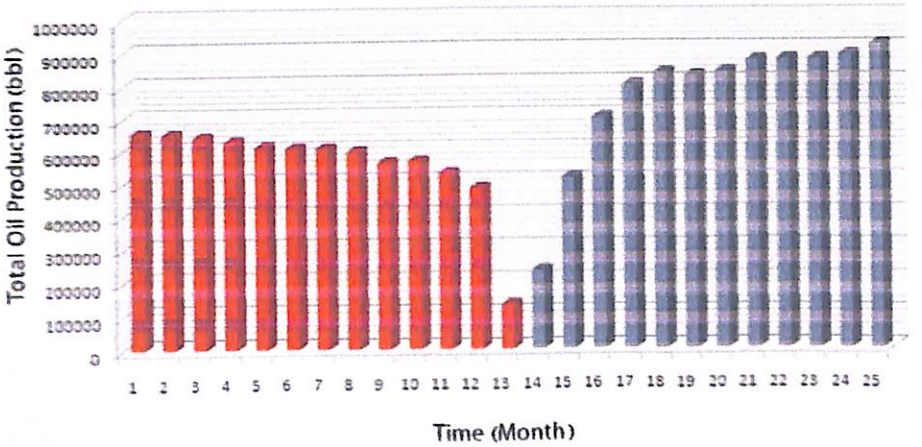
Total Oil production comparison before and after ESS installation in field A

In well A-102 after it completed with ESS, the well produced for three month and afterwards the well filled up with sand. The reason of this problem was the lower size of formation sand grains that passed through ESS screen. Oil production history of wells with ESS completion in field M is shown below. The production has increased for each well of the field after ESS has been installed.



Oil production comparison before and after ESS installation in field M

Total oil production increased 28 % after installation of ESS . All wells have increase in production except well M-60 which is not considered in the above graph because immediately after drilling this well, ESS was installed in the open hole and after a period of production due to high water cut, the well has been side tracked and completed directionally.



Total Oil production comparison before and after ESS installation in field A

Conclusion

According to different well conditions and various sand control techniques, appropriate tool selection to obtain optimum flow rate and minimum cost is extremely important. Consequently, this study was performed to confirm this fact and the following results are achieved. Since there is no unique solution for sand control in all wells, proper well candidate selection in these case studies seem to be performed appropriately. In general, with ESS completion, significant installation cost savings can be achieved in comparison with conventional sand control techniques. Based on production results of M and A fields at least after one year, it can be inferred that ESS technique is a good alternative for Iranian sandstone reservoirs specially in cased hole wells.

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