COMPLETION/STIMULATION

Sand Control: Why and How?

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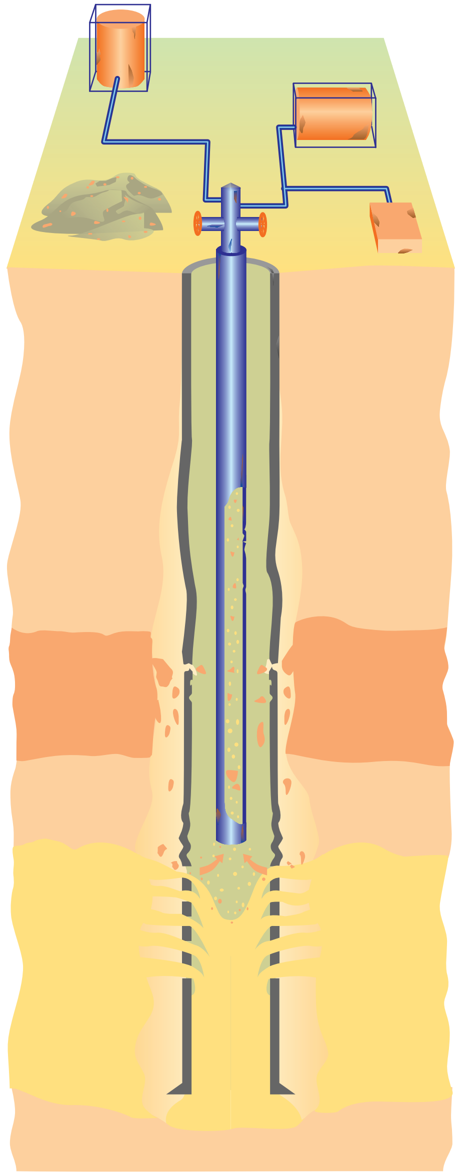
Sand production erodes hardware, blocks tubulars, creates downhole cavities, and must be separated and disposed of on surface. Completion methods that allow sand-prone reservoirs to be exploited often severely reduce production efficiency. The challenge is to complete wells to keep formation sand in place without unduly restricting productivity.



□Perils of sand production. At worst, sand production threatens a well. Voids can form behind the pipe, causing formation subsidence and casing collapse. The well may also fill with sand and cease flowing. Or the surface equipment may be catastrophically damaged by erosion or plugging.

Unconsolidated sandstone reservoirs with permeability of 0.5 to 8 darcies are most susceptible to sand production, which may start during first flow or later when reservoir pressure has fallen or water breaks through. Sand production strikes with varying degrees of severity, not all of which require action. The rate of sand production may decline with time at constant production conditions and is frequently associated with cleanup after stimulation.

Sometimes, even continuous sand production is tolerated. But this option may lead to a well becoming seriously damaged, production being killed or surface equipment being disabled (*left*). What constitutes an acceptable level of sand production depends on operational constraints like resistance to erosion, separator capacity, ease of sand disposal and the capability of artificial lift equipment to remove sand-laden fluid from the well.[1]

This article reviews the causes of sanding, and how it can be predicted and controlled. It will examine the four main methods of sand control: one that introduces an artificial cement into the formation and three that use downhole filters in the wellbore. The article then focuses on gravel packing, by far the most popular method of completing sand-prone formations.

Causes of Sanding

Factors controlling the onset of mechanical rock failure include inherent rock strength, naturally existing earth stresses and additional stress caused by drilling or production.[2] In totally unconsolidated formations, sand production may be triggered during the first flow of formation fluid due to drag from the fluid or gas turbulence. This detaches sand grains and carries them into

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In this article, NODAL (production system analysis) and IMPACT (Integrated Mechanical Properties Analysis & Characterization of Near Wellbore Heterogeneity) are marks of Schlumberger; PacCADE, ISOPAC and PERMPAC are trademarks or service marks of Dowell Schlumberger.

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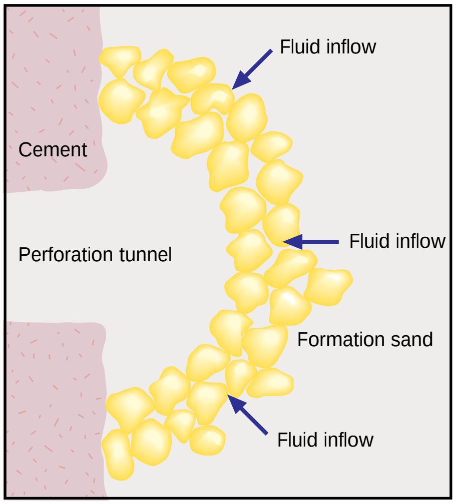


□***Doorway to the wellbore. A stable arch is believed to form around the entrance to a perforation cavity. This arch remains stable as long as flow rate and drawdown are constant. If these are altered, the arch collapses and a new one forms once flow stabilizes again.***

the perforations. The effect grows with higher fluid viscosity and flow rate, and with high pressure differentials during drawdown.[3]

In better cemented rocks, sanding may be sparked by incidents in the well's productive life, for example, fluctuations in production rate, onset of water production, changes in gas/liquid ratio, reduced reservoir pressure or subsidence.[4]

Fluctuations in the production rate affect perforation cavity stability and in some cases hamper the creation and maintenance of sand arches. An arch is a hemispherical cap of interlocking sand grains—like the stones in an arched doorway—that is stable at constant drawdown and flow rate, preventing sand movement (*above*). Changes in flow rate or production shut-in may result in collapse of the arch, causing sand to be produced until a new arch forms.[5]

Other causes of sanding include water influx, which commonly causes sand production by reducing capillary pressure between sand grains. After water breakthrough, sand particles are dislodged by flow friction. Additionally, perforating may reduce permeability around the surface of a perforation cavity and weaken the formation (*right*). Weakened zones may then become susceptible to failure at sudden changes in flow rate.

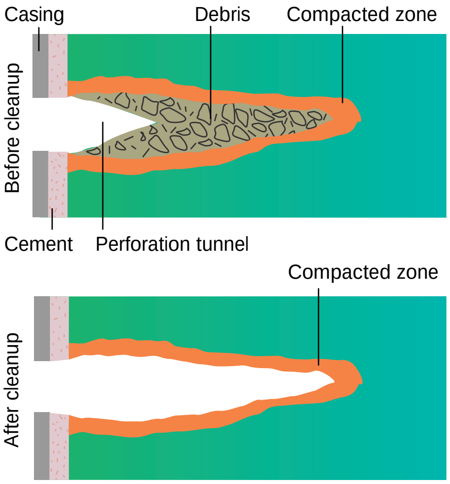
Predicting Sanding Potential

The completion engineer needs to know the conditions under which a well will produce sand. This is not always a straightforward task. At its simplest, sand prediction involves observing the performance of nearby offset wells.

In exploratory wells, a sand flow test is often used to assess the formation stability. A sand flow test involves sand production being detected and measured on surface during a drillstem test (DST).[6] Quantitative information may be acquired by gradually increasing flow rate until sand is produced, the anticipated flow capacity of the completion is reached or the maximum drawdown is achieved. A correlation may then be established between sand production, well data, and field and operational parameters.

Accurately predicting sand production potential requires detailed knowledge of the formation's mechanical strength, the in-situ earth stresses and the way the rock will fail. Laboratory measurements on recovered cores may be used to gather rock strength data. Field techniques like microfracturing allow measurement of some far-field earth stresses (see "Cracking Rock: Progress in Fracture Treatment Design," *page 4*). This information may then be used to predict the drawdown pressure that will induce sanding.[7]

Although these techniques provide direct measurement of critical input data, they are relatively expensive to acquire and are only available for discrete depths—in some of the zones of some of the wells. Downhole wireline log measurements provide continuous profiles of data. However, no logging tool yields a direct measurement of rock strength or in-situ stress. This has given rise to interpretation techniques that combine direct measurements with sonic and density logs to derive the elastic properties of rock and predict from these the sanding potential.[8]



□***Debris and damage in the perforation tunnel. Before cleanup, a perforation tunnel may be filled with pulverized sand and shaped-charge debris. First flow may remove this debris, but a compacted zone can remain around the surface of the cavity that is weakened and likely to suffer tensile failure.***

A example is IMPACT Integrated Mechanical Properties Analysis & Characterization of Near Wellbore Heterogeneity, recently developed by Schlumberger Well Services, Houston, Texas, USA. The IMPACT analysis predicts formation sanding potential using values for formation strength obtained by correlating logs and cores, in-situ stress parameters derived from geologic models that employ log and microfracture data and one of two rock failure models.

Despite the fact that cores may be significantly altered during the journey from wellbore to laboratory, rock strength measurements gathered from core tests are crucial to the IMPACT analysis computation of rock strength. In a uniaxial compressive test, a circular cylinder of rock is compressed parallel to its longitudinal axis, and axial and radial displacements are measured. The dynamic elastic properties—in particular Young's Modulus and Poisson's ratio—and uniaxial compressive strength may then be computed. Triaxial tests make the same measurements at different confining pressures and give a more complete picture of the rock's failure envelope as a function of confining stress.

Because there is no unifying theory that relates log measurements to rock strength, using the laboratory core data, empirical correlations are derived to obtain the desired rock strength parameters from log-derived elastic properties. The IMPACT software has several empirical correlations to choose from.

The earth's in-situ stresses are due to many factors including the weight of the overburden, tectonic forces and pore pressure. While the vertical stresses may be estimated using bulk density logs, horizontal stresses are more problematic. In IMPACT processing, accurate estimates of horizontal stresses are integrated with logs and, using a geologic model, a continuous profile of earth stresses is created. Various geologic models have been developed to cope with the different environments encountered. Reservoir pore pressure information is also needed and this may be estimated using wireline formation testing tools or DSTs.

Finally, rocks either fail in tension when they are pulled apart or they fail in shear when they are crushed. IMPACT analysis enables the interpreter to pick the most likely failure mechanism. From this, the program predicts sanding potential.

Completion Options

Once it has been established that at planned production rates sand is likely to be produced, the next step is to choose a completion strategy to limit sanding. A first option is to treat the well with "tender loving care," minimizing shocks to the reservoir by changing drawdown and production rate slowly and in small increments. Production rate may be reduced to ensure that drawdown is below the the point at which the formation grains become detached. More subtly, selective perforation may avoid zones where sanding is most likely. However, both options reduce production, which may adversely affect field economics.[9]

The most popular options for completing sand-prone reservoirs physically restrain sand movement. The four main classes of completion are resin injection, slotted liners and prepacked screens, resin-coated gravel without screens and gravel packing.

Resin Injection: To cement the sand grains in situ, a resin is injected into the formation, generally through perforations, and then flushed with a catalyst. Most commercially available systems employ phenolic, furan or epoxy resins. They bind rock particles together creating a stable matrix of permeable, consolidated grains around the casing.

Clay concentration can hinder the effectiveness of the consolidation process, so a clay stabilizer is often used as a preflush. Residual water may also interfere with the development of consolidation strength and may necessitate use of increased quantities of resin.[10] The quantity of resin injected is a compromise between enhancing consolidation strength and reducing permeability. For example, if an 8-darcy unconsolidated sand is resin treated to give a compressive strength of up to 3300 psi, permeability may be reduced by 25% and productivity cut by up to 10%.[11]

Further, sand production will not be prevented if chemical injection is uneven and some exposed sand is uncoated. Because of this, the technique tends to be reserved for short intervals, up to 10 to 15 ft [3 to 4 m]. Complete coverage of larger zones is difficult unless selective placement tools are used. Although resin consolidation is used successfully, it accounts for no more than about 10% of sand-control completions.

Slotted Liners and Prepacked Screens: Slotted pipes, screens and prepacked screens offer the lowest-cost downhole filtering. Slotted liners have the largest holes, wire-wrapped screens have smaller openings, while screens prepacked with resin-coated sand offer the finest filtering. Each type can be run as part of the completion string and are particularly suited for high-angle wells, which cannot be easily completed otherwise (see "Screening Horizontal Wells," *page 45*).

Slots are typically sized to cause bridging of the largest 10% of the formation particles, filling the annulus between the screen and casing, or open hole, with formation sand creating a filter for remaining particles. However, production can be restricted by this relatively low-permeability, sand-packed annulus. Also, production of even a small amount of fines can plug many screens, particularly prepacked screens, within a few hours of installation.

Slotted liners and screens are best suited to formations that are friable rather than completely unconsolidated. They are mostly used in California, USA, and some Gulf of Mexico, USA fields where permeabilities are greater than 1 darcy. Slotted liners and prepacked screens are used in only about 5% of sand-control completions.

Resin-Coated Gravel Without Screens: Resin-coated gravel may be used as a downhole filter without installing a screen. The gravel is circulated into position as a slurry, either inside casing or open hole and then squeezed to form a plug across the production zone. Adjacent particles are bonded together by the resin, strengthening the pack.

In cased hole, the plug may be completely drilled out to leave gravel-filled perforations. Alternatively, the pack may be drilled out to the top of the perforations/open hole so that hydrocarbons are produced through the pack. A narrow hole can be drilled through the pack to provide a conduit to reduce drawdown through the pack. This can be achieved using coiled tubing if a conventional rig is not available.

Resin-coated gravel has the advantage of needing no special hardware. But the pack creates significant additional drawdown that may affect productivity. If the drillout technique is employed to reduce drawdown, all perforations must be evenly packed and the resulting pack may be fragile. Complete coverage of intervals longer than about 20 ft [6 m] is difficult to achieve. The technique represents about 5% of sand-control treatments, mainly concentrated on low-cost onshore markets.

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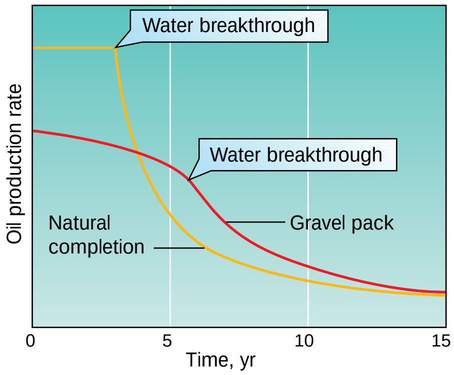
[10] Pelgrom J and Wilson RA: "Completion Developments in Unconsolidated Oil-Rim Reservoirs," paper OSEA 90123, presented at the Eighth Offshore South East Asia Conference, Singapore, December 4-7, 1990.

[11] Davies, DR: "Applications of Polymers in Sand Control," paper presented at Use of Polymers in Drilling and Oilfield Fluids, organized by the Offshore Engineering Group of the Plastics and Rubber Institute, London, England, December 9, 1991.

Gravel Packing: Gravel packing has been used by the oil industry since the 1930s. Today, it is the most widely employed sand control measure, accounting for about three-quarters of treatments.[12] A slurry of accurately sized gravel in a carrier fluid is pumped into the annular space between a centralized screen and either perforated casing or open hole. The gravel also enters perforations if a cased-hole gravel pack is being performed. As pumping continues, carrier fluid leaks off into the formation or through the screen and back to surface. The gravel pack creates a granular filter with very high permeability—about 120 darcies—but prevents formation sand entering the well (*below*).

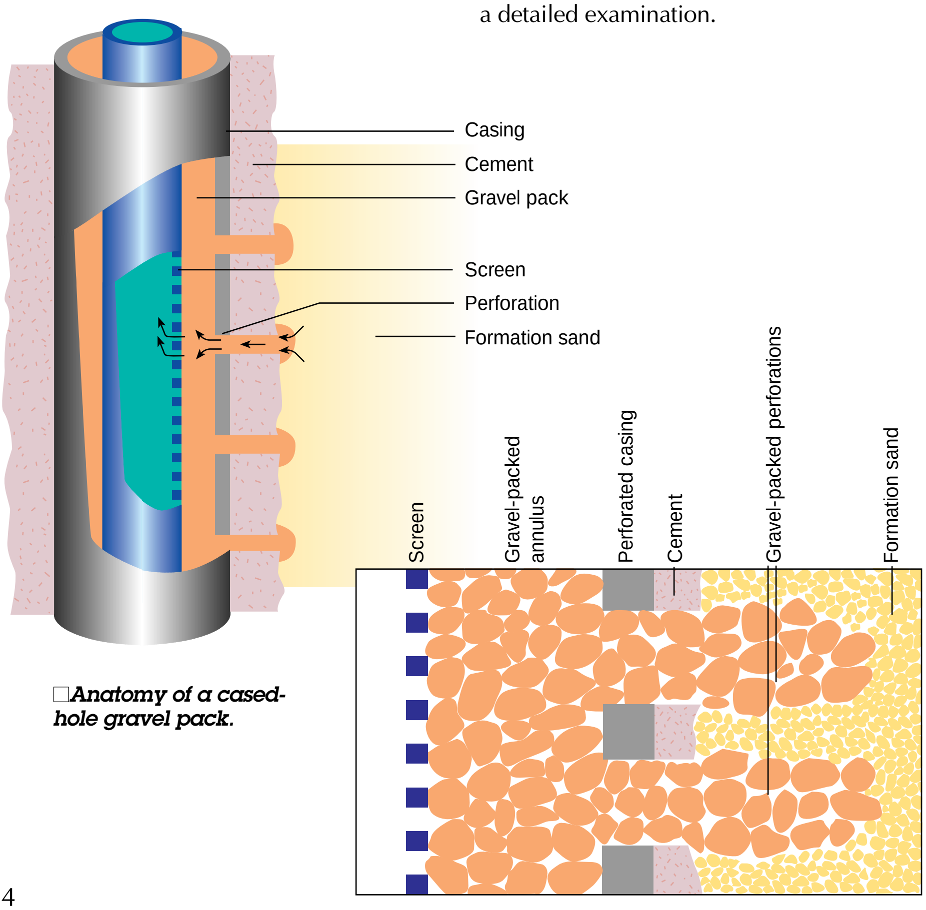
Gravel packs are not without their drawbacks. During installation, carrier fluid is injected into the formation which may damage the reservoir permeability and restrict production. The pack then tends to trap the damage in the perforations, preventing clean up. Once in place, the pack in perforation tunnels increases drawdown which may seriously affect productivity.[13] Gravel packs reduce the operating wellbore diameter, usually necessitating artificial lift equipment to be set above the zone. Completing multiple zones with gravel packs is difficult, and almost all well repairs involve the removal of the screen and pack.



Assessing the viability of a gravel pack. The oil production rate for natural completion—unstimulated and not gravel packed—is compared with that for a gravel pack in an intermediate-strength rock that is sensitive to water breakthrough.

The technique is also a relatively expensive method of completion. A sophisticated way of establishing the viability of a gravel pack is to construct well performance curves for a range of completion methods using a reservoir simulator and predictions of sand movement and how this affects drawdown (*above*).

Although gravel packing has these drawbacks, it is the most effective method of stopping sand movement and permitting production, albeit at a reduced rate. Because of this, gravel packing is the predominant method in use today and warrants a detailed examination.

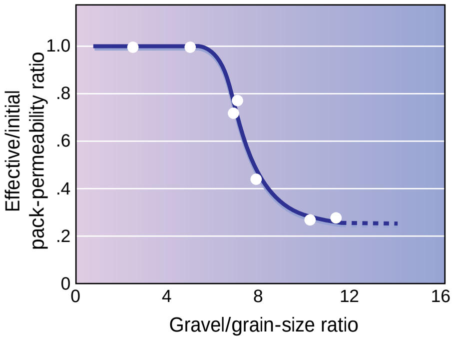


Anatomy of a cased-hole gravel pack.

Designing Gravel Packs

For a gravel pack to maintain long-term productivity, the gravel must be clean, tightly packed and placed with the minimum damage to the formation. These requirements depend on the correct selection of gravel, carrier fluid and placement technique. They also rely on scrupulous cleanliness during placement operations to prevent the contamination of the gravel pack by small particles that significantly reduce pack permeability.

Minimizing the pressure drop in the perforation tunnels is vital to successful gravel packing and this requires gravel that is as large as possible. But since the pack must act as an effective filter, the gravel also has to be small enough to restrain formation particles. This depends on the size of the formation sand, which is usually measured using sieve analysis.



Choosing gravel size range. The ratio of the effective pack permeability and the initial pack permeability represents the effect of the formation sand particles as they partially plug the gravel pack. When the gravel size/grain-size ratio reaches about six, the particles can enter the pack and seriously diminish pack permeability.

Formation samples from cores are passed through successively smaller sieves to separate particles into a number of size groups that are then weighed and plotted. If the samples are aggregated, they need to be broken up before the analysis—clay and silt particles binding the rock together may be removed by washing with chemicals. The resulting sand grains may then be dried and sieved.

There are various methods for translating the formation sand size distribution into a design size for the gravel. One of the most widely used methods is based on work carried out by R.J. Saucier that recommends the median gravel size should be up to six times the median formation grain size but no more (*above*).[14]

(*continued on page 47*)

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[12] Winchester, reference 4.

[13] Welling R and Nyland T: "Detailed Testing of Gravelpacked Completions" paper OSEA 90121, presented at the Eighth Offshore South East Asia Conference, Singapore, December 4-7, 1990.

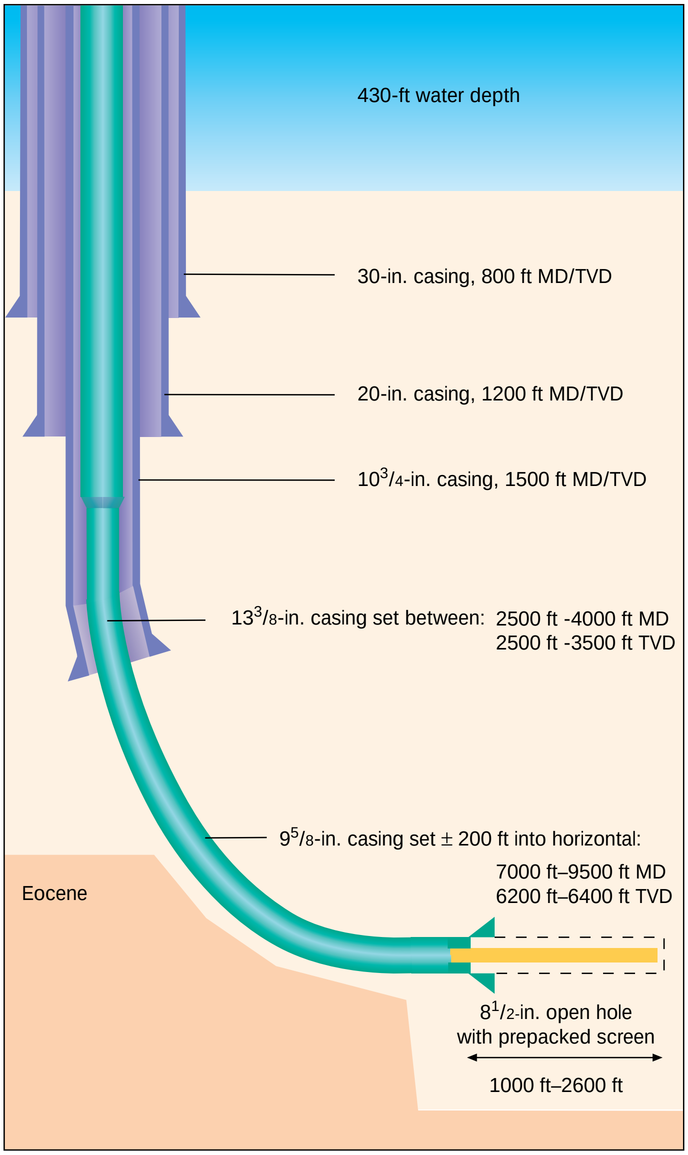
[14] Saucier RJ: "Considerations in Gravel Pack Design," *Journal of Petroleum Technology* 26, (February 1974): 205-212.

Studies generally conclude that the most effective technique for excluding sand in high-angle and horizontal wells is gravel packing.[1] Although there have been some notable operational successes, the technical complexities of high-angle gravel packing and its relatively high cost mean that alternative techniques are often considered.[2]

A case in point in the UK North Sea is the Alba field which is operated by Chevron UK Ltd. The 350-ft [107-m] thick Eocene sand reservoir is completely unconsolidated and currently under development. Most of the field's production wells will have horizontal sections of up to 2600 ft. When the field comes onstream, each well will produce up to 30,000 B/D using electric submersible pumps.

Water breakthrough is expected after only two months of production and 40% water cut is expected by the end of the first year. Early water production will exacerbate sand production by reducing the interstitial tension between sand grains, making sand control a major factor of the development plan.

Initial plans called for horizontal cased-hole gravel packs. However, the company continued to study alternative solutions and concluded that prepacked screens could successfully keep sand at bay (right). Prepacked screens cost significantly less than gravel packs and are simpler to install. What convinced Chevron was not the cost but the increased internal diameter (ID) afforded by the prepacked screens—4.4 in. [11 cm] as opposed to the 2.9 in. [7.4 cm] of the planned gravel packs.



☐Horizontal well completion design for the Alba field.

Larger ID reduces the pressure drop along the horizontal length of the well, leading to a better inflow distribution—when the pressure drop is high, production from the near end of the wellbore is favored. In the field's conventionally deviated wells, where pressure differential will not significantly affect inflow performance, Chevron will employ conventional gravel packs.

The prepacked screens will comprise 5-in. pipe wrapped with two layers of screen with an outside diameter of 6 $^5/_8$-in. [16.8-cm]. Between the screen will be a $^1/_2$-in. [1.3 -cm] thick pack of resin-coated gravel. The screens will be inserted into open hole, 8 $^1/_2$-in. [22-cm] diameter, so there is a likelihood of sand sloughing around the screens. Chevron tested the effects of sloughing on permeability around the wellbore. At worst, it reduced permeability from 3 darcies to 1, not enough to significantly limit production.

On the downside, the longevity of the screens is uncertain and there is a lack of zonal isolation afforded by an openhole completion. In an effort to combat this, blank sections with internal seals will be deployed every 400 ft [120 m] of screen, allowing fluids to be spotted, and plugs and straddle packers to be set using coiled tubing.

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   Sparlin DD and Hagen WH Jr: "Gravel Packing Horizontal and High-Angle Wells," *World Oil* 213, no. 3 (March 1992): 45-49.
2. Wilson DJ and Barrilleaux MF: "Completion Design and Operational Considerations for Multizone Gravel Packs in Deep, High-Angle Wells," paper OTC 6751, presented at the 23rd Annual Offshore Technology Conference, Houston, Texas, USA, May 6-9, 1991.

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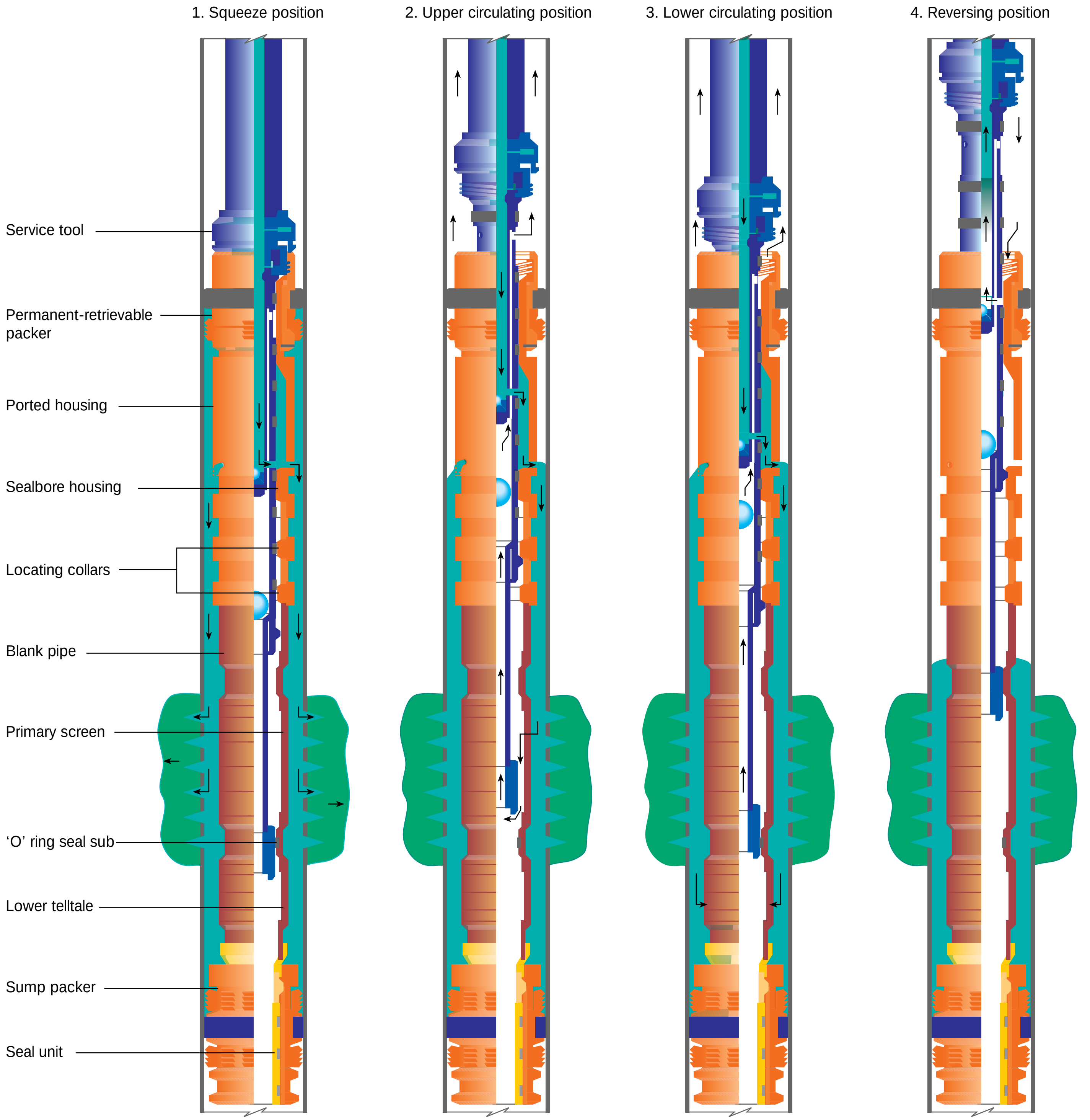

□*The four positions for gravel packing. In squeeze position, the service tool seals into the packer and does not allow circulation. When slurry is pumped in this mode, all the carrier fluid leaks off into the formation.*

In upper circulating position, slurry is pumped down the casing-screen annulus and the carrier fluid can be squeezed through any part of the screen, into the washpipe at the bottom of the service tool and back to surface via the service tool-casing annulus above the packer.

In lower circulating position, slurry is also pumped down the casing-screen annulus, but returns of carrier fluid have to pass through the bottom of the pack where the washpipe is sealed into the lower telltale—a sealbore with a short piece of screen below—located below the main screen. The aim is try to maintain flow in the casing-screen annulus and ensure that there is not a void in the gravel in the annulus below the screen.

However, if the interval being packed is longer than 25 ft [8 m], backpressure on the fluid may cause the fluid to bypass the pack and pass down the well via the screen/washpipe annulus, which may encourage bridging off higher up the well.

Reverse circulation involves pumping fluid through the washpipe, up the screen/washpipe annulus and back up to surface.

Recently, work by B.W. Hainey and J.C. Troncoso of ARCO points to the possibility of using larger gravel, offering higher pack permeability.[15] To explain this, Hainey and Troncoso argue that in some cases formation sand grains move as larger agglomerates rather than as individual grains.[16]

Average grain size is not the only determinant of gravel-pack permeability. The best gravel-pack sands are round and evenly sized. The most common way of estimating roundness and sphericity is by examining the gravel through a 10- to 20-power microscope and comparing the shapes with a reference chart. Gravel-size distribution can be monitored by sieve analysis.

The next decision facing the engineer is whether the completion should be cased or openhole. Openhole gravel packs have no perforations and therefore offer the minimum pressure drop across the pack. But placement may be time-consuming. Care must be taken to remove the filter cake deposited on the formation by drilling fluid and to avoid abrading the formation and contaminating the gravel. Cased-hole gravel packs present the additional challenge of properly packing the perforations.

To check that a well is suitable for cased-hole gravel packing, productivity may be calculated using NODAL production system analysis. This models the pressure drop as reservoir fluid flows through the perforations into the completion hardware to surface.

Pressure drop in perforation tunnels is a major impediment to production and varies with tunnel length, perforation area, pack permeability, viscosity of the produced fluids and reservoir pressure (see "Choosing a Perforation Strategy," *page 54*). The gravel size range determines pack permeability—the smaller the grains, the more the pack restricts formation flow—and is fixed by the size of the formation sand. Formation fluid viscosity and reservoir pressure are also fixed. To reduce pressure drop, inflow area may be raised by increasing perforation diameter and/or increasing the number of perforations. If the well is perforated with tubing-conveyed perforating (TCP), high shot density guns, gravel packs can nearly match the inflow performance of openhole packs for many reservoirs. Pressure drop may also be reduced by increasing the diameter of casing in which the gravel pack is to be placed. If sufficient inflow area cannot be achieved through perforation, openhole completion is required.

Once the method of completion is selected, the hardware may be chosen. At its simplest, a packer and screen assembly with a washpipe inside are usually run in hole with a service tool. However, when multiple zones are to be completed in stages, the hardware becomes a complex series of screens and packers.

The service tool is then used to set the packer above the zone to be completed. Thereafter, the positions of the service tool in the packer and washpipe in the screen assembly determine the flow direction of fluids pumped downhole. Sophisticated systems have four positions: squeeze, upper circulating, lower circulating and reverse circulating and therefore allow single-trip treatments (*previous page*).

In a single-trip gravel-pack treatment, the perforation guns are fired and lowered into the rathole. The perforations may be filled with gravel with the packer in the squeeze position and the annulus is filled with it in either the upper or lower circulating positions. Excess gravel is then reversed out.

However, the hardware used in many gravel-pack operations does not permit single-trip operations. For a cased-hole gravel pack, the TCP guns must be retrieved and then the workstring must removed after gravel packing so that the completion string may be run. During these trips, the service tool and the washpipe are withdrawn from the packer, exposing the relatively high-permeability formation to the hydrostatic pressure of the completion fluid above the packer. This usually causes fluid to be lost into the formation.

To reduce losses, particulate loss control material (LCM) suspended in a viscous fluid is commonly pumped downhole before each trip. The LCM plugs the completion fluid's flow path into the formation. After the trip, the LCM is removed. Common LCMs include marble chips (calcium carbonate, removable with acid), oil-soluble resins or salt pills (see "Gravel Packing Forth Field Exploration Wells," *next page*).

Each time LCM is used, there is a danger of incomplete removal damaging the reservoir. To avoid the need to pump LCM when the washpipe and workstring are removed from the packer, a flapper valve can be employed below the packer. This valve is capable of accommodating a large-diameter washpipe to direct flow to the casing-screen annulus. It closes after the service tool and washpipe are removed, preventing completion fluid from passing through the pack and into the permeable formation. When the completion string is run, the flapper valve is opened—either mechanically, with wireline or using pressure.

Wire-wrapped screens are usually used to retain the gravel. Selection of wire spacing is not subject to any hard and fast rules, but a common rule of thumb calls for the slots to be 75% of the smallest gravel diameter. Screen diameter depends on the inlet area, the pack thickness and the ability to fish the screen out of the hole. This normally leads to using screens with at least 1-in. [2.5 cm] annular clearance. Screens are normally run 5 ft [1.5 m] above and below the producing zone and centralized every 15 ft [5 m] to improve the chances of a consistent gravel fill.

Transporting gravel into the perforations and annulus is the next consideration. Gravel can sometimes bridge off prematurely, leaving voids in the annulus. In vertical wells, incomplete fill may be rectified when pumping stops and gravel in the annulus collapses into the voids. This ceases to be the case in wells deviated more than 50°, where voids below a bridge are likely to remain. Transport is a function of the suspension properties of the fluid and the energy required to move the slurry. Important factors determining settling are pump rate, the relative densities of the gravel and the carrier fluid, gravel diameter and the apparent viscosity of the fluid when pumped downhole.[17]

There is also a relationship between gravel concentration and carrier fluid viscosity when it comes to "turning the corner" in the annulus and entering perforations. Fluid viscosity must increase if gravel concentration in the slurry increases, otherwise the gravel will tend to sink to the bottom of the well. Packing efficiency is also affected by the rate the carrier fluid leaks off into the formation. If leakoff is rapid, the gravel is likely to be carried to the perforation tunnel-formation interface and held there as the fluid leaks off. If leakoff is slow, the gravel has more time to settle and will not effectively pack the perforations.

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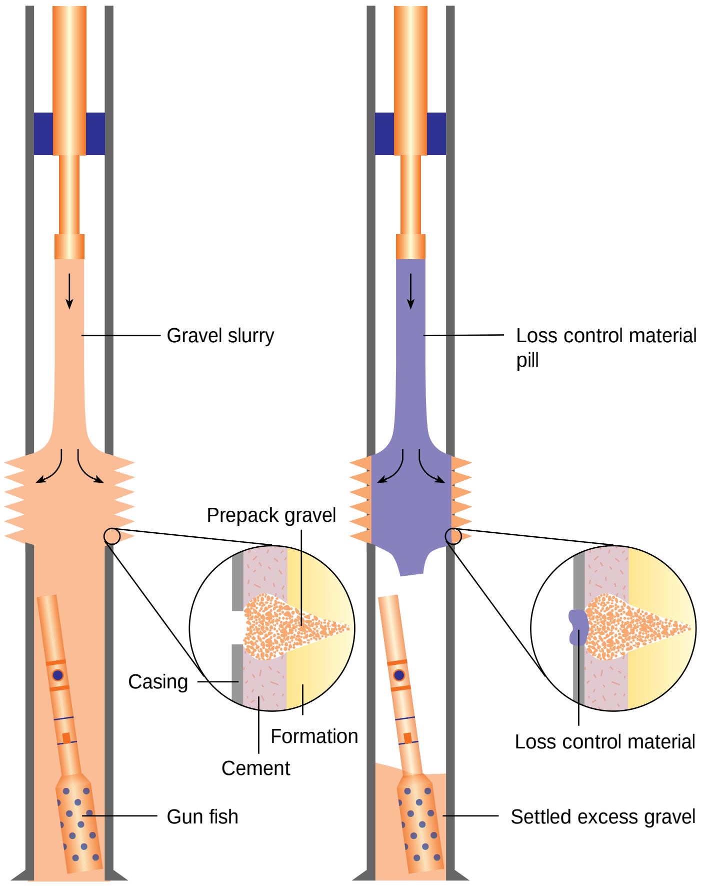
15. According to American Petroleum Institute recommended practices (RP 58), the designation 40/60 indicates that not more than 2% of the gravel should be smaller than the 40-mesh sieve and not more than 0.1% should be larger than the 20-mesh sieve.
16. Hainey BW and Troncoso JC: "Frac-Pack: An Innovative Stimulation and Sand Control Technique," paper SPE 23777, presented at the SPE International Symposium on Formation Damage Control, Lafayette, Louisiana, USA, February 26-27, 1992.
17. Gurley DG and Hudson TE: "Factors Affecting Gravel Placement in Long Deviated Intervals," paper SPE 19400, presented at the SPE Formation Damage Control Symposium, Lafayette, Louisiana, USA, February 22-23, 1990.

Gravel Packing Forth Field Exploration Wells



☐Prepacking the perforations. Prepacking the perforations prevents loss control material from entering the perforation tunnels; this improves subsequent cleanup and reduces damage. Tubing-conveyed perforating guns were dropped, gravel was bullheaded into the perforations and loss control material spotted across the tunnel entrances.

There is no such thing as a typical gravelpack; each is a complex combination of relatively simple operations. This example is based on a gravel-packing procedure used on several vertical appraisal wells in the Forth field in the UK North Sea operated by BP Exploration. Forth, discovered in 1986, has an Eocene reservoir comprising massive, clean sand located at a depth of about 5500 ft [1675 m]. Permeability is 6 to 12 millidarcies and porosity is 35%.[1]

Cleanliness is fundamental to gravel packing efficiency. Any contaminants that may plug the gravel pack and decrease productivity must be removed. In preparation for the gravel packing, the mud pits were cleaned and the mud changed to brine completion fluid. Tubulars were externally shot blasted, internally jetted and steam cleaned before being run in hole. Because the dope used to lubricate pipe joints is a serious contaminant, it was applied sparingly to the pin end only.

Cement for the production casing was displaced with seawater. The cement scours the casing, but to further clean the wellbore, scrapers were run and seawater circulated at high pump rates. Cleanup pills of detergent, scouring pills with gel spacers and flocculants were also circulated. The well was then displaced to brine. Initial returns of seawater-contaminated brine were discarded before the system was closed and surface filters employed to reduce the maximum particulate size to less than 2 microns [µm]. Solids in the brine were monitored to ensure that there were fewer than 10 parts per million.

Perforation was carried out using tubing-conveyed perforating (TCP) guns with an underbalance of about 300 psi. A short flow of 2 ft^3/ft of perforation was performed to remove debris. The TCP guns were then dropped off. BP decided to prepack the perforations with gravel prior to running the screen assembly. This strategy was used to limit formation damage and prevent loss control material from entering the perforation tunnels (above)**.**

Gravel in gelled carrier fluid was circulated into place and then squeezed into the perforations. This was repeated two or three times to ensure that all the perforations were packed. An LCM pill of sodium chloride in xanthan gum and a modified starch was then spotted across the packed perforations to prevent loss of completion fluid while the tubing was pulled.

A sump packer was set below the zone to be completed and above the dropped TCP guns. The main packer, service tool and screen assembly were then run and the packer set.

The LCM pill was dissolved by circulating unsaturated brine and the main gravel pack circulated into place. A second LCM pill was then spotted across the screen to allow recovery of the service tool without losing completion fluid into the formation (next page, left)**. The final completion hardware was run and the LCM dissolved.**

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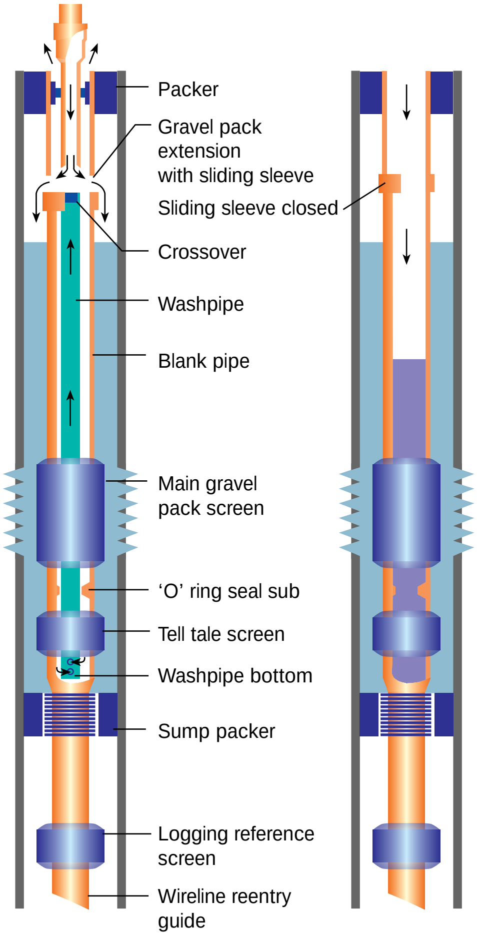
1. Gilchrist JM and Gilchrist AL: "A Review of Gravel Packing in the Forth Field," paper SPE 23128, presented at the Offshore Europe Conference, Aberdeen, Scotland, September 3-6, 1991.



☐Dissolving the loss control material and circulating an annular gravel pack.

There is no industry consensus on governing choice of fluid viscosity and gravel concentration, but the following three combinations are the most common:

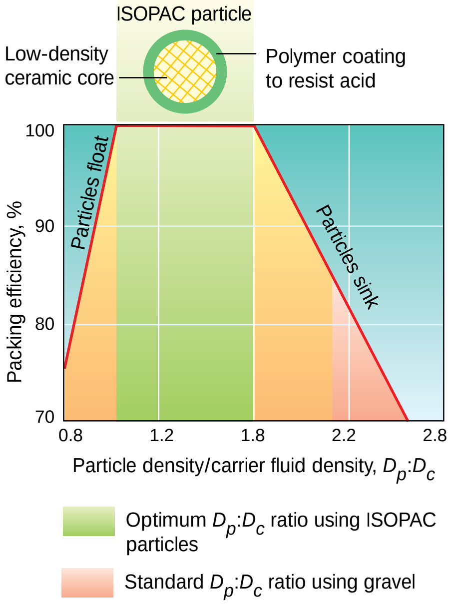
- In conventional, circulating gravel packs, most of the carrier fluid squeezed out of the slurry is circulated back to surface. The slurry usually has a low-viscosity carrier fluid of less than 50 centipoise (cp) and ungelled water is a common carrier. Gravel concentration can range from 0.25 to 15 lbm/gal depending on the carrier fluid viscosity and company preference. The technique is generally employed for intervals of more than 50 ft [15 m] and deviated holes up to horizontal. Fluid leakoff is essential to ensure that perforations are packed, but excessive leakoff may lead to bridging.
- High-density circulating gravel packs are used for medium to long intervals—25 ft [8 m] to more than 100 ft [30 m]. The slurry usually has a viscosity of more than 50 cp and a gravel concentration of 7 to 15 lbm/gal.
- Squeeze packs, in which all the carrier fluid leaks off into the formation, are used for short intervals of less than 25 ft.

The conventional approach to controlling settling—decreasing gravel concentration and increasing carrier-fluid viscosity—has drawbacks. To place an equivalent quantity of gravel, more carrier fluid must be lost, increasing the potential for formation damage. However, increased viscosity slows the rate of leakoff—a 250-cp fluid will leak off more than six times slower than a 40-cp fluid.[18] Increasing carrier-fluid viscosity may also increase formation damage.

Sometimes, in an effort to improve placement, carrier-fluid viscosity and gravel concentration are both increased to create a plug of slurry. But increased slurry viscosity raises friction pressure and may increase the possibility of bridging in the annulus.

Another way of reducing settling, helping gravel to turn the corner and efficiently pack perforations is to use a gravel and carrier fluid of closely matched densities—not the case when using conventional gravels or low-density brines. For this purpose, Dowell Schlumberger has developed ISOPAC low-density, high-strength particles. Because settling is not a major problem when the densities are matched, the pump rate can be slowed, improving tightness of the pack and increasing the time available to pack all the perforations (*below and next page*). The reduced viscosity increases the rate of leakoff and reduces the potential for formation damage.

ISOPAC particles have been used in over 30 Gulf of Mexico and North Sea jobs since introduction in 1991. The efficiency with which perforations have been packed cannot be measured directly. One indirect diagnostic method is based on the average volume of gravel placed per foot of interval (ft^3/ft). Rules of thumb derived from experience consider the placement efficiency of about 0.25 ft^3/ft of conventional gravel as being satisfactory for intervals of less than 60 ft [18 m]. For longer intervals it is more difficult to fill all the perforations equally and, if the interval is 100 ft or so, an average placement efficiency of only about 0.1 ft^3/ft



☐***Effect of particle-carrier fluid density ratio on perforation-pack efficiency—percent volume of perforation filled with gravel. Efficient packing may be achieved with a density ratio between 1.05 and 1.8. This range may be designed using low-density ISOPAC particles. ISOPAC particles have a polymer coating with a low-density ceramic core. Conventional gravel provides a ratio of about 2.4.***

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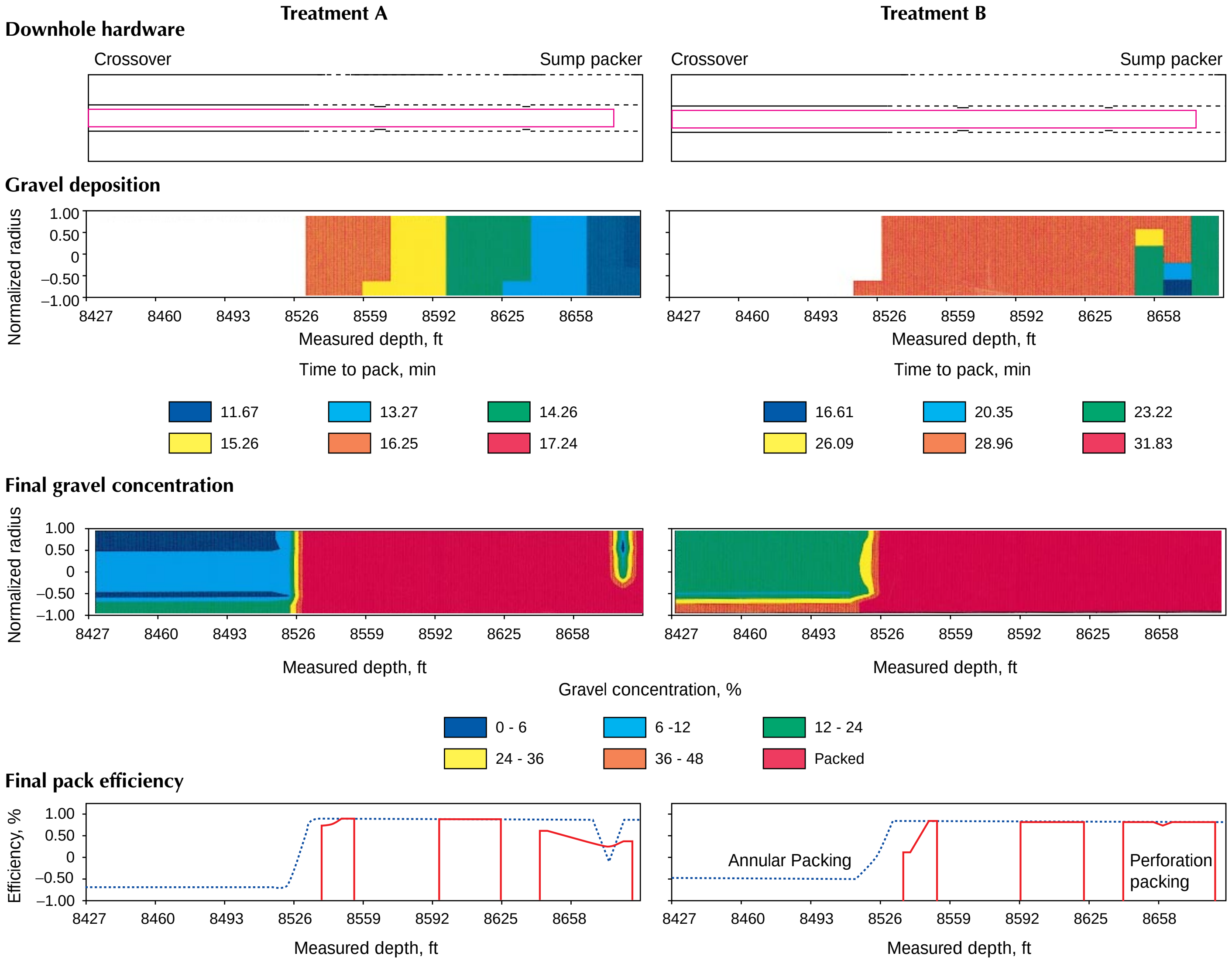
[18] Hudson TE and Martin JW: "Use of Low-Density, Gravel-Pack Material Improves Placement Efficiency (Part 2)," paper SPE 18227, presented at the 63rd SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, October 2-5, 1988.

Bryant D, Hudson T and Hoover S: "The Use of Low-Density Particles for Packing a Highly Deviated Well," paper SPE 20984, presented at Europec 90, The Hague, The Netherlands, October 22-24, 1990.



□*Comparing conventional* (treatment A) *and ISOPAC particle* (treatment B) ***placement. To aid the design of gravel-pack treatments, Dowell Schlumberger has developed PacCADE computer-aided design and evaluation software that can simulate gravel-packing operations. Plots of gravel deposition time to pack, final gravel concentration and final pack efficiency—all versus depth—may be used to compare proposed gravel-pack treatment designs. In treatment A using conventional gravel, the lowermost perforations have not been completely packed. In treatment B using lightweight ISOPAC particles in a prepack, good perforation packing efficiency has been maintained for the whole interval.***

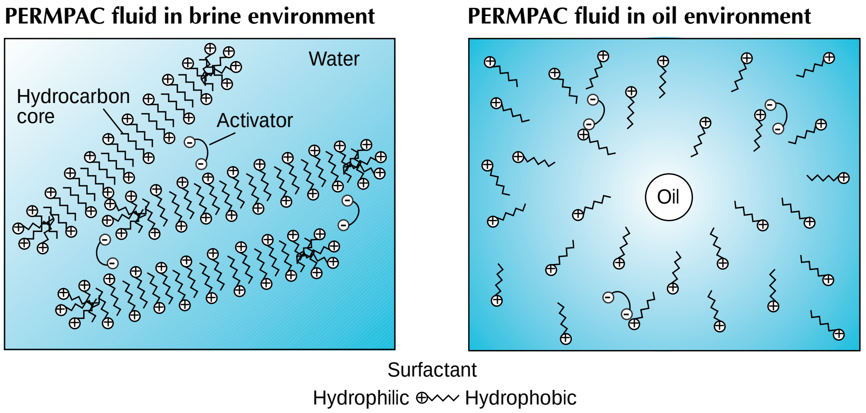
has been found to be common using conventional gravel. However, long-interval gravel packs using ISOPAC particles have easily exceeded these figures. For example, in the Norwegian North Sea, a 400 ft [122 m] interval was packed with an efficiency of 0.64 ft^3/ft.

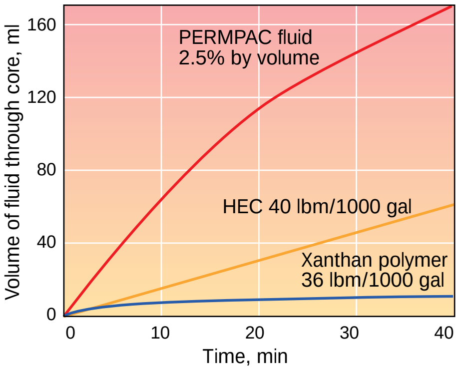
While gravel and placement technique are being selected, the carrier fluid must also be chosen. In some cases, plain water is used. In others, additives are used to increase carrier-fluid viscosity. High-viscosity fluids are commonly water-base, although oil-base fluids are used for severely water-sensitive formations. Water-base fluids are gelled with familiar stimulation chemicals like hydroxyethyl cellulose (HEC) or xanthan polymer. To reduce the concentration of nonhydrated polymer that may damage the formation, fluids gelled with these polymers are often sheared using a pump and filtered prior to blending with the gravel.

Breaker is added to reduce fluid viscosity once the job is complete and therefore minimize formation damage.[19] HEC is normally the polymer of choice because it has low residue after breaking and does not build a filter cake on the formation, minimizing permeability damage.

A radically different type of gelling agent, developed by Dowell Schlumberger, uses PERMPAC viscoelastic surfactant-based carrier fluid. This fluid forms rod-shaped micelles that have a high viscosity in low-concentration aqueous solution. It shows high rates of leakoff into the formation, and has good suspending capabilities compared to conventional polymers. Unlike HEC, PERMPAC fluids do not require a breaker because they are thinned by temperature and shear, and by crude oil or organic solvents, all of which tend to increase as the fluid penetrates deeper into the formation (*above, right*).

To improve perforation packing, both conventional and high-density circulating gravel packs may be preceded by prepacks—where the perforations are filled with gravel either before the screen has been run in hole or as a separate operation prior to packing the casing-screen annulus. Perforations can be prepacked effectively using either water or gelled fluid provided fluid loss into the formation is finite.[20]





□***Leakoff tests** (left) **for different carrier fluids. The leakoff for three fluids—containing respectively the PERMPAC system, hydroxyethyl cellulose (HEC) and xanthan polymer, in concentrations that give equivalent viscosity—were tested on Berea sandstone cores with nominal air permeabilities of 300 millidarcies. The PERMPAC fluid shows an enhanced leakoff, because contact with oil causes the fluid's micelles to break up** (above). **Final leakoff rate becomes constant as contact with oil is reduced.***

Prepacking prior to running the screen, as outlined in the Forth field example (see "Gravel Packing Forth Field Exploration Wells," *page 48*), is used to limit the penetration of LCM into the perforation tunnels during tripping. Determining the prepack volume is important. Too little gravel will result in the LCM penetrating unpacked perforations. Too much may necessitate a trip to clean out the excess in the sump and covering perforations. Volume depends on a number of factors, such as the competence of the formation, the quality of the cement job, the design and size of the perforation charges, the extent of cleanup flow after perforation and the formation permeability.

Prepacking with the screen in place is carried out with the service tool in the squeeze position before the annular pack is circulated into place. The process takes less time than the alternative prescreen technique.

The prepack may be pumped as several stages of gravel slurry interspersed with stages of acid to clean up damage around the perforations. The gravel slurry not only prepacks the perforations but also acts as a diverter, probably because of pressure that results when the higher viscosity carrier fluid leaks off into the formation. Diversion ensures that more perforations are acidized and then prepacked than would normally be the case.[21]

Sometimes acidization is carried out as a separate stage, prior to the gravel pack. The primary aim of this treatment is to increase the rate at which the carrier fluid will leak off during the subsequent gravel pack, although the acid also stimulates the well. When stimulation is required that matrix treatments cannot deliver, one alternative is to create short, wide fractures by carrying out a tip-screenout fracturing treatment followed by a circulating gravel pack (see "Rewriting the Rules for High-Permeability Stimulation," *page 18*).

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[19] Gulbis J, Hawkins G, King M, Pulsinelli R, Brown E and Elphick J: "Taking the Breaks Off Proppant-Pack Conductivity," *Oilfield Review* 3, no. 1 (January 1991): 18-26.

[20] Penberthy WL Jr and Echols EE: "Gravel Placement in Wells," paper SPE 22793, presented at the 66th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 6-9, 1991.

[21] Matherne BB and Hall BE: "A Field Evaluation of a Gravel-Diverted Acid Stimulation Prior to Gravel Packing," paper SPE 19741, presented at the 64th SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, October 8-11, 1989.

Evaluating the Gravel Pack

With the gravel pack in place, there are two elements to be evaluated: that gravel has been packed everywhere it was supposed to go, and that the well is producing hydrocarbons satisfactorily.

Since voids in the pack may lead to early completion failure, postpack evaluation is essential to detect incomplete fill and allow repairs to be undertaken. Prior to placement, gravel may be coated with radioactive isotopes and the pack assessed using gamma ray logging. However, the coating is usually inconsistent and may wash off, making quantitative analysis unreliable.

One way to improve the accuracy of such logs is to use ISOPAC particles that have been manufactured with isotope encapsulated within each particle's resistant shell. This also offers increased subtlety through use of multiple isotopes. The perforations may be prepacked using particles containing scandium followed by particles containing iridium. Packing placement efficiency can be monitored, using a multiple-isotope, gamma spectroscopy tracer log (*right*).

Alternatively, the effectiveness of fill may be gauged using nuclear density logging to estimate the density of material in the annulus. However, not all changes in density are related to changes in gravel-pack quality—changes in the screen, pipe base, casing, tubing and formation sand all affect the reading. A base log run prior to the gravel packing can iron out these discrepancies (*next page, left*). In addition, a reference screen may be set below the sump packer to register zero pack response.[22]

Density measurement is not appropriate when the completion fluid has a high density (more than 14 lbm/gal) or where low-density particles have been employed. In these cases, neutron activation logging can be used. The neutron activation logging technique uses a pulsed-neutron logging tool modified to allow a gamma ray device to be mounted below it. The pack is bombarded with fast neutrons. Silicon and aluminum in the gravel are activated and gamma rays are emitted as the elements return to their natural stable state. The number of gamma rays is proportional to the amount of silicon and aluminum activated, and pack quality may be inferred. [23]

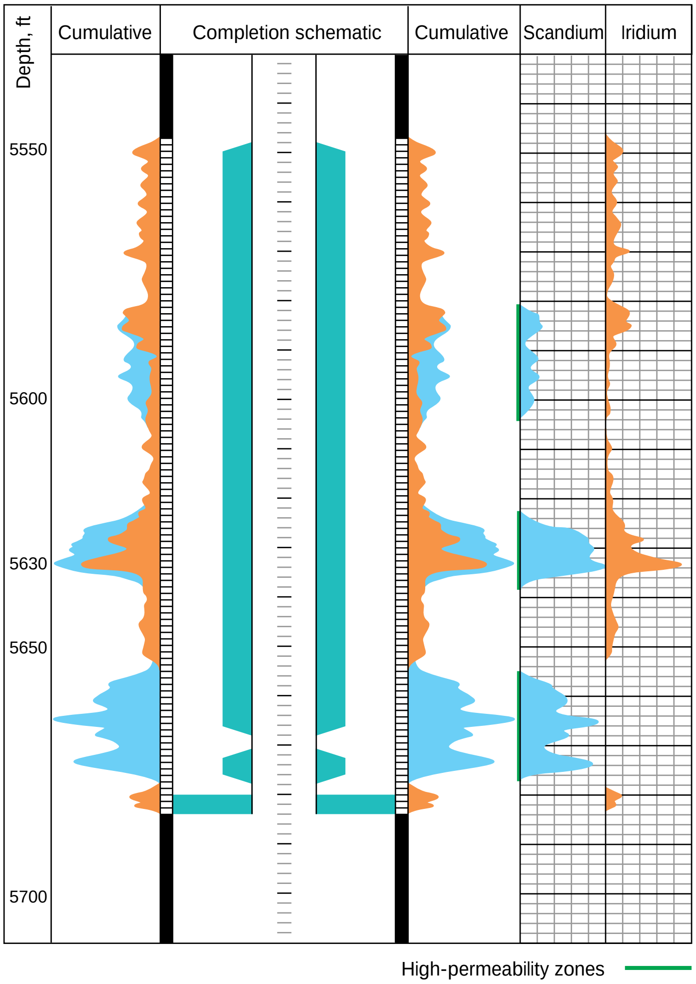
In openhole packs, a compensated neutron log can be used to detect hydrogen-rich fluids in the gravel-pack pore space, making it sensitive to changes in pack porosity. The tool's near and far detectors are used to partly eliminate the effects of hole conditions. The curves of the two detectors are scaled to overlay in areas of low porosity—good pack. Areas of high porosity—poor pack—are indicated by a shift of the curves, especially the near-detector curve, toward decreasing count rate (*next page, top right*).

Once voids in the pack are identified, a wireline shaking device attached to the evaluation tools may be used to break up bridges and allow the pack to settle. The shakes create local turbulence in the fluid which agitates the bridged gravel until it settles into the void.[24]

The other main strategy for testing gravel packs centers on assessing performance using well tests and production logging. In assessing gravel pack performance a number of diagnostics are available, including skin factor (which measures formation damage as a function of its permeability) and multirate flow tests.[25]

Differentiating between the effects of the formation and the gravel pack, often requires a DST prior to packing. With these data it is possible to identify the pressure

Multiple Isotope Log



□***Isotope logging of a prepack using ISOPAC particles containing scandium and iridium. The initial slurry with particles containing scandium tracer packed the three high-permeability zones. Then a slurry with particles incorporating iridium was pumped that filled in the zone at 5630 ft and diverted to the remainder of the perforated interval. The cumulative tracks—the superposition of scandium and iridium— indicate 100% perforation packing over the entire interval.***

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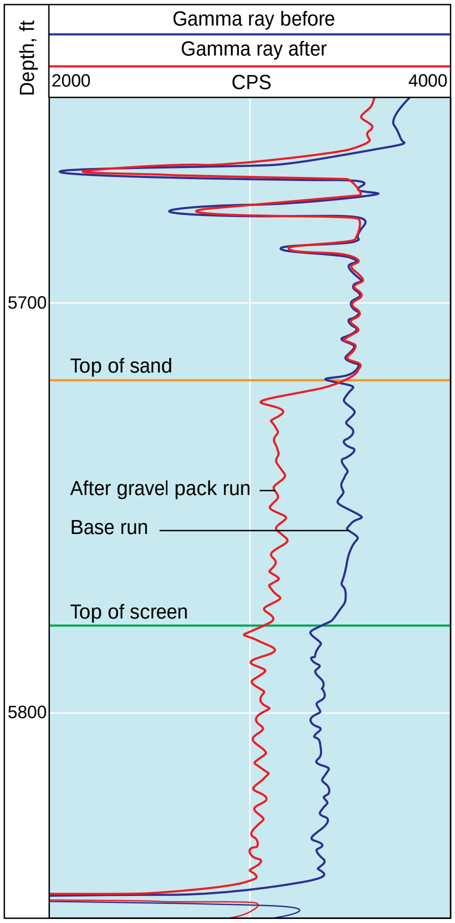
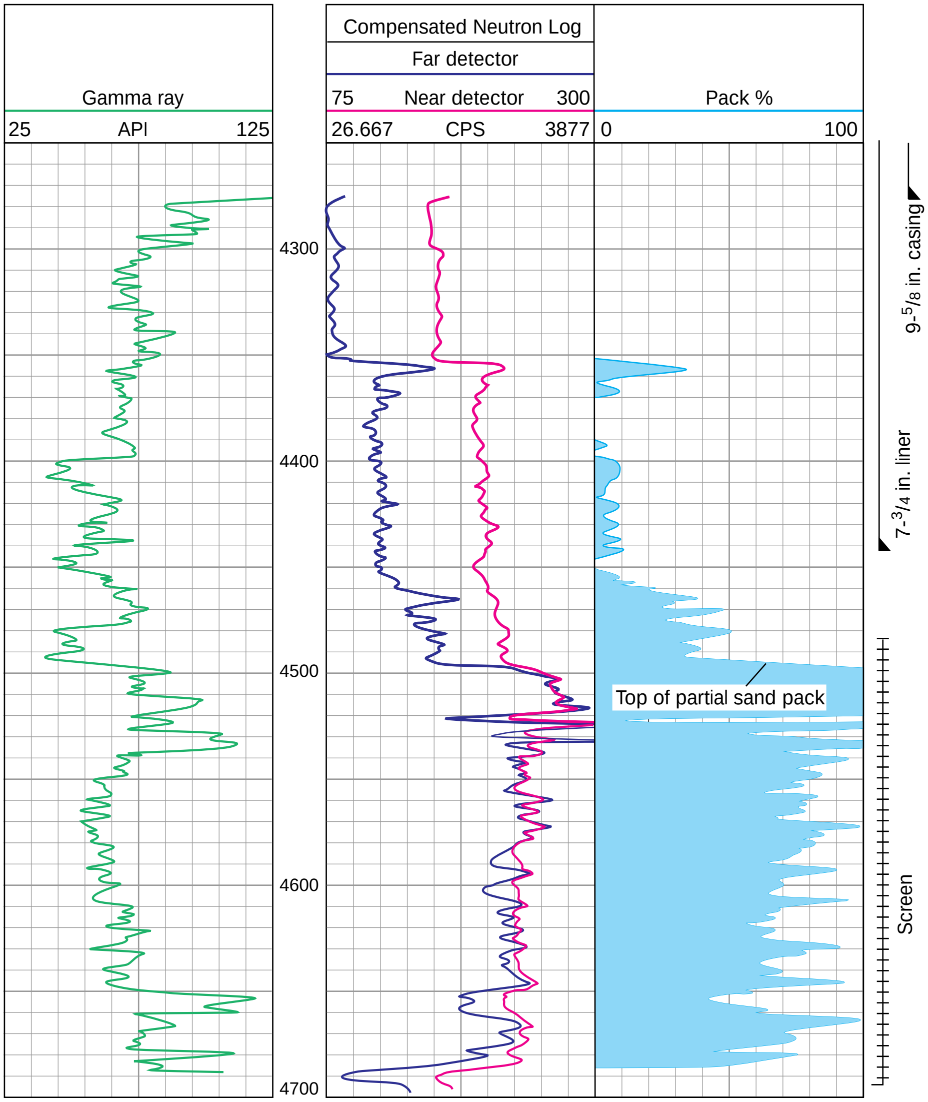
22. Gilchrist JM and Gilchrist AL: "A Review of Gravel Packing in the Forth Field," paper SPE 23128, presented at the Offshore Europe Conference, Aberdeen, Scotland, September 3-6, 1991.
23. Watson JT, Carpenter WW, Carroll JF and Smith BC: "Gravel Pack Field Examples of a New Pulsed Neutron Activation Logging Technique," paper OTC 6464, presented at the 22nd Annual Offshore Technology Conference, Houston, Texas, USA, May 7-10, 1990.
24. "Jim Carroll: The Gulf Coast WID Kid," *The Technical Review* 35, no. 2, (April 1987): 19-26.
25. Deruyck B, Ehlig-Economides C and Joseph J: "Testing Design and Analysis," *Oilfield Review* 4, no. 2 (April 1992): 28-45.
26. Unneland and Waage, reference 9.

drop caused by the gravel pack. Production logging may be used to evaluate each layer in the formation assessing the flow profile across the interval.[26] Gravel-pack performance versus time is another indication of performance. Pressure drop across the pack is one measure. An increase could indicate that fines like kaolinite have migrated into the pack and around the gravel or that unpacked perforations have collapsed.

In the past, the successful accomplishment of a gravel-packing operation has often been the main criterion used to judge its success. This judgement often fails to consider that the treatment may have damaged the well. Today, more attention is being paid to performance, and completion engineers are increasingly seeking ways of stopping formation sand without seriously restricting productivity. —CF



□***Nuclear density logging of a gravel pack. Running a base log prior to gravel packing allows the density effects of the bottomhole assembly to be taken into consideration and the gravel pack to be evaluated.***



□***Compensated neutron log of a gravel pack using near and far detectors. The near detector is affected mostly by the screen and wellbore fluids. The far detector is affected by the gravel pack, the casing, and in some cases the formation and its fluids.***