The Ultrashort-Radius Radial System

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Summary. A group of interrelated horizontal drilling and completion technologies, collectively called the ultrashort-radius radial system (URRS), was developed and is being progressively applied in the field. Multiple radials can be placed at the same level and on multiple levels. Three-dimensional (3D) surveying is supplied. Horizontal completions can be provided, including 100%-fill gravel packing, in-situ electrolytic perforation and cutting, and flexible sand barriers (FSB's). Initial field applications were in unconsolidated formations.

Introduction

The URRS was developed, tested, and applied over the past 10 years. This paper reviews the drilling and completion technologies, presents results from initial field applications, and outlines ongoing research. With this technology, more than 27,000 ft [8230 m] was drilled and more than 500 horizontal radials were placed by use of various embodiments of the system.

System Concepts

The objective for the URRS is to provide an extended wellbore radius by means of multiple radials from a vertical wellbore (i.e., to effect an extended completion or extended piped perforations). These radials may be placed in one layer or multiple layers, depending on reservoir thickness and vertical communication. Figs. 1 and 2 show two arrangements of multiple radials in multiple layers.

The choice of radial length, number of radials, and radial array is a function of the reservoir properties. A study to optimize these radial parameters for various reservoir conditions is currently under way. The specific variables included in this study are reservoir thickness, vertical and horizontal permeabilities, oil properties, well spacing, outer-boundary reservoir pressure, gravity drainage, thermal and nonthermal processes, and presence of impermeable partings within the reservoir. The choice of radial length and arrangement generally is unique to each reservoir.

System Processes and Equipment

The basic URRS uses an erectable whipstock lowered downhole by a 4½-in. [114-mm] workstring into an underreamed cavity or hydraulically slotted opening of 22-in. [56-cm] diameter. The whipstock (Fig. 3) is designed for use in a 7-in. [178-mm] casing. The drillstring is made of 1¼-in. [32-mm] electric-resistance welded tubing (A-606). The drillstring may be provided from a coiled-tubing rig or it may be fabricated on site from 30- to 40-ft [9- to 12-m] tubing joints.

A hydraulic drill head is welded to the nose of the first joint of the drillstring (radial tube). If the drillstring is fabricated on site, subsequent 30- to 40-ft [9- to 12-m] joints of drillstring are welded by automatic computer-controlled welding on the rig floor to form the drillstring. A hydraulic motion controller that regulates rate of penetration (ROP) is welded to its tail.

As the drillstring is fabricated, it is lowered inside the vertical 4½-in. [114-mm] workstring. The nose (drill head) of the drillstring enters a high-pressure removable seal at the top of the whipstock. The seal provides the bottom closure of the workstring. Hence, the 1¼-in. [32-mm] drillstring is fully contained within the 4½-in. [114-mm] workstring at the outset of drilling (Fig. 3).

A wireline cable attached to the tail of the drillstring runs to the surface within the workstring and passes through the top closure of the workstring. Thus, a long sealed chamber containing the 1¼-in. [32-mm] drillstring and its connecting cable is created by the 4½-in. [114-mm] vertical workstring.

Water drilling fluid at 8,000 to 10,000 psi [55 to 69 MPa] is pumped into the long vertical workstring at the surface with a conventional fracture pump. The drilling fluid is then pumped down the workstring where it enters the drillstring. The internal water pressure of the drilling system propels the drillstring through the high-pressure bottom seal and through the bending and confining slides and rollers of the whipstock. Traversing the 12-in. [30-cm] radius and 90° bend of the whipstock, the drill head enters the formation horizontally. The drillstring is not rotated.

These separate components of the URRS—the drillstring, the motion controller, and the whipstock—combine to propel and to control the motion of the drillstring into, through, and out of the whipstock, resulting in three load conditions of the drillstring.

The first URRS component related to propulsion and control is the drillstring (radial tube), which is propelled out of the vertical workstring by the fluid pressure within the workstring.

The second component is the motion controller (Fig. 4) on the tail of the drillstring, which acts as a hydraulic restraint. In essence, it is a piston with external seals that slide within a special smooth borehole portion of the vertical workstring. The high-pressure water pushes on the top of the motion controller, and water is trapped between it and the high-pressure seal at the bottom of the workstring. Water can escape only through a central orifice within the controller (Fig. 4). The result is a hydraulic restraint, or brake, on the forward motion of the 1¼-in. [32-mm] drillstring.

The third URRS component of the propulsion and control system is the whipstock, which bends the drillstring from vertical to horizontal.

Fig. 5 shows the loads on the drillstring that result from propulsion and restraint forces. In its passage into, through, and out of the whipstock, the drillstring is subjected to axial, internal-pressure, and bending loads.

In Section A of the drillstring (above the high-pressure seal), the drillstring stresses are below the elastic limit. In Section B, where the drillstring is below the high-pressure seal and within the whipstock, the drillstring stresses exceed the elastic limit and the drillstring deforms plastically. Because the drillstring is internally pressurized and is constrained by rollers and slides within the whipstock, it does not buckle while it is being bent. In Section C, the 1¼-in. [32-mm] drillstring exits the whipstock horizontally. There it is under only axial and internal-pressure loads. Again, the stresses are below the elastic limit.

The pressure on the water drilling fluid in the system not only propels the drillstring, but also drills the horizontal borehole in the formation. To drill the formation, the water drilling fluid is accelerated through the conical-jet drill-head nozzle, creating a conical shell of water particles traveling at 800 to 900 ft/sec [244 to 274 m/s].

Fig. 6a shows a schematic of the conical jet. At the top of the figure is a standard collimated jet nozzle. The addition of fixed vanes within the nozzle causes a conical shell of high-velocity water particles to form a conical jet (Fig. 6b). The size of the horizontal borehole is established by the twist of the vanes, which in turn controls the angle of divergence of the cone of water particles. Figs. 6c and 6d show vanes for two different conical angles.

Fig. 7 shows water jets resulting from various degrees of vane twist in 1-microsecond flash photographs of a collimated jet and two different conical jets. The conical angle is not affected by drilling-fluid pressure. These conical jets function at both ambient and elevated backpressures. At higher backpressures, cavitation does not appear to be an important cutting mechanism. Fig. 8 shows test results of submerged conical jets at ambient and elevated backpressures (2,000 psi [13.8 MPa]).

The conical jets cut through unconsolidated and consolidated formations and produce a radial borehole with a diameter of about 4 in. [10 cm] or more in unconsolidated formations; a smaller-diameter hole is produced in hard rocks. Its ROP is 6 to 60 ft/min

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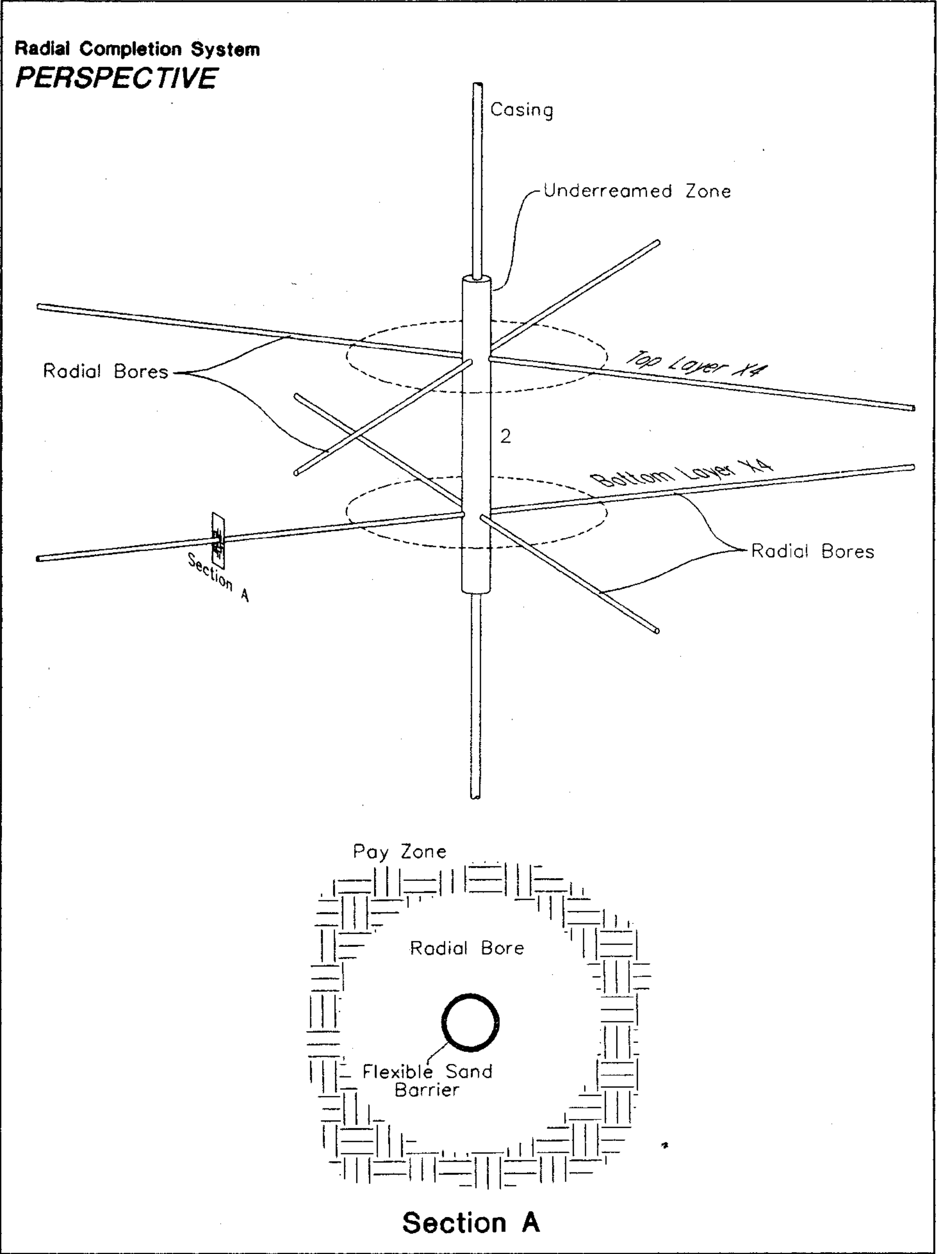


Fig. 1—URRS.

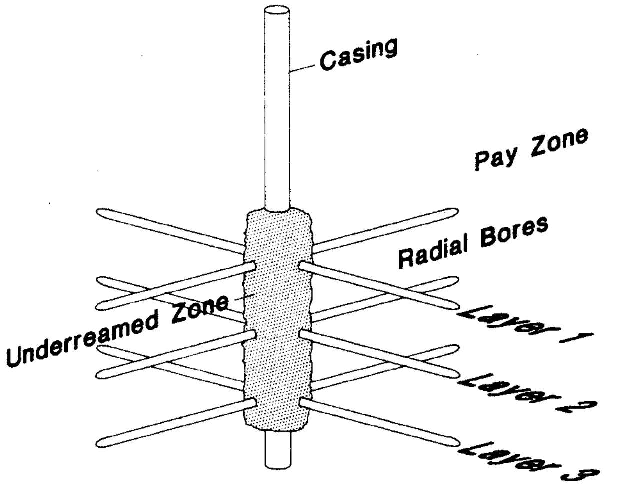


Fig. 2—Multiple-radial completion.

[0.03 to 0.3 m/s] in unconsolidated formations and about ½ ft/min [0.003 m/s] in hard rocks (e.g., granite). Typical oil-bearing rocks (e.g., sandstones and limestone) are penetrated at ½ to 10 ft/min [0.003 to 0.05 m/s].

Whipstock. Fig. 3 shows the basic whipstock configuration, a doubly curved inverted question mark. Inside the URRS whipstock is a series of rollers and slides that causes a progressive deflection and bending of the 1¼-in. [32-cm] drillstring as it moves through the whipstock.

The whipstock is held in place by downhole anchor jaws engaging the well casing. The anchoring jaws are set by rotating the 4½-in. [114-mm] vertical workstring. To erect the whipstock, the workstring is raised about 1 ft [30 cm] by the blocks. The resulting vertical motion erects the whipstock. The workstring and whipstock are held erect by a set of hydraulic cylinders at the wellhead that maintains constant tension.

After each radial placement, the steps are reversed. The whipstock can then be de-erected, rotated, and re-erected downhole without losing its calibration. A gyroscope is used to set the whipstock azimuth for each radial. Thus, multiple radials can be placed

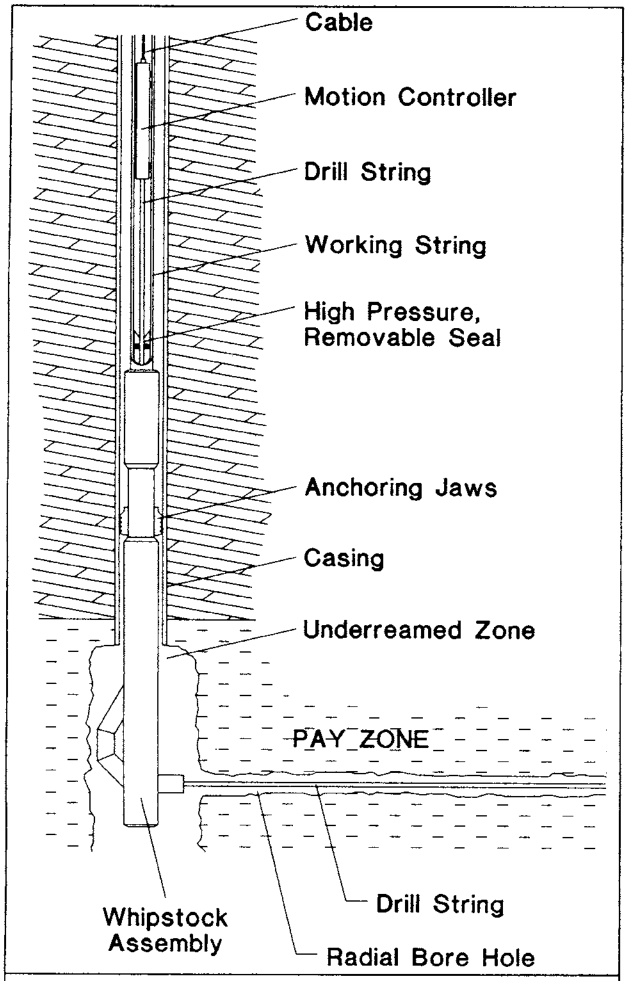


Fig. 3—URRS.

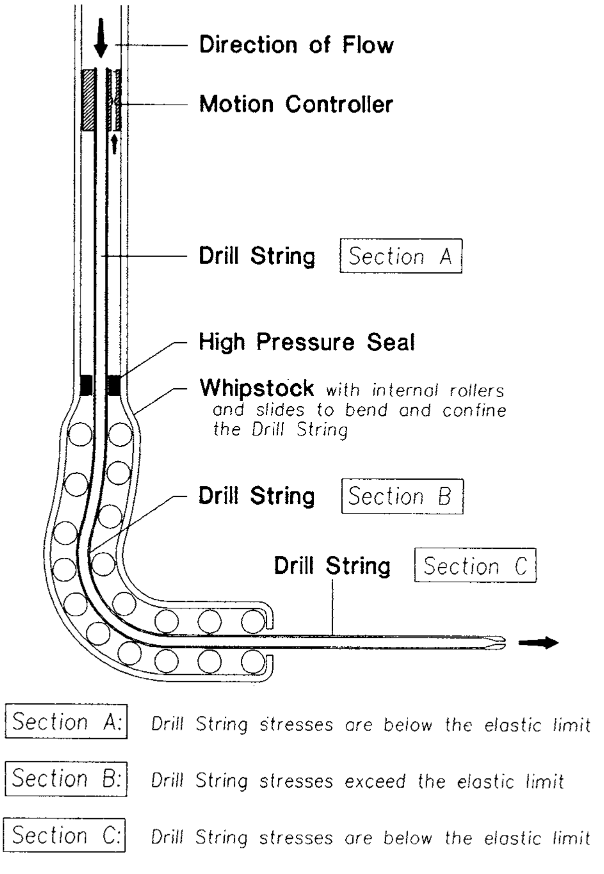


Fig. 5—Stresses on drillstring.

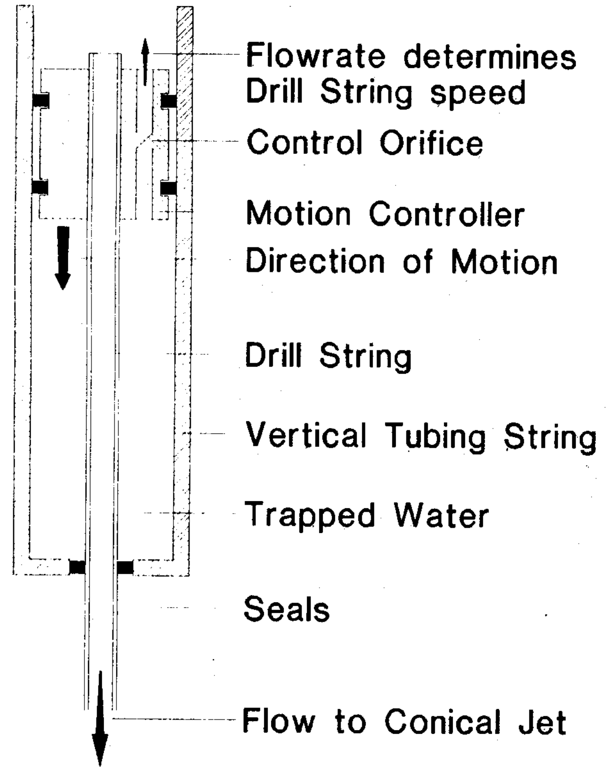
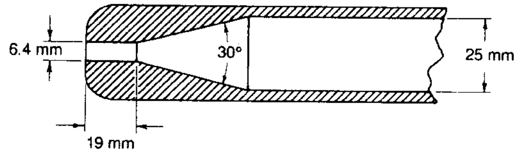
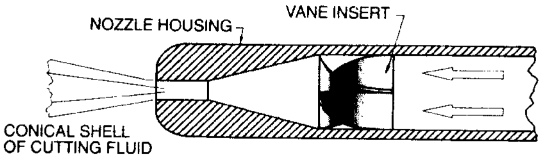


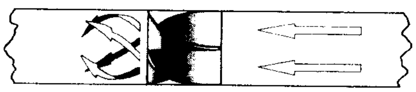
Fig. 4—Penetration control while drilling.



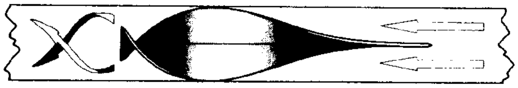
a) LEACH AND WALKER CONFIGURATION



b) CONICAL JET NOZZLE IN SECTION

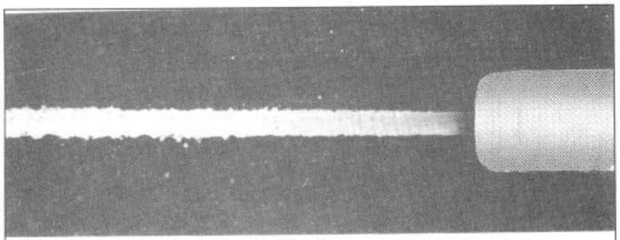


c) VANE USED IN 30° CONICAL JET NOZZLE

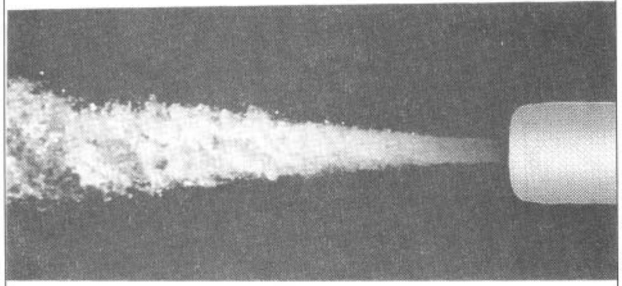


d) VANE USED IN 10° CONICAL JET NOZZLE

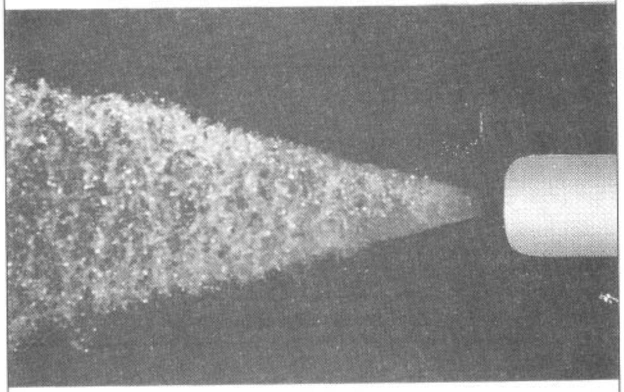
Fig. 6—Conical jet nozzle.



a) Leach and Walker nozzle at 0.4 MPa

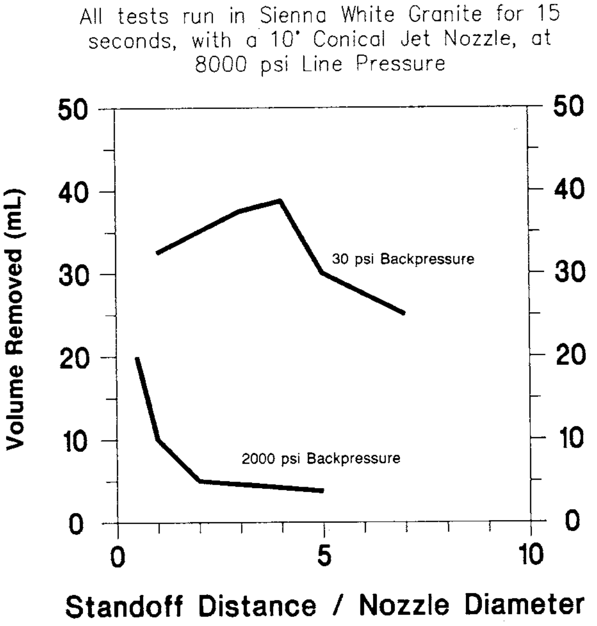


b) 14° Conical Jet nozzle at 0.4 MPa



c) 30° Conical Jet nozzle at 0.4 MPa

Fig. 7—Water jets.



All tests run in Sienna White Granite for 15 seconds, with a 10° Conical Jet Nozzle, at 8000 psi Line Pressure

Fig. 8—Backpressure and standoff tradeoffs.

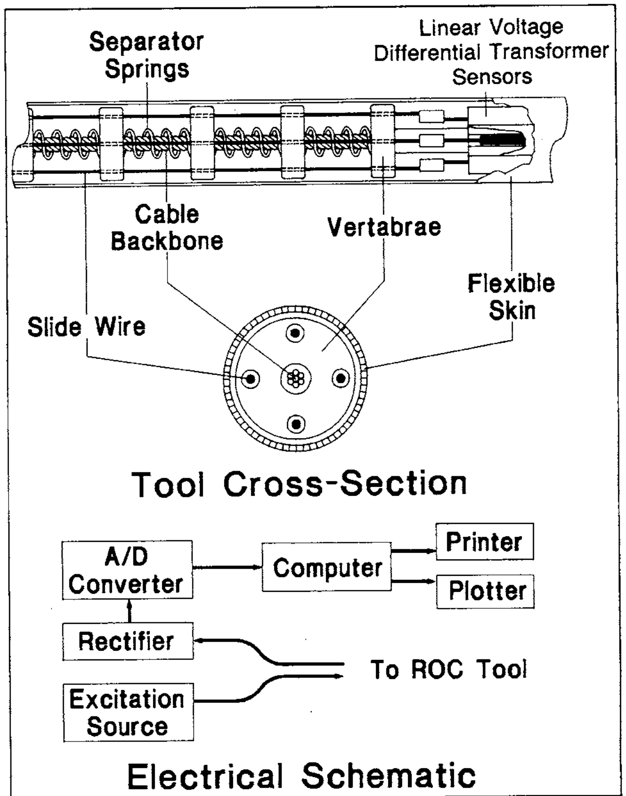


Fig. 9—ROC tool.

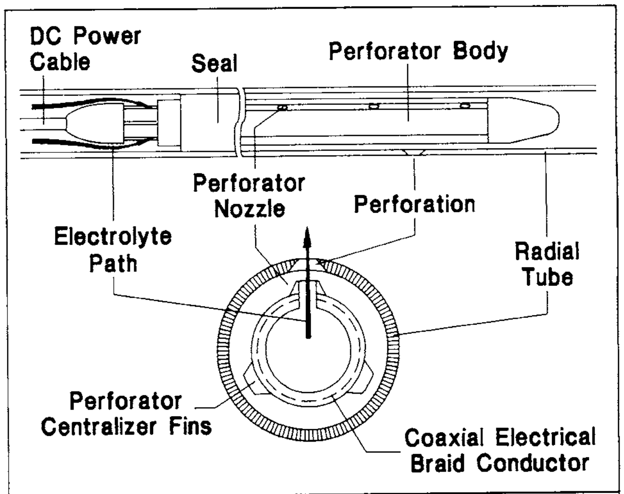


Fig. 10—Electrochemical perforator.

at different azimuths downhole without having to trip the whipstock back to the surface between each successive radial.

3D Positional Survey. After each radial borehole is drilled, the 1¼-in. [32-mm] drillstring can be surveyed to determine its trajectory with special flexible radius-of-curvature (ROC) survey tools designed to pass through the 12-in. [30-cm] (or smaller) bend radius of the drillstring. The ROC survey tool was developed to provide both plan (azimuth) and profile (up/down trajectory) data. It is pumped down the workstring and enters and passes through the drillstring as a wireline tool. The tool (Fig. 9) resembles an animal backbone and has long slide wires placed at each quadrant that move within vertebrae attached to a flexible, torque-resistant, wire-cable backbone. The slide wires actuate very precise sensors that measure the movement of each slide wire separately, translating directly into the curvature of the ROC tool and, in turn, of the drillstring.

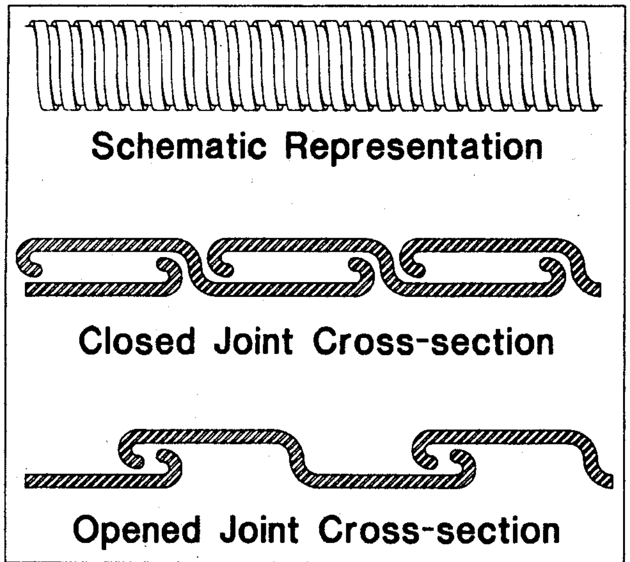


Fig. 11—FSB.

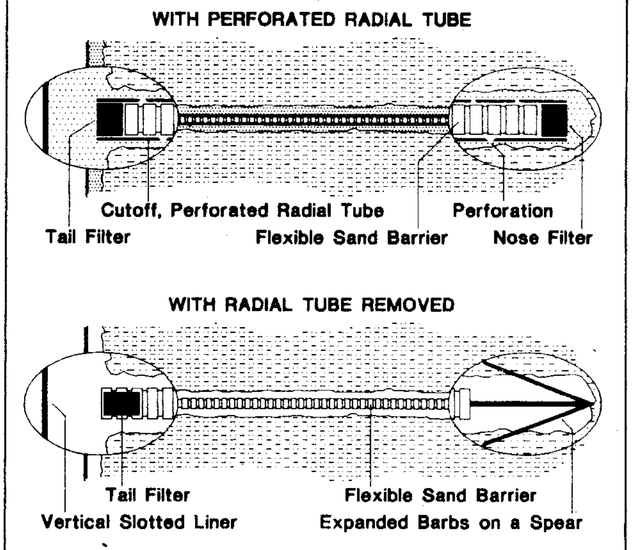


Fig. 12—FSB.

Within the ROC tool are an inclinometer and a roll sensor. All these data are transmitted to the surface by wireline. The curvature is converted into conventional azimuth and inclination by uphole software, providing a 3D printout of both the azimuth and the borehole inclination.

Completion Technologies. Fig. 3 shows the radial borehole condition after drillstring placement. At that point the system consists of a horizontal radial borehole containing a drillstring with its drill head in place. To provide sand control or flow regulation, the radials may be completed by alternative processes.

The first process involves only an FSB and includes (1) electrochemical cutoff of the drill head from the drillstring; (2) pumping down of the FSB through the open-ended drillstring to permit a barbed spear anchor to expand against the formation; and (3) withdrawal of the drillstring to leave the FSB anchored in place.

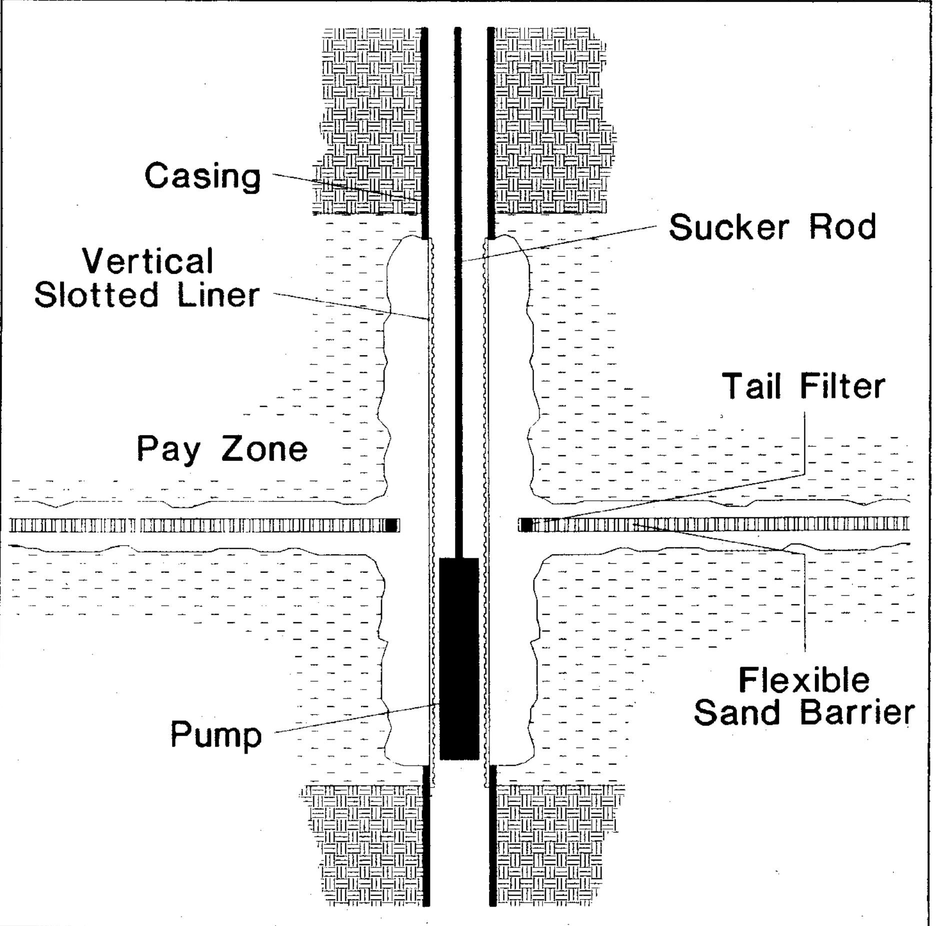


Fig. 13—Completed radial system with gravity drainage.

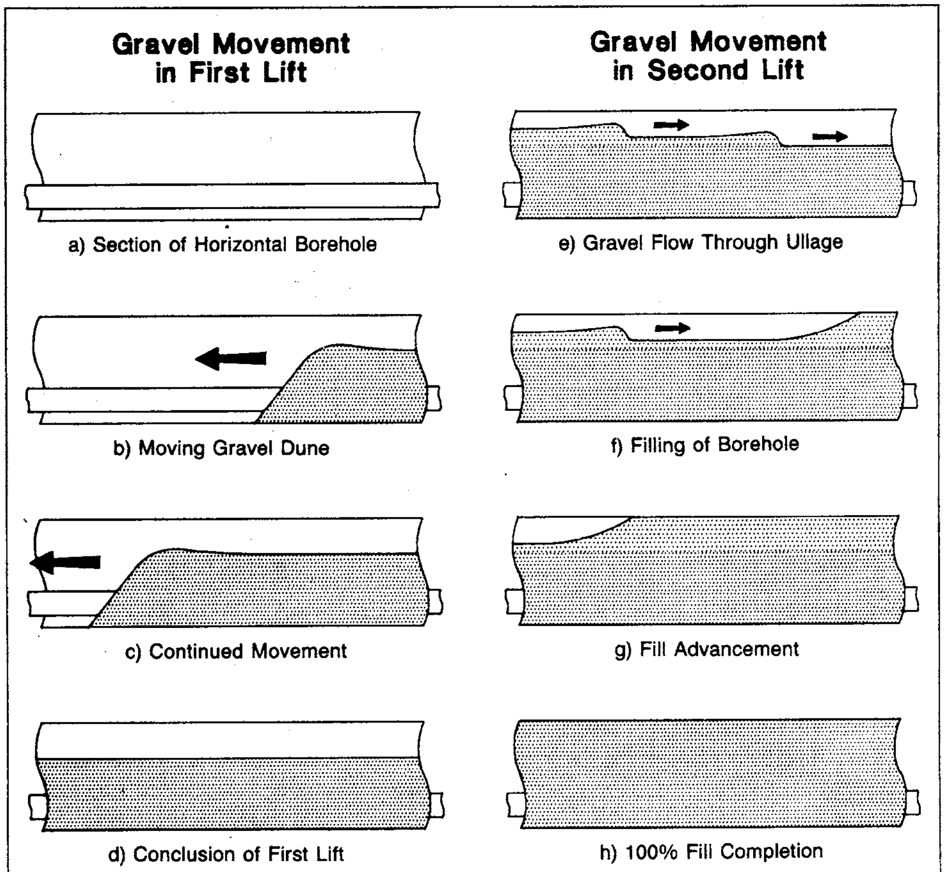


Fig. 14—Progressive stages of gravel packing.

The second alternative process involves use of the drillstring as a radial tube for production. It includes gravel packing, perforation, and the FSB with (1) electrochemical cutoff of the drill head from the drillstring, (2) a two-step (two-lift) gravel-packing process to provide 100% fill of the radial borehole annulus around the drillstring, (3) electrochemical perforation of the drillstring along its entire length downhole after the first lift of gravel packing, and (4) placement of the FSB within the 1¼-in. [32-mm] drillstring to minimize gravel entering the drillstring through its perforations.

Electrochemical Cutoff. The first electrochemical process is to cut off the drill head at the nose of the drillstring after placement. The cutoff tool is simply an insulated metal disc connected by an electric cable to an electric well or power source. A cable stop is placed on the cable that will stop at the top of the drillstring and accurately locate the cutting tool at the desired position.

Electrochemical cutoff can be thought of as a controlled corrosion process in which a current is passed between a cathode (tool) and an anode (drillstring). In the presence of an electrolyte (e.g., brine and DC), an electrochemical reaction occurs that puts iron from the drillstring into a solution, forming a precipitate (sludge) and gaseous byproducts (H_2 and O_2). (The volume of precipitate is very small.)

The electrochemical cutoff tool has been used successfully in the field to cut off more than 500 drillstrings. The process does not appear to be affected by depth. The advantage of electrochemical cutting over explosives is that no shattered pipe or sharp edges are formed. The tool is very cost effective and reliable downhole. The electrolyte can be selected to be compatible with most formations. The low volume of corrosion byproducts has had no observed deleterious effect on the wells. The power supply is a common welding machine.

Electrochemical Perforation. Perforation by electrochemical processes is accomplished downhole after the 1¼-in. [32-mm] drillstring is in place. A flexible tube (Fig. 10) is pumped down the vertical workstring and out through the 1¼-in. [32-mm] drillstring. The perforator tube contains an insulated flexible conductor within the tube wall. Small ports lined with electrically conductive material are installed in the tube and connect to the conductor within the perforator-tube wall. When brine is pumped down the well and enters the perforator tube, a jet of electrolyte flows through each port. An electric welder is used to create a DC in the perforator-tube conductor. Each port becomes an electrochemical drilling jet. The result is a series of oriented perforations in the 1¼-in. [32-mm] drillstring. These perforator tools provide about 120 simultaneous perforations that can be oriented in any direction.

FSB. A flexible slotted liner was developed to be used alone or to back up the perforations. It is a helically formed metal tube, superficially similar to conventional flexible-metal conduit for electrical wiring. The FSB may be pumped out of the cutoff nose of the 1¼-in. [3.2-cm] drillstring and anchored into the formation by an expanding set of barbs on a spear. The drillstring can then be pulled back to leave the bare FSB anchored in place.

Alternatively, the FSB may be pumped down the drillstring to serve as an inner slotted liner for the perforations. Fig. 11 shows a schematic and two cross sections of the FSB. Figs. 12 and 13 show schematic placements in a formation. Initial tests show a combined effect of good sand exclusion and effective transport of high-viscosity oil through the helical joints at low pressure drop.

Horizontal Gravel Packing. Gravel packing can be accomplished by a two-lift filling process with a water/gravel slurry. In the first lift, gravel is pumped down the drillstring and out of its cutoff nose. Conventional surface gravel-packing equipment is used. After leaving the open nose of the drillstring, the gravel slurry flows back toward the wellbore through the horizontal borehole annulus around the drillstring. Fig. 14 shows the progressive stages of gravel packing.

To gravel pack successfully during the first lift, the material must be pumped at a sufficient rate to ensure transport of the gravel within the 1¼-in. [32-mm] drillstring. We have found that a suitable pumping rate is in excess of 7 ft/sec [2.1 m/s]. Once the slurry mixture passes out of the drillstring at its open (cutoff) nose, the gravel slurry enters the annulus of the horizontal radial borehole, which is typi-

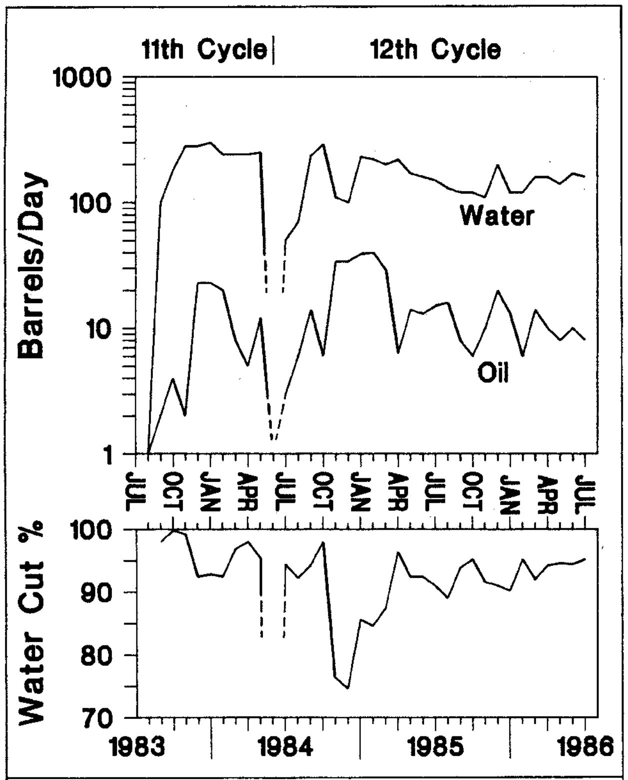


Fig. 15—Well 378 huff 'n' puff—comparison of last two cycles.

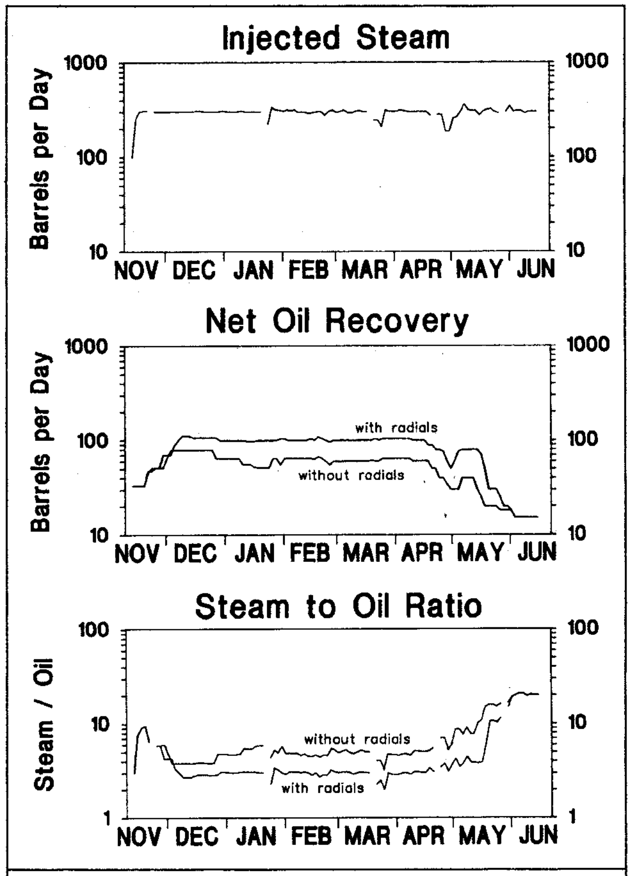


Fig. 16—Olinda field steamdrive five-spot production (1985-86) with and without radial on injector.

cally about 4 in. [10 cm] in diameter. This larger diameter of the radial borehole causes the slurry mixture to slow and the gravel to settle, forming a dune within the annulus that moves from the nose of the drillstring back toward the vertical wellbore. As the dune partially fills the radial borehole annulus, an ullage (a flow space with a flat bottom and curved top) is created between the top of the radial borehole and the deposited gravel dune.

The ullage is the foundation of the self-regulating characteristics of this horizontal gravel-packing process. If gravel gradually closes off the ullage in a sandoff, it causes the fluid velocity to increase and thus erode out, carrying more of the gravel back toward the wellbore. If the ullage enlarges, the velocity of the slurry slows and more gravel settles, forming a higher dune. In effect, if the water maintains a velocity of about 3 ft/sec [0.9 m/s] in the ullage, it remains open. Hence, gravel transport is self-regulating.

This self-regulation process was proved successful over a wide range of conditions, including 5- to 60-mesh screen sizes of gravel, drillstring inclinations ±20° off horizontal, and radial borehole diameters of 4 to 12 in. [10 to 30 cm]. For the process to work, it is necessary to keep the viscosity of the slurry liquid at or near that of water and the gravel concentration at about 0.1 to 4 lbm/gal [12 to 480 kg/m^3].

The volume of gravel used in the first lift is arbitrarily sized to fill to about 80% of the normal 4-in. [10-cm] borehole provided by the conical jet. There is no measurement of the fill percentage provided in the first lift because overfill or underfill is not important.

The second lift of horizontal gravel packing occurs after all radial boreholes on a level are drilled and gravel packed separately in a first lift. At that point all radials are partially gravel packed (70 to 90% or greater fill). The second lift, 100%-fill gravel packing of all radial boreholes, occurs automatically while the vertical underreamed zone of the vertical wellbore is conventionally gravel packed. The second lift uses the same type of fluid and slurry concentration as the first lift, but the gravel slurry flows out of the ullages of all the radials (see Fig. 14). The water enters the formation and the gravel progressively sands off each radial. Hence, it progressively fills back toward the vertical wellbore until all radials are fully packed.

Figs. 12 and 13 show total completion systems incorporating FSB alone or gravel packing and perforation and FSB placement in the drillstring.

Continuing R&D

The initial URRS applications had several limitations—e.g., requirement for real-time control of the drillstring trajectory when it extended beyond the 30-ft [10-m] zone of whipstock influence on the trajectory and the strength and design of the helical joint in the FSB.

Control While Drilling. To provide trajectory control for radials longer than 30 ft [10 m], the control-while-drilling system was developed and is now under field trial. Control is provided by automatic switching of multiple-reaction jets (side jets oriented perpendicular to the drill axis). An internal gravity sensor within the drill head provides real-time up/down and roll-position control.

FSB. The design of the helical joint in the FSB must combine high axial and torsional strengths with a satisfactory sand-filtering action. The initial commercially available FSB pulled apart when the 1¼-in. [32-mm] drillstring was removed. New designs are in hand and will be field tested.

Results

About 500 radials have been placed in various system embodiments. Most of these involved progressive improvement of the system, which is still under development.

Figs. 15 and 16 illustrate examples of field applications for two specific wells in unconsolidated formations. Fig. 15 shows the 11th and 12th cycles of a huff 'n' puff process (steam stimulation) from a typical well. Well 378 previously required a 6- to 9-month peri-

TABLE 1—PERCENTAGE IMPROVEMENT FOR FIRST 2¼ YEARS, WELL 378

Oil Production	Improvement (%)
Total	365
Daily	126

odic workover to remove sand and to maintain production. The 11th cycle is typical of its performance before radial placement. At the end of the 11th cycle, four ultrashort-radius radials were installed in the well, and the underreamed zone was gravel packed. The radial boreholes may have been partly gravel packed by a second-lift effect. A portion of the resulting 12th cycle demonstrates the improvement compared with the previous 11th cycle without radials. Table 1 shows the percentage improvement for the first 2¼ years. The well did not sand off in that period.

Fig. 16 presents two nearby five-spot steamdrive patterns. Both had very similar formation and mechanical properties. One pattern had a conventional vertical injector; the other had an injector with four ultrashort-radius radials. The same amount of steam was applied to both five-spots. Both produced net oil and the steam/oil ratio (SOR) improved significantly for the pattern where the injector had four radials. The average oil production was increased from 64 B/D [10.2 m^3/d] on the five-spot pattern without radials to 100 B/D [16 m^3/d] on the five-spot pattern with a four-radial injector. The respective SOR dropped from 4.6 to 2.9 bbl steam/bbl oil [0.7 to 0.5 m^3 steam/m^3 oil]. The net effect was increased production and a saving of about 2 bbl steam/bbl oil [0.3 m^3 steam/m^3 oil].

Conclusions

The URRS successfully demonstrated ten capabilities: (1) ultrashort-radius radials (1-ft [30-cm] radius); (2) multiple radials on the same level or multiple levels; (3) rapid penetration with conical jets, even at significant backpressure; (4) case while drilling (multiple long-piped perforations); (5) control while drilling; (6) 3D ROC survey; (7) 100%-fill bidirectional gravel packing; (8) electrochemical cutting and perforating; (9) FSB; and (10) horizontal completions to provide gravity drainage.

These capabilities may (1) permit wider spacing between steam-injection or oil-production wells, (2) provide better waterflood efficiency and production from thin reservoirs, (3) facilitate gravity drainage of low-pressure reservoirs, (4) avoid or eliminate water or gas coning when combined with polymers, (5) penetrate spaced vertical fractures, and (6) distribute heat more efficiently and economically in thermal projects.

Acknowledgment

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SI Metric Conversion Factors

bbl × 1.589 873 E−01 = m^3
in. × 2.54* E+00 = cm
psi × 6.894 757 E+00 = kPa

*Conversion factor is exact.

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