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Gravel Packing of Horizontal Wells

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ABSTRACT

One hundred percent gravel packing of horizontal wells has been demonstrated in the laboratory using bidirectional (two lift), water slurrified gravel packing. The first lift provides 70-90+% fill. A second, subsequent, reverse direction lift provides both 100% fill and consolidation. Deviation has been varied from 70° to 110°; the process is self-regulating.

INTRODUCTION

The process of gravel packing horizontal wells has greatly benefited from from the success of reverse gravel circulation, developed first by The Texas Company for vertical wells.[1,2,3,4] But problems arise when the axis of the well is rotated from the vertical to the horizontal, which fundamentally changes the gravity effects on sedimentation and gravel deposition. Hence the method to achieve a 100% gravel pack for a highly deviated well bore hole is different from that for a vertical bore hole.

As a part of a continuing research and development program for radial placement using water jet drilling, Petrolphysics has evolved a step by step Petrolphysics Radial Placement (PRP) system, which is described in References 5, 6 and 7. In summary, for an existing vertical well these steps include:

1. Section milling of a window in the existing vertical casing.
2. Underreaming the formation in the casing window.
3. Lowering an erectable whipstock into the underreamed zone on a conventional work string and positioning in azimuth with a gyro.
4. Erecting the whipstock.
5. Lowering a continuous electric resistance welded (ERW) tube through the working string into the whipstock high pressure seal.
6. Pressurizing the vertical working string and hydrodynamically propelling the ERW tube into the formation via a horizontal bore hole cut by the water jets.
7. Positional logging of the radial ERW tube.
8. Electrolytic cut-off of the drill head from the radial ERW tube.
9. First lift of gravel slurry into the horizontal bore hole.
10. Perforation of the radial ERW tube.
11. Placement of the outer end filter in the radial ERW tube.

12. Electrolytic cut-off of radial ERW tube at the whipstock exit.

13. Removal of the stub end of ERW tube and de-erection of the whipstock.

14. Reposition the whipstock and align its azimuth with a gyroscope.

15. Repeat steps 4-14 for additional radials.

16. Remove whipstock and working string.

17. Placement of a vertical slotted liner in the underreamed zone.

18. Gravel pack of the vertical underreamed zone and concurrent second lift of gravel into all horizontal bore holes.

THEORY AND DEFINITIONS

The basic theory underlying this work with horizontal gravel packing is derived from the mechanics and practice of slurry pipelines.[8,9,10] With them a wide spectrum and volume of material sizes, shapes and densities have been successfully transported for great distances. Much of the fundamental physics of this gravel packing system is derived from the technology and experience of the Slurry Pipeline Group of Bechtel.

Several new terms will be used in this paper regarding the two lift gravel packing process.

1. Radial ERW Tube: The radial ERW tube is a continuous electric resistance welded metal tube (A-606 Steel) which is propelled radially (horizontally) into a formation and remains as casing within the open horizontal bore hole. The propulsion force system for the ERW tube is totally hydrodynamic.

2. Drill Head: The drill head contains a Conical Jet[(7)] nozzle system capable of rapidly drilling both large or small diameter bore holes through both soft and hard formations using high pressure fluids.

3. Whipstock: The whipstock is a small, erectable rolling mill which bends the vertical ERW tube. It contains a set of low friction rollers and slides. To place a radial, the whipstock is lowered down a vertical well bore, then erected to provide a right angle turning mechanism from vertical to horizontal for the radial ERW tube.

4. Radial Tube Cutting and Perforating: The electrochemical cutting and perforating techniques herein use dc electric current combined with a pumped down KCl electrolyte.

Other special terms will be defined as they arise in the paper.

DESCRIPTION AND APPLICATION OF EQUIPMENT AND PROCESSES

PROCESS OBJECTIVES

The objectives set for the development of the horizontal gravel packing process include:

1. Applicable to a wide spectrum of formation permeabilities ranging from near impermeable to 5 darcys ($4.9 \times 10^{-12} m^2$).

2. Utilization of gravel of screen size from 5 to 60 mesh.

3. Adaptable to non uniform boreholes over the range of 2 - 12 in. (15 - 30 cm) diameter, 70^o-110^o deviation and helical or curved orientation.

4. Minimization of pickup and mixing of formation fines with the gravel pack.

5. Provides 100 or more simultaneous perforations in terms of : (a) Size: 1/8 - 1/2 in. (.3 - 1.3 cm), (b) Spacing: 3 - 12 in. (7.5 - 30 cm) and, (c) Pattern: axial or helical.

DESCRIPTION OF PROCESS

The basic method for the horizontal gravel packing described in this work is a two step (two lift) process. Consider that one or more radial bore holes (horizontal wells) are to be placed at the same level from a vertical well. The Petrolphysics Radial Placement (PRP) system provides such multiple, cased radial bore holes. Each contains a radial ERW tube. A schematic of the PRP system with the first of several radials at the same level is shown in Figure 1.

The first step application of this PRP system in an existing vertical well is to section mill the casing. The milled zone is then underreamed and a whipstock is lowered into that underreamed zone and aligned with a gyro to a desired azimuth. Typical dimensions with the initial commercial PRP system are: 1) Radial ERW tube: 1-1/4 in. (3.2 cm) OD by 1 in. (2.5 cm) ID, 2) High pressure screwed joint vertical working string:

2-7/8 in. (7.3 cm) and 3) Horizontal bore hole hydraulically cut into the formation: 4 in. (10 cm) diameter.

The radial ERW tube is placed into the formation as follows: First, the radial ERW tube is propelled by its own hydrodynamic forces and concurrently cuts the bore hole into which it moves. The radial drilling would proceed to the horizontal extent desired, typically 100-200 feet as shown schematically in Figure 1. The radial ERW tube would then be positionally logged with a flexible wire line tool. If the trajectory of the radial tube is satisfactory, the wire line logging tool is pulled back and an electrolytic cutting tool is pushed and pumped down the working string and out to the end of the radial ERW tube.

Next the drill head is electrochemically cut off. The electrolytic cutter which is attached to a commercial heavy duty electrical cable, is pushed and pumped into place and a 12% KCl solution is pumped down the working string. Electric power is supplied to the cable by a field electric dc welder or power supply (50 v, 100 amps) on the surface. The drill head is clearly and squarely cut off in 15 - 30 minutes. At this point in the process the first step or first lift of the two lift horizontal gravel packing process can begin.

As shown in Figure 1, the radial ERW tube provides a continuous high pressure conduit back through the whipstock into the vertical working string. The working string, in turn, provides a continuous high pressure fluid conduit to connect to the gravel slurry pumping system at the surface.

Water based gravel slurry, prepared by conventional equipment, is pumped down the vertical working string into the radial ERW tube and thence flows out the horizontal portion of the radial ERW tube, exiting at its outer end from which the drill head was cut off. As an example, for a 1 in. (2.5 cm) radial ERW tube, the slurry flow rate is controlled to about 20 gpm (1.5 l/s) so as to assure that the slurry velocity is above 7 ft/s (2.1 m/s) within that ERW tube. (Seven feet per second is the velocity which is generally required to slurrify the gravel.)

At the ERW tube exit, the velocity of the slurry rapidly drops to about 1/2 ft/s (0.2 m/s) in a normal 4 in. (10 cm) bore hole in the formation. Of course, the gravel immediately falls out of slurry suspension and a gravel dune is rapidly built up in the 4 in. (10 cm) bore hole, both in the forward direction (away from the vertical well bore) and in the reverse direction (back toward the vertical bell bore). The gravel dune fills the horizontal borehole cut by the water jet drill head to about 70 - 90+% fill .

The wedge shaped form of the leading edge of the deposited dune of gravel proceeds at about 1 ft/min (0.5 cm/s) back toward the vertical well bore. The slurrifying water fluid partitions into two paths within the horizontal bore hole. The principal portion of the water moves back to the well bore after having dropped its slurrified gravel burden. The other portion of the water enters the formation depending upon its permeability. The water moving back toward the vertical well bore is in an ullage flow space. (An ullage space is defined by a flat bottom, formed herein by the top of the gravel dune, and a curved top, formed herein by the horizontal bore hole in the formation.)

The water velocity in the ullage flow space appears to stabilize automatically at 1-3 ft/s (30 - 91 cm/s). If the water velocity is greater than 1-3 ft/s (30 - 91 cm/s), the gravel is washed ahead to open a larger ullage flow space. If the water velocity is less than 1-3 ft/s (30 - 91 cm/s), the gravel deposits more rapidly to fill in and reduce the cross section of the ullage flow space. Based upon many experiments with a widely varying conditions of flow, gravel concentration, gravel size and shape, this gravel deposition process appears to be virtually self-regulating.

The actual movement of gravel in the ullage space is not by slurrification. Instead the gravel moves by hopping (saltation) of individual gravel grains along the top of the gravel dune, much like the sedimentation process in a river bed. The net saltation velocity along the base of the ullage flow space on top of the gravel dune surface is about 1 ft/s (30 cm/s). The water in the ullage space remains clear as the gravel dune moves. The progressive movement of the dune in the first lift of gravel is shown in Figure 2.

In this process, the gravel dune movement continues through the total horizontal bore hole length. If gravel enters the underreamed zone, it will deposit in the underreamed zone or rat hole. Thus either the total gravel volume may be estimated or an experimental gravel dune location tool, later described, can be applied.

Excess gravel can be flushed out of the underreamed zone or rat hole. In any event, the first lift of gravel yields about a 70 - 90+% fill of the horizontal bore hole through the formation. Obviously, there are many side effects which will be discussed later.

The next step in this horizontal gravel packing process involves perforation of the horizontal portion of the radial ERW tube, which is an integral part of this gravel packing process. Explosive (shaped charge), chemical and mechanical techniques of perforation were tried. All caused failure of the 1 in. (2.5 cm) ID by 1.25 in. (3.2 cm) OD radial ERW tube. Hence an electrochemical technique was developed for perforation, similar to the cutting process for the radial ERW tube. Because the exit velocity of electrolyte is small, neither the gravel pack nor the formation are damaged thereby.

For this perforation process, a hollow electrical cable is pushed and pumped down the vertical well bore. It enters the radial ERW tube and is guided out to the full horizontal length of that ERW tube. The electrical perforating cable is shown schematically in Figure 3. Controlled positioning of the perforator cable, as with the electrochemical cutter, is by a chord bar attached to the perforator cable. (A chord bar is a stiff bar like a sinker bar that is attached to the perforator. It catches within the 90° whipstock turn of the radial ERW tube in a precise location. This chord bar thus provides a reproducible mechanical downhole location mechanism for all downhole tools and processes.)

The perforator cable contains about 120 small, spaced apart, metal lined ports which penetrate the cable covering and which are electrically connected to the internal wire braid of the perforator cable. The whole perforator cable is connected back to the surface by an electrical cable within the 2-7/8 in. (7.3 cm) working string and uses the same field electric dc welder or power supply (50v, 100 amps), as powered the cutting tool. (The electrolyte is also 12% KCl pumped down the working string.) This perforation process provides 120 perforations (sharp edged orifices), simultaneously. Perforation spacing can be selected within the constraint that 120 perforations can be made simultaneously because of KCl flow limits in this present tool. (KCl was selected as an electrolyte to avoid formation damage with swelling clays. The total required volume amount of KCl is small, 20 gpm (1.3 l/s) for 30 minutes, both for both cutting and perforating.)

The perforations are made with the first lift of gravel in place. In the laboratory tests, so long as the perforation size was smaller than about five times the 50 percentile average diameter of the gravel, the gravel bridged the orifices of the perforation, as predicted by the many early references and workers such as Coberly and Wagner[11] and Sage and Lacey[12].

Next a small wire brush, shown in Figure 4, is pushed and pumped down to act as a permeable plug or filter at the open cutter end of the radial ERW tube. It precludes gravel back filling the radial ERW tube during production operations. This filter placement step may be combined with the perforation process using an electrical fuse to release the wire brush filter and thus minimize tool trips down the hole. In the next step, a combination brush filter and electrolytic cut-off tool, can be applied to cut off and place a filter in the radial ERW tube just outboard of the whipstock. This latter filter unit also precludes any cuttings entering the radial ERW tube during additional radial placement operations. A chord bar is again used for positioning this tool downhole.

In some circumstances, it may be desirable to place a slotted liner within the radial ERW tube to further assure that no gravel enters the radial tube during oil production. For this purpose, a slotted flexible tube, much like B-X electrical conduit has been preliminarily developed. It would be pushed and pumped down and into the radial ERW tube prior to placing the end filter brushes. A photograph of a portion of a flexible slotted liner is shown in Figure 5

After cut-off of the radial ERW tube, the stub of the tube is then withdrawn back through the whipstock to the surface by a spear placed into the end of the ERW tube by a sucker rod through the vertical working string. The whipstock is then de-erected and rotated to another azimuth, as determined by gyro measurement. And another identical radial ERW tube is similarly drilled into another horizontal radial borehole through the formation by a repetition of the complete radial placement process.

With that second radial ERW tube, the same first lift of gravel and other completion processes are applied.

When all desired radial bore holes with their ERW tube casings are in place at a given level and all contain a first lift of gravel, perforations, liners and filters, the whipstock is de-erected and is withdrawn to the surface with the working string. A conventional vertical slotted liner is then placed in the vertical underreamed zone.

At this point the second lift of gravel in the horizontal bore holes is accomplished as a part of a conventional vertical gravel pack around the vertical slotted liner in the underreamed zone. In this second lift, the gravel flows out automatically and simultaneously from vertical well bore toward the outer end of the horizontal borehole along the ullage flow space. This is schematically shown in Figure 6.

The gravel movement in the second lift is in successive waves wherein the gravel moves in a wedge shaped front along the flat top of the gravel dune which had been placed in the first step (lift). The water, which propels the gravel along the dune top (by saltation), moves into the formation. The final result is a set of fully packed horizontal boreholes. The process works even if the radial bore holes are of irregular or varying cross section, such as is shown in the larger diameter section simulated bore hole section in Figure 7. Of course, the vertical underreamed zone is concurrently gravel packed with the second lift.

When the vertical underreamed zone and horizontal bore holes are filled during the second lift, it is observed in the laboratory that the gravel still moves in the horizontal bore holes, almost as a quasi-solid mass, so as to effectively consolidate the horizontal gravel pack.

This total process is the bidirectional (two lift) horizontal gravel packing process.

DATA AND RESULTS

LABORATORY TEST APPARATUS

The laboratory apparatus used to test this horizontal gravel packing process is schematically shown in Figure 8 including: 1) A cased vertical well bore, 2) a perforated horizontal well bore, 3) a smaller radial ERW tube within the horizontal bore, and 4) appropriate pumps and plumbing. All these components are integrated into a simulated full scale plastic vertical/ horizontal well laboratory set-up. The vertical well bore is constructed of 4 in. (10 cm) methyl methacrylate (Lucite). The horizontal bores are constructed of 2 - 12 in. (5 - 30 cm) methyl methacrylate. The radial ERW tube is a 1-1/4 in. (3.2 cm) OD by 1 in. (2.5 cm) ID.

The 4 in. (10 cm) horizontal plastic tube is perforated in a calculated pattern to simulate formation permeabilities from completely impermeable to 5 darcys. It is internally lined with brass screen to preclude plugging these perforations, which would change its permeability. This simulated horizontal well bore has been arranged both in straight paths and undulated paths and with controllable leak-offs to simulate formation permeability inhomogeneities.

Since many tests were performed, only the boundary conditions of the examined test variables and overall results will be cited:

1. Range of slurry flow: 1 - 20 gpm (.06 - 1.2 l/s).
2. Range of Water Based Slurry Concentration: .05 - 4 lb/gal (6 - 480 kg/m^3).
3. Range of Gravel Screen Mesh Size: 5 - 60.
4. Varieties of Gravel Type and/or Sources: Ottawa Sand, Heart of Texas Sand, Monterey Sand, and Sintered Bauxite.
5. Deviation of Horizontal Bore Hole: 70° - 110° ($\pm$20° off horizontal).
6. Range or Horizontal Bore Hole Permeability: 0 - 5 darcy (0 - 4.9 x 10^{-12}m^2).
7. Length of Horizontal Bore Hole: 10 - 70 ft (3 - 21.3m).
8. Perforation: 1/8 - 1/4 in. (.3 - .6 cm) perforations arranged helically in the radial ERW tube.

   Obviously, with this scope of variables, not all combinations of all variables were examined.

SUMMARY OF LABORATORY TEST RESULTS

1. So long as the slurry velocity within the radial ERW tube was above 7 ft/s (2.1 m/s), there was no plugging (slurry fall-out) in that ERW tube.
2. The deceleration of the slurry at the exit of the radial ERW tube occurred over about 3 - 5 in. (7.6 - 12.7cm). The gravel fell out quickly and a dune formed in both directions. As soon as a gravel dune formed, the local water velocity could be measured. It generally remained at the low end of the range 1 - 3 ft/s (.3 - .9 m/s). Based on observed

gravel turbulence and its low velocity below 7 ft/s (2.1 m/s), local scouring and formation pickup of fines should be small.

3. The velocity of the water in the ullage flow space stabilized at the low end of the velocity range 1 - 3 ft/s (.3 - .9 m/s).

4. The velocity of the wedge shaped gravel dune front (saltating transport) was about 1 ft/min (0.5 cm/s).

5. The velocity of the saltating gravel along the top of the dune (bottom of the ullage space) was about 1 ft/s (.3 m/s).

6. The percentage fill in the first lift was generally substantially greater than 90% and very seldom less than 80%. The fill in the second lift was 100%.

7. Sand-off did not occur in the first lift. The process was self regulating within the cited range of slurry flow rates.

8. Even with abrupt changes in simulated bore hole diameter (4 in. to 12 in. to 4 in. [10 cm to 30 cm to 10 cm]), the horizontal bore hole filled with gravel regularly and fully in the two lift process, including at the corners of abrupt diameter changes.

9. Within the limits of near impermeable to 5 darcy ($4.9 \times 10^{-12} m^2$) in the simulated 4 in. (10 cm.) horizontal bore hole, there was no sand-off.

10. Sand-off in the first lift can be created by a large leak-off (thief zone or fracture) in the simulated horizontal bore hole. But that very leak-off creates a self-correcting action in the second lift, i.e., the gravel pack fills to the leak-off point when the second lift is made.

11. An experimental electronic tool was preliminarily developed to locate the gravel pack in the horizontal bore hole around the radial ERW tube. The measurement to detect the gravel dune was made through perforations in that metal ERW tube.

12. After complete filling of the horizontal bore hole in the second lift, the gravel continued to move as a quasi-solid. The apparent action was to open and refill voids along the length of the gravel pack; it strongly suggests a consolidation process.

INTERPRETATION OF THE DATA

In a laboratory set up, these test data suggest that a 100% gravel pack, which has some consolidation, is feasible in a highly deviated well of varying diameter and of varying geometry over a wide range of formation permeabilities.

There has been no full field test yet; and, of course, many real field problems will probably occur. But it is of interest that in one commercial application of the Petrolphysics Radial Placement System, involving four radials, sintered bauxite gravel amounting to about 300% of the calipered volume of the underreamed zone was placed in the underreamed zone. Any gravel placement in the radial boreholes was fortuitous and unplanned. But the subsequent several year production data on the well suggest that gravel packing, analogous to a second gravel pack lift, may have placed gravel in the horizontal bore holes.

CONCLUSIONS

A process of providing a 100% fill of gravel and some consolidation of horizontal bore holes has been demonstrated in a full size laboratory test incorporating an extensive range of process and simulated formation variables. The horizontal gravel packing process is self regulating and does not result in sand-off. It would appear applicable to many highly deviated well situations with many different drilling processes.

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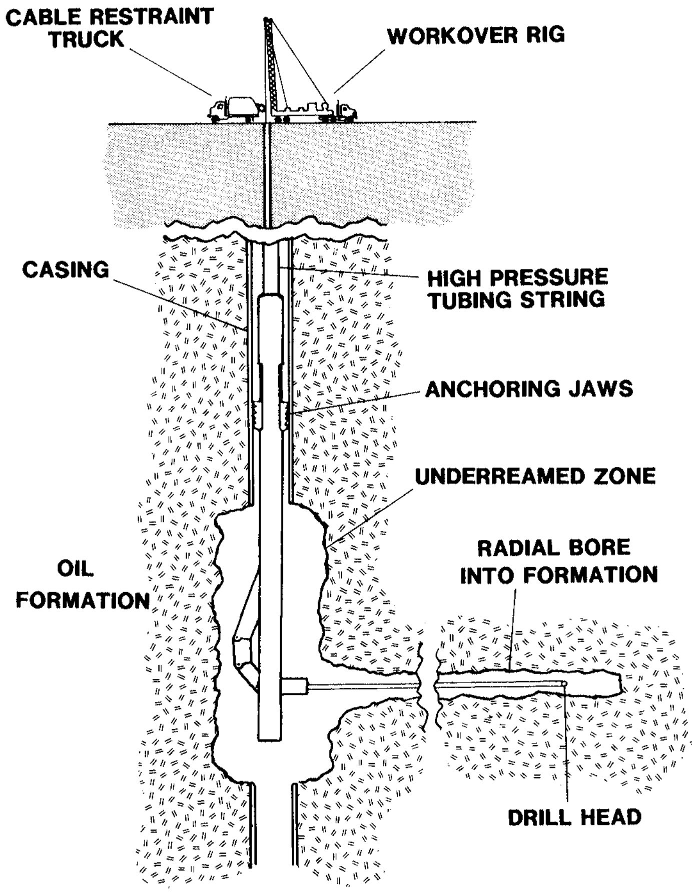

Fig. 1—Petrolphysics radial placement system schematic.

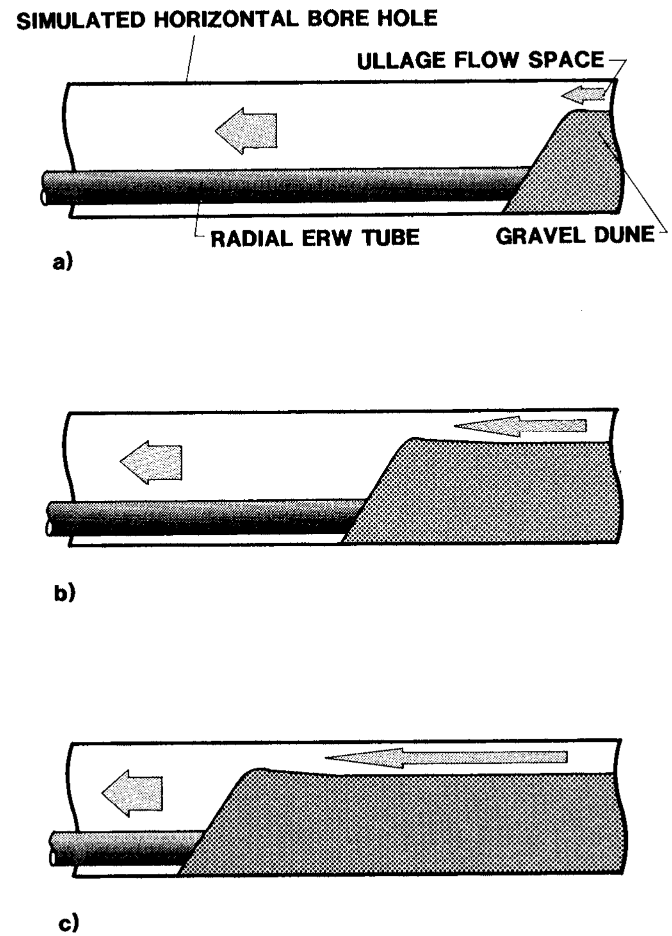

Fig. 2—Progressive movement of gravel dune in first lift.

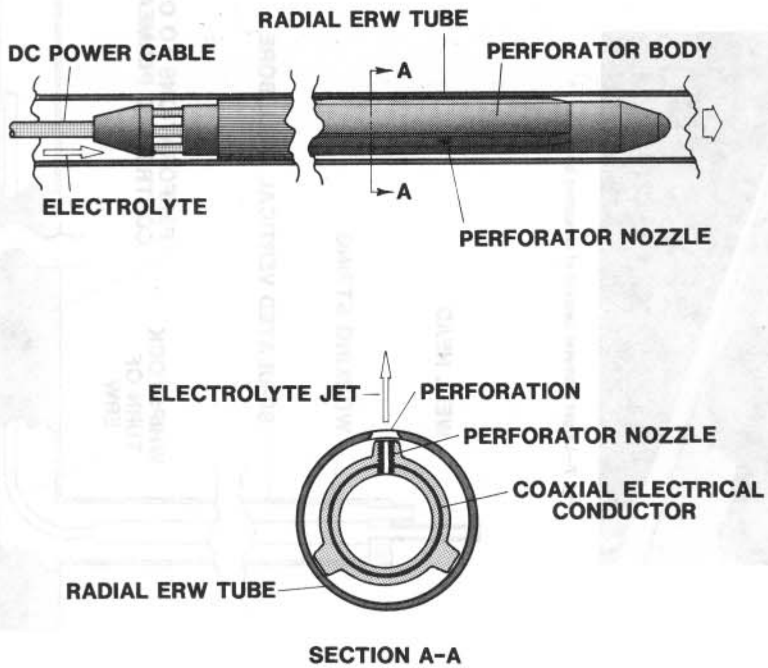

Fig. 3—Electrochemical perforator.

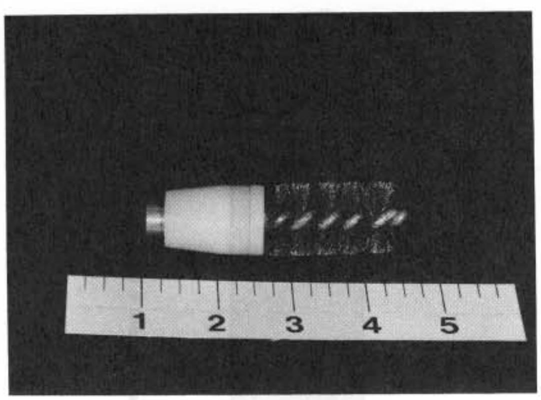

Fig. 4—Wire brush filter for radial ERW tube.

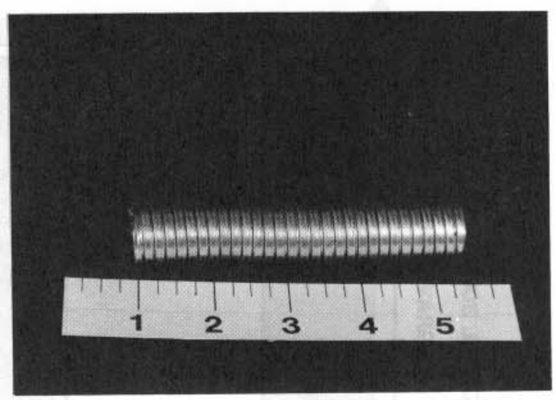

Fig. 5—Slotted liner for perforated radial ERW tube.

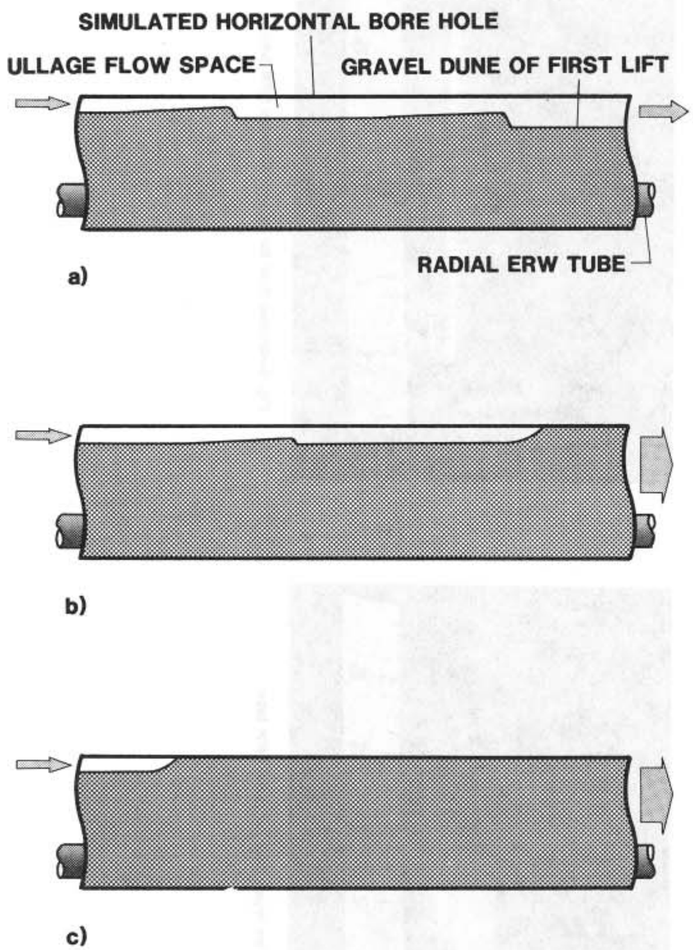

Fig. 6—Progressive movement of gravel in Ullage flow space in second lift.

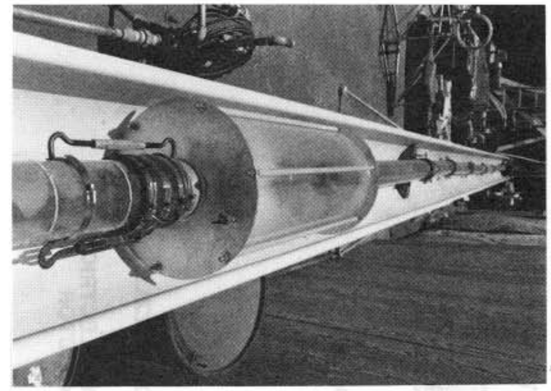

Fig. 7—Larger diameter section of simulated borehole.

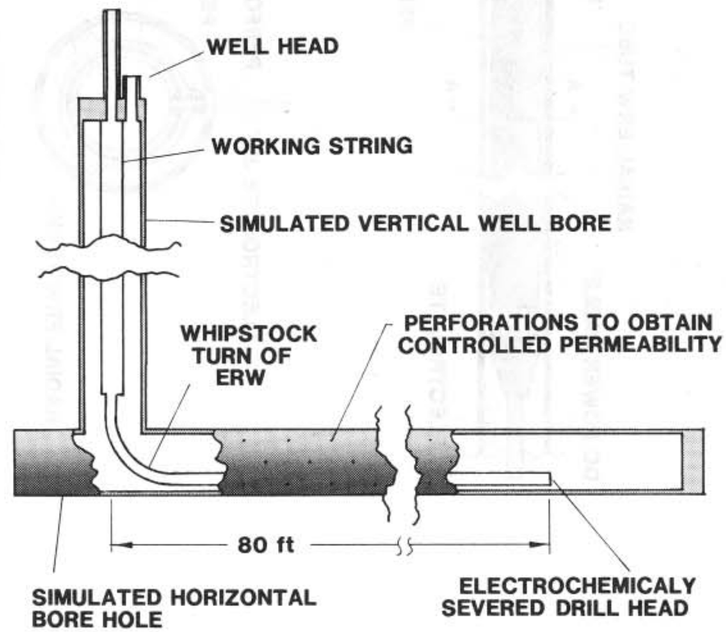

Fig. 8—Horizontal gravel pack laboratory test setup.