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Results of Thermal Horizontal Completions with Sand Control in Lake Maracaibo, Venezuela: Case Histories of Horizontal Gravel Packs in Bachaquero-01 Reservoir

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Abstract

The heavy-oil reservoir Bachaquero-01, in the Lagunillas district of Venezuela's Lake Maracaibo, has been productive since 1934. Because the oil gravity is only 12º API, steam has been injected since 1971 to increase production. To further optimize production, stand-alone horizontal wells have been drilled since 1996. However, in only 4 months after steam was injected into the horizontal wells, a very fast decline of up to 50% of initial production was observed in these nongravel-packed wells.

In a drilling-and-completion campaign from October 2000 to January 2001, 18 horizontal wells were successfully drilled and gravel-packed. In this paper we describe the gravel-pack techniques applied to minimize the rapidly declining rate of production in horizontal alternate steam-injection wells. We explain the method used for screen and gravel-size selection and summarize the completion operations and gravel-pack fluids that were used. We describe the modification of an existing hydraulic packer with a high-temperature seal of 600ºF—a combination used for the first time worldwide. Finally, we illustrate the successful drilling-and-completion campaign with case histories and production performance.

The gravel-packed wells had an average increase of 15% productivity after 1 year with no sand production. The gravel-pack operations were executed at a pump rate of 2 to 3 bbl/min with a sand concentration of 0.5 to 0.7 pounds of proppant per gallon added (ppa), observing continuous fluid returns of 50% to 80%. The packers were successfully field tested after a period of three weeks of steam injection.

Introduction

In Lake Maracaibo, Venezuela, considerable experience has been gained on vertical steam-injection wells. The operator has more than 55 years of production experience from vertical wells in the heavy-oil reservoir Bachaquero-01, which has an oil gravity of 12º API. In 1996, the operator decided to optimize production by drilling wells with 1000 ft of horizontal section; using a 0.012-in. gauge screen and 20/40 U.S.-mesh gravel, and then injecting steam. However, the initial production of 1000 BOPD decreased by 50% within 4 months. To prevent rapidly declining production, it was decided to apply horizontal gravel-packs. NODAL* production system analysis calculations were performed, and a small production increase was predicted if the wells were gravel-packed because of better permeability compared to natural sand packs. A drilling-and-completion campaign was started in October 2000 to gravel-pack horizontal thermal wells in Lake Maracaibo for the first time. Through December 2001, 18 horizontal wells were successfully drilled and gravel-packed. The average production for six of the wells increased by 135 BOPD after 8 months, compared to nine nearby nongravel-packed horizontal wells. This rate is 18% higher than the declining rate of the nongravel-packed wells.

Problem Statement

The high declining rate of production of nongravel-packed, alternate steam-injection horizontal wells may be caused by screen plugging. Initially, it was believed that the formation would collapse around the screen, providing a formation pack and limiting fines movement. In reality, it appears that the open hole remained intact. Higher-velocity annular flow could then transport formation fines that would lead to screen plugging. Screen plugging would lead to areas of localized high-velocity flow that would eventually cause screen erosion.[1,2]

When steam injection is applied, the production rate increases, which causes more production of fines[3,4] and plugs off the screens, leading to sand production.

Reservoir Description

The reservoir is located south of the city of Lagunillas on the east side of Lake Maracaibo. It has an area of approximately

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36.7 mi^2 in the lake and 46.3 mi^2 located eastward on land. Fig. 1 shows a map of the Bachaquero-01 reservoir.

Stratigraphy and Sedimentology. The stratigraphic column of the Miocene epoch has three formations: La Rosa, Lagunillas and Isnotú. The Lagunillas formation is divided into three members: Lagunillas Inferior, Laguna, and Bachaquero, from deepest to shallowest. The Bachaquero member consists mainly of fluvial deposits alternating with flood plain deposits. This member is subdivided into nine chronological intervals: AA, BB, CC, DD, EE, FF, GG, HH, and AP (Arena Principal),[5] from deepest to shallowest. The horizontal wells are drilled in the AP interval, the most prospective sandstone. Fig. 2 shows a standard stratigraphic column of the Miocene epoch.

History. The recoverable reserves of the Bachaquero-01 reservoir are calculated at 1072.6 million bbl with a 16.2% rate of recovery. Production started in 1934 with wells LL-231 and UNA-35. Initially, there was little development activity because of low productivity and problems related to sand production. Beginning in 1955, when gravel-pack techniques were developed, more wells were drilled. In 1971, the wells were stimulated with alternate steam injection. By November 2001, 360 wells had been injected with more than 1050 cycles of steam.

The accumulated production is 413.1 million bbl or 38.5% of the reserves. Actual production is 36.1 thousand BOPD with a gas/oil ratio of 390 ft^3/bbl and 33% water cut. By November 2001, 52 horizontal wells out of 55 were active. The horizontal wells produce 18.6 thousand BOPD or 51.6% of total production per day.

Petrophysical and Reservoir Characteristics. The reservoir has the following characteristics:

- Average reservoir pressure: 860 psi @ 3000 ft
- Net oil sand: 70 to 120 ft
- Formation fracture gradient: 0.60 psi/ft
- Oil saturation: 77% to 84%
- Oil gravity: 12º API
- Permeability: 600 to 2000 md
- Resistivity of oil: 50 to 100 ohm-m
- Porosity: 28 to 32%

Screen and Gravel Selection

The screens had to resist a steam injection temperature of up to 600ºF and relatively high flow velocities after steam injection that might cause erosion. NODAL analysis comparisons were made to enable decisions for changing openhole size, screen type and size, and openhole gravel-packed versus nongravel-packed.

The final choice was made for dual prepacked wire-wrapped screens with 4.55-in. outside diameter (OD), an open borehole of 6 1/8 in., and an openhole gravel-pack. The production index (PI) is calculated to be 2.6 B/psi/D.

The screens have the following characteristics:

- Pipe inside diameter (ID): 2.99 in.
- Pipe weight: 9.2 lb/ft
- Holes: 108/ft
- Hole size: 3/8 in.
- Open area of holes: 11.93 $in.^2$/ft
- Screen OD: 4.55 in.
- Inner screen open area: 18.19 in.
- Outer screen open area: 20.99 in.

Because no sand cores were available, the operator used the following equations of Coberly[6] and Blick and Civan[7] to estimate the mean formation sand diameter:

Coberly:

$$\mu_{avg} = D_{50formation}/6.5, \quad (1)$$

Blick and Civan:

$$\mu_{avg} = [32*K/\varphi]^{0.5}, \quad (2)$$

Combination of Coberly, Blick and Civan:

$$D_{50formation} = 6.5*[32*K/\varphi]^{0.5}, \quad (3)$$

Saucier[4] was used to calculate the mean gravel-pack size:

$$D_{50gravel} = 5.5*D_{50formation}, \quad (4)$$

Final results of the calculations were that 20/40 U.S.-mesh gravel size was selected with 0.012-in. gauge screen opening.[8] The gravel size calculations were confirmed by the field experience of the vertical wells in the Bachaquero-01 reservoir. In these wells it was observed that 20/40 U.S.-mesh gravel retains better fines then 16/30 U.S.-mesh gravel after steam was injected. The ratio of the wire-wrapped screen's openings is less than twice the estimated mean diameter of the formation sand and should retain somewhat uniform formation sands. This was measured by a screen provider in laboratory tests.[9] The type of gravel for the prepacked screens and the gravel for the openhole gravel-pack were selected to be ceramic proppant. This type of gravel has better resistance to the high temperature, 600ºF, during steam injection. Underdown and Das[10] measured that sintered bauxitic materials have only a 3.5% weight loss at a pH of 11 and temperature of 600ºF. In comparison, Ottawa sand has a 46.1% weight loss at a pH of 11 and temperature of 540ºF.

Construction of Horizontal Wells

The horizontal section was directionally drilled with Measurement While Drilling (MWD) direction and inclination at 30.4 ft from the bit, Logging While Drilling (LWD) gamma ray at 32.6 ft, and resistivity in real time at 25.2 ft from the bit.

Drilling and Completion Fluids

An oversaturated brine of 10.5 lbm/gal was used for the drilling fluid. The main components were viscosifier (polymer), pH control, filtrate control (starch), hole stabilizer, potassium chloride (KCl), and sodium chloride (NaCl). The fluid contained controlled bridging salt solids with a range

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from 3 to 174 μm, with D_{50} of 35 μm. The salt particles create a filter cake, trapping the polymer and starch molecules within the bridging agent on the formation.

After having drilled 1000 ft of horizontal section of 6 1/8-in. hole, a wiper trip was made up to the 7-in. casing shoe. Next, a viscous pill of 10.5 lbm/gal was displaced 200 ft into the casing shoe. The main components were viscosifier, KCl and NaCl. The fluid contained bridging salt solids with a range from 3 to 24 μm, with D_{50} of 10 μm.

When the screens are run, the viscous pill is circulated to the surface with brine of 10.0 lbm/gal filtrated to 5 μm. It is very important to have in the returns clean fluid[11] with less than 20 nephelometric turbidity units (NTU). The greater part of the viscous pill will be circulated to surface. The remaining particles of the filter cake will be produced through the screens. In addition, during the 8000-t steam injection, the salt will dissolve and the polymer will break because of the high temperature.

The ideal fluid used for the gravel-pack is clean, undersaturated brine of 9.5 lbm/gal, filtered at 2 μm with less then 20 NTU. The main components are KCl and NaCl. Some wells have been gravel-packed with KCl brine of 8.5 lbm/gal. However, the filter cake may dissolve during the operation, resulting in high losses, which may prevent completing the gravel-pack.

Completions Equipment and Procedures

The thermal completion equipment is presented in a general well sketch in Fig. 3.

The following horizontal completion equipment was used:

- Bull-plug, 3 1/2 in., Butt
- One dual prepacked screen, 3 1/2-in., Butt, N-80
- One O-ring seal sub with ID of 2.400 in., 3 1/2-in., Butt
- 32 dual prepacked screens, 3 1/2-in., Butt, N-80
- 10 to 14 blank pipes, 3 1/2-in., N-80
- One expansion joint, total length of 12 ft with 5 ft of stroke, pinned at 90,000 lbm
- Hydraulic liner hanger with gravel-pack extension
- Washpipe, 2 3/8 in., Hyd-511; relation of OD washpipe/ID screens, 0.79. Recommended clearance between washpipe OD and the screen ID is 0.8.[12, 13]

The following completion procedures were used:

- Run in 6 1/8-in. openhole the dual prepacked screens with washpipe and thermal hydraulic packer.
- Space out screens: minimum 5 ft from bottom of openhole, top of screens 15 to 20 ft inside the casing shoe, and packer setting. Depth at an inclination of approximately 45º.
- Displace viscous pill of 10.5 lbm/gal with brine of 10.0 lbm/gal at maximum pump rate of 2.5 bbl/min.
- Set the hydraulic packer and release setting tool.
- Perform gravel-pack with brine of 9.5 lbm/gal until final gravel-pack pressure of 1200 psi is reached, using a conventional crossover tool method. Circulate the gravel slurry through the crossover tool into the screen-openhole annulus and returns of fluid through the screen and up the washpipe to the surface.
- Pull out the washpipe and run in the final completion.

Thermal Packer Test in Laboratory

For the first wells, existing thermal packers were used. To continuously improve the equipment, an existing nonthermal hydraulic packer was modified with a high-temperature seal of 600ºF. This combination was introduced successfully for the first time worldwide.

Previously, pressure and temperature tests[14] were performed in the laboratory. The lightest-weight casing for which the packer is rated, with the fixture at the maximum calculated ID, per API standard, 5CT, were used in the tests. The test fluid was water, and the packer was set at ambient conditions. The packer was subjected to a differential pressure of 4500 psi, 5000 psi from above and 500 psi from below, at 150ºF. The packer was heated to 550ºF and was subjected to a pressure of 2500 psi from above and 1050 psi from below. The packer was then cooled to 150ºF. Next, during its second cycle, the packer was heated again to 550ºF, and 1050 psi differential pressure was applied. After the packer was cooled, a third and final cycle was applied, repeating the procedure of the second cycle. Each test had a 30-minute holding period.

Figs. 4A to 4H shows the different laboratory test results.

Gravel-Pack Pumping Design

The basic method for the horizontal gravel-packing process has two steps.[15] The slurry (brine and gravel) is pumped at rates where gravel transport is achieved by propagating dune, referred to as the "alpha wave." This step will fill about 70% to 90% of the horizontal annulus.[16] As this dune reaches the toe of the completion zone, a backward-packing process is initiated and propagated back toward the heel. This step is referred to as the "beta wave." A gravel-pack simulation was performed with a gravel-pack design and evaluation software. It showed that, at a pump rate of 2 to 3 bbl/min and a sand concentration of 0.5 to 0.7 ppa, a successful gravel-pack can result.

Risk Analysis

Before the gravel-pack was executed, the following risks were analyzed:

- If not able to gravel-pack, a production gain of +/- 135 BOPD would be lost.
- With changing drilling rates from 60 to 120 ft/hr in the horizontal section, different borehole diameters could appear. When running the screens in the horizontal section, they might become trapped when reaching an abrupt diameter change. Drilling rates should be controlled and kept as constant as possible.
- If the screens are not located at least 20 ft inside the casing shoe, the final screenout pressure might not be reached. The formation could be fractured when reaching higher pack pressures.

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- Because of the relatively low formation fracture gradient, there is a risk of the formation to break down. Wells should not be gravel-packed if the hydrostatic columns break the formation.
- In addition, when losses occur, the hydraulic packer might activate because of hydrostatic differential pressure when lowering in the hole or when displacing the viscous pill.

Results of Case Histories and Production Performance

A total of 18 wells were successfully gravel-packed and no sand production has been observed to date. The gravel-pack operations were executed at a pump rate of 2 to 3 bbl/min, with a sand concentration of 0.5 to 0.7 ppa. Continuous fluid returns of 50% to 80% were obtained. Fig. 5 shows an example of a pump chart for Well LL-3673, in which the final pump pressure of 1500 psi at 0.7 bbl/min was reached.

Case Histories

Table 1 presents an overview of the gravel-pack operational results for the 18 wells. The production rates were measured as follows: initial rate just after steam injection and rate as of December 31, 2001.

For all wells, a final screenout pressure of 1500 psi or higher was reached. A total of 15 wells were packed using more proppant than calculated. In Figs. 6A and 6B, the gravel-pack index and its distribution are presented for 17 wells. The pack index is used to measure the positive or negative deviation from the calculated amount of sacks needed to gravel-pack. It is observed that 41% of the wells were packed with a pack index greater then 0.80. This concludes that seven wells are packed in a range of plus or minus 20% of the calculated amount of sacks needed to gravel-pack. Of the other 10 wells, 59% were packed with more sand than calculated and have a pack index less then 0.80.

Well LL-3696 was drilled with a bi-center bit of 6 1/8-in. to 7-in., in which 4 1/2-in. prepacked screens with an OD of 5.38 in. were lowered. Bigger screens were needed to complete the well with five control lines inside the screens. The control lines measure the reservoir temperature and pressure. When the gravel-pack was initiated, an early screenout took place and only a pack index of 0.48 was reached. Most probably, the bi-center bit did not drill exactly to 7 in. of open hole. Because of the different hole and screen size this well was not added in the pack index comparisons.

For economic reasons, only seven wells were gravel-packed with ceramic proppant; 11 wells were gravel-packed with Ottawa sand. The long-term performance will be investigated in the future. As of December 2001, the average production declines 6.0% per month of the initial production rate when ceramic gravel is used, and 5.4% average production decline per month when Ottawa gravel is used (Table 2).

In addition, the gravel-pack fluid varied for economic reasons, from brine with 8.5 lbm/gal to brine of 10.0 lbm/gal. Calculations from Table 2 indicate that when undersaturated gravel-pack fluids of 8.5 lbm/gal are used instead of brines of 9.0 to 10.0 lbm/gal: initial production increases by 7.3% and the average production declines 4.1% less per month. The difference can be explained by the dissolving capacity of the undersaturated brine of 8.5 lbm/gal. The undersaturated brine dissolves the salt solids of the mudcake faster than brines of 9.0 to 10.0 lbm/gal. In three wells, fluid losses of more than 200 bbl per job were reported when using brine of 8.5 lbm/gal. In the other wells, reduced or no losses were observed.

Table 2 also indicates that 33% more gravel-pack sand is used to screen out when a gravel-pack fluid of 10.0 lbm/gal is compared with a brine of 8.5 lbm/gal. Slight fracturing of the formation with gravel-pack fluid of 10.0 lbm/gal may be the cause of this increase.

The well that gravel-packed with a pack index in the range of 0.61 to 0.80, has the lowest average production decline per month—4.8 %. Most probably the openhole was larger than the theoretical 6 1/8-in, and more sand was needed to gravel-pack. For the other pack index ranges—0.00 to 0.20, 0.21 to 0.40, 0.41 to 0.60, and 0.81 to 1.00—the average production declines differ from 6.0% to 6.9% per month (Table 2).

Two modified thermal packers with high-temperature seals were successfully run, exposing the packers to a period of 3 weeks of steam injection. In other areas where steam injection took place, six more modified packers were run, and to date four were successfully submitted to steam injection.

Production Performance of Gravel-Packed Wells Compared to Nongravel-Packed Wells

To compare the production results of different wells, the actual production Q is divided by the initial production Qi. Only the wells producing longer than or equal to 6 months after steam injection are compared. The first production results show that the average production for six gravel-packed wells was increased by 135 BOPD after 8 months of production, compared to nine nearby nongravel-packed horizontal wells. This increased rate is 18% higher than the declining rate of the nearby nongravel-packed wells, an average of 15% increase in productivity after 1 year. After 10 months, no further difference in average production is measured, as shown in Fig. 7A. However, production results are available for only two gravel-packed wells for the entire year. Maps with the locations of the six gravel-packed and nine nongravel-packed wells and their production decline are presented in Figs. 7B through 7F.

Of the remaining 12 wells, six that were injected with steam have produced for less then 6 months. Three wells have produced longer then 6 months, but have no nearby nongravel-packed horizontal wells against which to compare the production rate. As of December 2001, three wells had not yet been injected with steam.

Lessons Learned and Recommendations

The following lessons were learned from gravel-pack applications in the Bachaquero-01 reservoir:

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- In two nearby horizontal wells, a circulation float shoe was used. Through the shoe the viscous pill was displaced to the surface by a clean brine of 10.0 lbm/gal. However, very high pressures were observed, up to 1200 psi at only 0.5 to 1.0 bbl/min rate of displacement. The hydraulic packer was set at 1600 psi. It was suspected that the float shoe might have been plugged when the screens were run in the open hole. For that reason, a bull-plug was used instead of the float shoe on subsequent wells. The O-ring seal sub was moved up and placed between the screens, one screen from the bottom. The viscous pill was displaced through this one screen below the O-ring seal sub. Results were that no high pressures were observed during the displacements of the following wells.
- Use a stinger of at least 7 ft and space out only 1 ft - inside the O-ring seal sub. If the expansion joint closes because of friction while lowering the screens in the horizontal section, the washpipe will not buckle or break.
- The displacement rate of the viscous pill should be lower than 2.5 bbl/min to avoid damaging the packer elements.
- Gravel-pack with at least 50% of gravel-pack fluid returns.
- All wells should be gravel-packed with ceramic proppant for maintaining longer life because of its superior physical characteristics, as compared with Ottawa sand. However this is not supported by the results and needs to be subject to a long term performance review.
- If the calculated hole volume with a diameter of 6 1/8 in. is made, and 59% of the wells have a pack index smaller than 0.80, most probably the open hole is larger then the calculated one. Therefore, if a bigger calculated hole volume will be used, the pack index number will improve for these wells. This will result in a different pack index distribution.
- Evaluate filter cake cleanup methods and shunt packing technology.
- Obtain cores to perform gravel and screen selection[17,18] to optimize the sand control design.
- For future evaluation, a horizontal well, LL-3696, was gravel-packed in December 2001 with seven control lines. Two control lines contain optic fiber, which will help to locate the part of the horizontal section in which steam will be injected and locate the producing interval.

Conclusions

On the basis of field experience, the following conclusions can be made:

- The gravel-pack operations were executed successfully at a pump rate of 2 to 3 bbl/min with sand concentration of 0.5 to 0.7 ppa, obtaining continuous fluid returns of 50% to 80%.
- Horizontal gravel-packed wells in the Bachaquero-01 reservoir show an average increase of 15% in productivity after 1 year of production.
- The production increases when undersaturated gravel-pack fluids of 8.5 lbm/gal are used instead of brines of 9.0 to 10.0 lbm/gal: initial production increases by 7.3% and the average production declines 4.1% less per month.
- The well that gravel-packed with a pack index in the range of 0.61 to 0.80 has the lowest average production decline per month, 4.8%. In the future, more wells gravel-packed with the same pack index range should be evaluated to determine whether this 4.8% production decline is a trend, or valid for this well only.
- Eight modified thermal packers were successfully run with high-temperature seals: six packers were exposed to a period of three weeks of steam injection per well.

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Nomenclature

$D_{50gravel}$	mean diameter gravel sand, L, μm
$D_{50formation}$	mean diameter formation sand, L, μm
K	permeability, L^2, md
pH	potential hydrogene, a measure of the acidity or basicity of a solution
φ	porosity, %
μ_{avg}	average pore diameter, L, μm
ppg	pound per gallon, M/L^3, lb/gal

Subscripts

avg	average

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Metric Conversion Factors

bbl x 1.589873	E-01 = m^3
ºF : (ºF -32)1.8	E+00 = ºC
ft x 3.048	E-01 = m
gal x 3.785412	E-03 = m^3
in x 2.54	E-02 = m
lbm x 4.535924	E-01 = kg
lb/ft x 1.488164	E+00 = kg/m
lb/gal x 1.19826	E+02 = kg/m^3
md x 9.869233	E-04 = μm^2
mi^2 x 2.589998	E+06 = m^2
psi x 6.894757	E+03 = Pa

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TABLE 1—TABLE WITH GRAVEL-PACK RESULTS OF 18 HORIZONTAL WELLS.

Well name	Completion date	TVD (ft)	Reservoir pressure (psi)	Gravel 20/40	Gravel pack fluid (Brine) (ppg)	Gravel calculated (sacks)	Gravel placed (sacks)	Placed sacks / required sacks (%)	Pack index (-)	Final pressure (psi)	Fluid returns (%)	Fluid lost (bbl)	Steam injected as of 31 Dec 2001	Estimated production (BOPD)	Initial production after steam (BOPD)	Production as of 31 Dec 2001 (BOPD)	Months producing till Dec 2001 (months)	Production decline per month (%)
LL-3630	10-Oct-00	2940	1080	Ottawa	10.0	95	185	195	0.05	1500	73	82	Yes	800	1138	300	12	6.1
LL-3632	30-Sep-00	3205	1100	Ottawa	10.0	96	185	193	0.07	1500	-	-	Yes	800	700	200	12	6.0
LL-3643	26-Nov-00	3434	631	Ottawa	8.5	90	90	100	1.00	1800	67	100	Yes	800	690	350	12	4.1
LL-3651	01-Jan-01	3005	950	Ottawa	8.5	99	170	172	0.28	1500	-	-	Yes	800	1021	400	12	5.1
LL-3655	05-Jan-01	3074	1088	Ottawa	8.5	90	73	81	0.81	1500	51	345	Yes	800	1034	366	11	5.9
LL-3660	20-Apr-01	3194	1113	Ottawa	8.5	98	166	169	0.31	1600	60	200	Yes	800	1210	950	7	3.1
LL-3661	30-Apr-01	3191	1112	Ottawa	8.5	95	124	131	0.69	1500	73	80	Yes	800	1200	850	7	4.2
LL-3662	13-May-01	3350	1100	Ceramic	9.5	106	116	109	0.91	1700	-	-	Yes	800	1110	750	6	5.4
LL-3663	10-May-01	3042	1050	Ottawa	8.5	104	115	111	0.89	1500	100	0	Yes	800	1050	430	7	8.4
LL-3665	27-May-01	3259	1000	Ceramic	9.5	105	156	149	0.51	1800	-	-	Yes	800	1200	1190	1	0.8
LL-3669	12-Jun-01	3020	1000	Ceramic	10.0	105	156	149	0.51	1500	100	0	Yes	800	1100	1050	1	4.5
LL-3673	24-Jul-01	3067	980	Ceramic	9.0	105	110	105	0.95	1500	93	20	Yes	800	700	487	4	7.6
LL-3677	14-Aug-01	3181	1000	Ceramic	9.5	105	95	90	0.90	1500	-	-	Yes	600	839	754	1	10.1
LL-3681	04-Sep-01	2902	900	Ceramic	8.5	95	160	168	0.32	1500	63	220	Yes	900	1210	750	3	12.7
LL-3683	14-Sep-01	3187	1128	Ceramic	8.5	95	160	168	0.32	1500	100	0	Yes	900	910	900	1	1.1
LL-3686	05-Oct-01	3024	1100	Ottawa	9.0	107	110	103	0.97	1500	93	22	No	900	N.A.	N.A.	0	N.A.
LL-3695	05-Dec-01	3076	1000	Ottawa	10.0	98	192	196	0.04	1600	100	0	No	900	N.A.	N.A.	0	N.A.
LL-3696*	30-Dec-01	2986	976	Ottawa	10.0	95	46	48	0.48	3000	54	320	No	800	N.A.	N.A.	0	N.A.

* Well LL-3696 is drilled with a bi-center bit of 6 1/8-in. to 7-in. and the OD of the screens were 5.38-in.

TABLE 2—COMPARISONS OF GRAVEL-PACK RESULTS, INITIAL AND ACTUAL PRODUCTION AND AVERAGE PRODUCTION DECLINE RATES PER MONTH AS OF DECEMBER 2001.

Different cases, comparing all wells gravel packed with:	Number of wells	Average (placed sacks / required sacks) [%]	Average initial production after steam [BOPD]	Average actual production [BOPD]	Average production decline per month [%]
Ceramic 20/40	7	134	1010	840	6.0
Ottawa 20/40	11	126	1005	481	5.4
Brine 10.0 ppg	4	183	979	517	5.5
Brine 9.5 ppg	3	116	1050	898	5.5
Brine 9.0 ppg	2	104	700	487	7.6
Brine 8.5 ppg	8	138	1041	625	5.6
Ceramic & brine 8.5 ppg	2	168	1210	750	12.7
Ottawa & brine 8.5 ppg	6	127	1034	558	5.1
Pack index range 1.00 - 0.81	5	101.2	916.8	476.6	6.3
Pack index range 0.80 - 0.61	1	130.5	1200.0	850.0	4.2
Pack index range 0.60 - 0.41	0	N.A.	N.A.	N.A.	N.A.
Pack index range 0.40 - 0.21	3	169.8	1147.0	700.0	6.9
Pack index range 0.20 - 0.00	2	193.7	919.0	250.0	6.0

Notes: Well LL-3696 is not included in the gravel-pack comparisons. Wells without steam injection and production less than or equal to 1 month are not included in the production comparisons.

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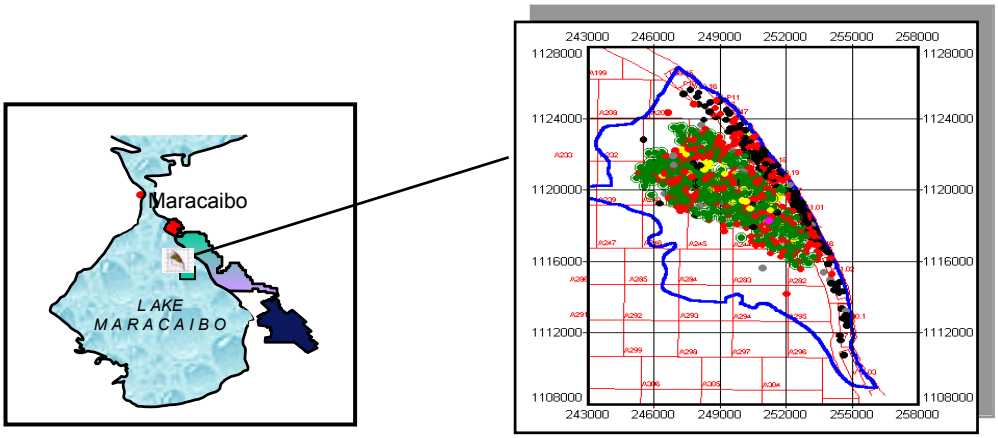

Fig. 1-Map of the Bachaquero-01 reservoir.

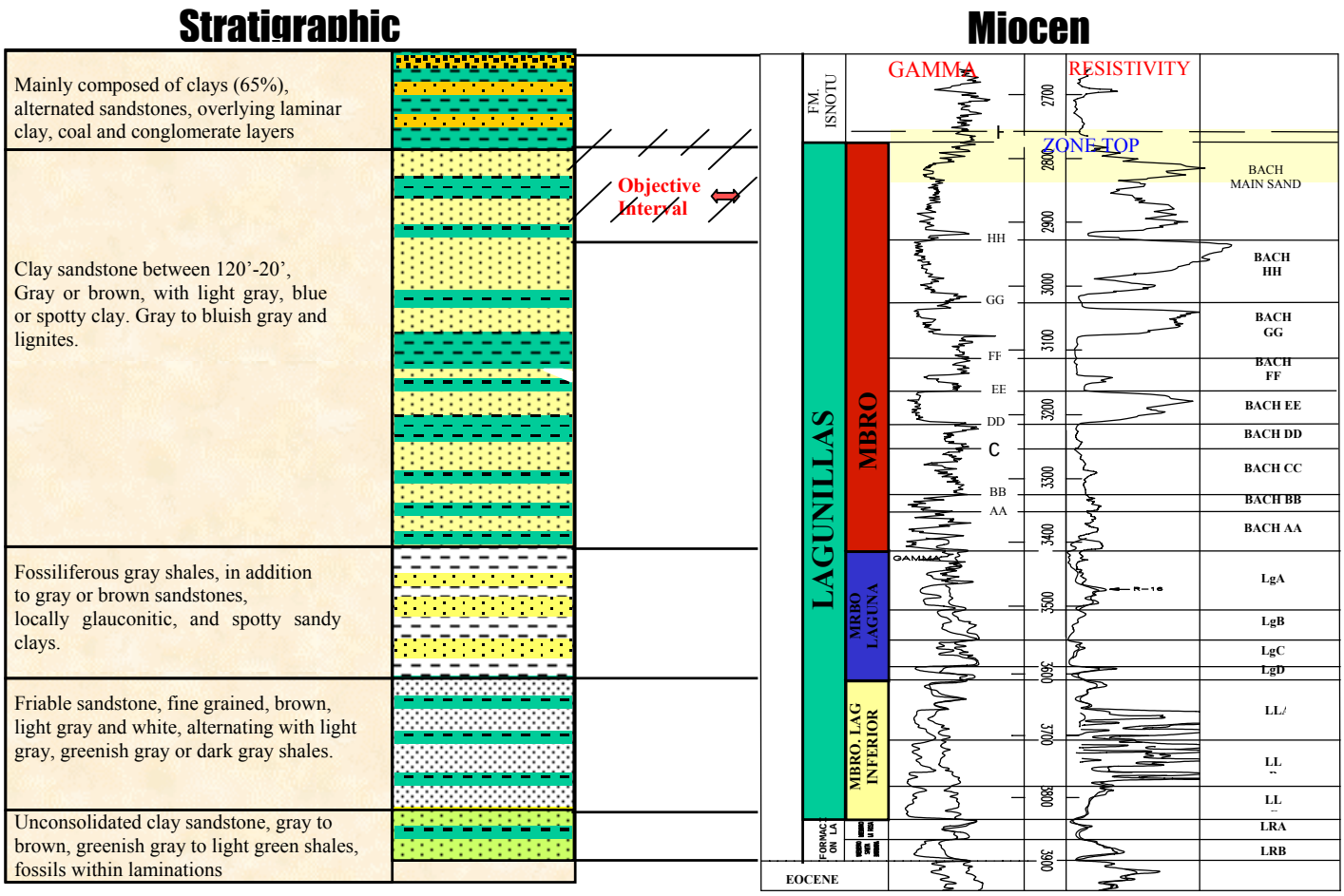

Fig. 2—Stratigraphic column of the Miocene.

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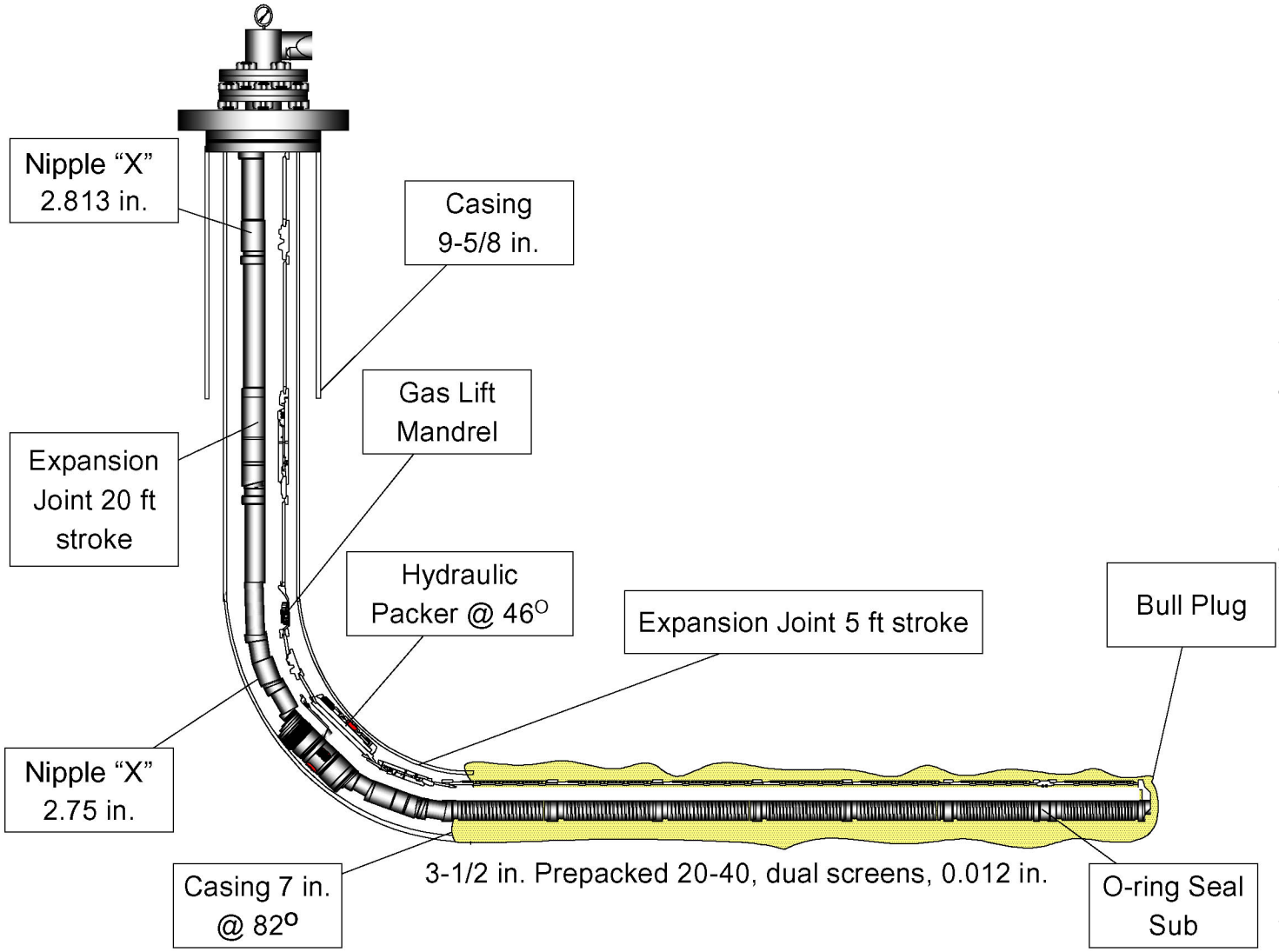

Fig. 3—Horizontal well sketch.

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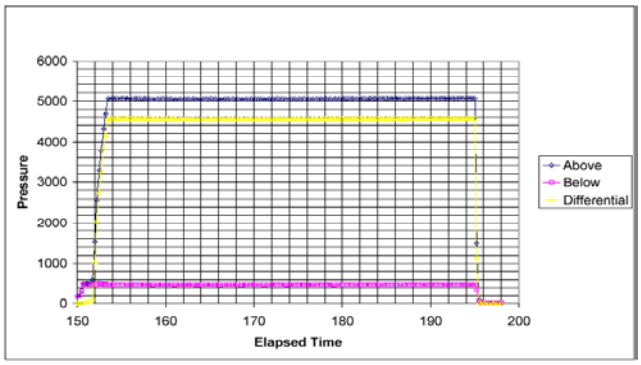

Fig. 4A—Pressure test @ 150ºF and ΔP 4500 psi.

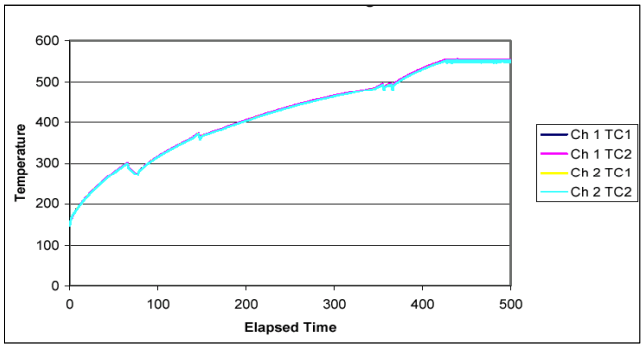

Fig. 4B—First steam injection cycle of 550ºF.

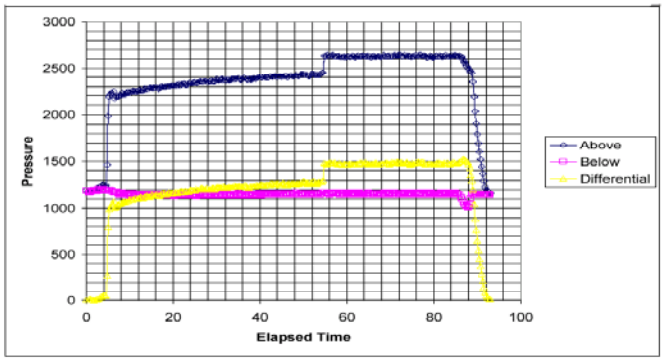

Fig. 4C—First cycle of 550º F and ΔP 1500 psi.

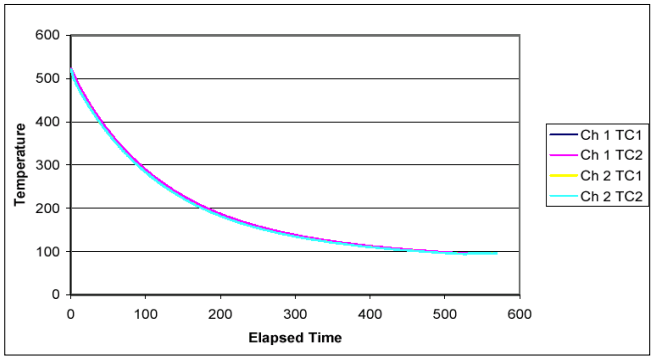

Fig. 4D—Cooling to 150ºF.

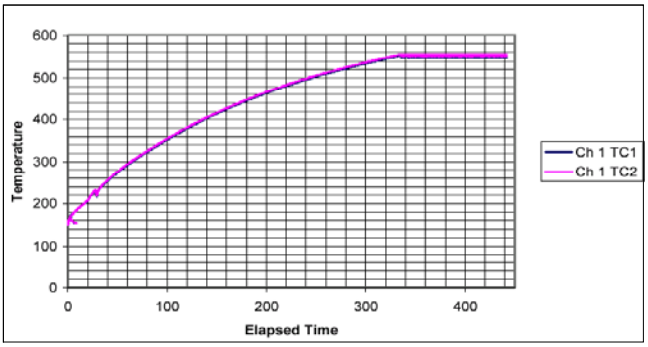

Fig. 4E—Second steam injection cycle of 550ºF.

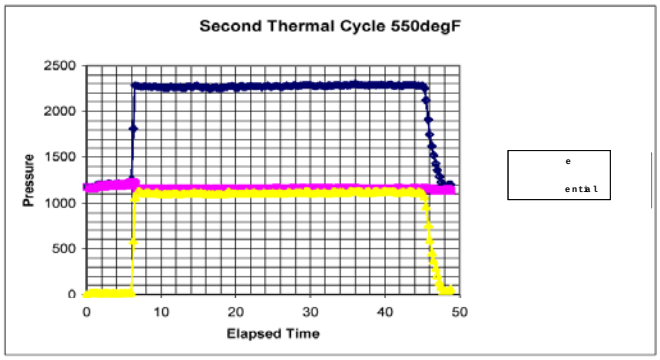

Fig. 4F—Second cycle of 550ºF and ΔP 1050 psi.

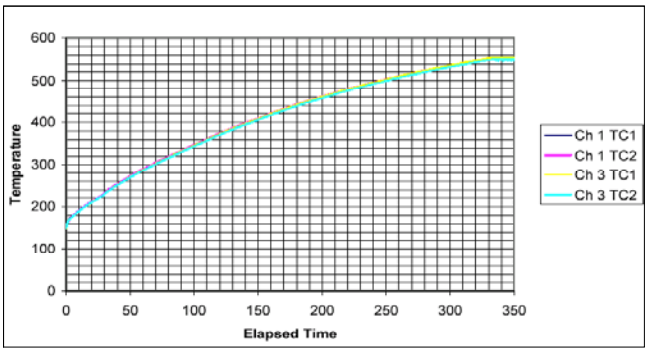

Fig. 4G—Third steam injection cycle of 550ºF.

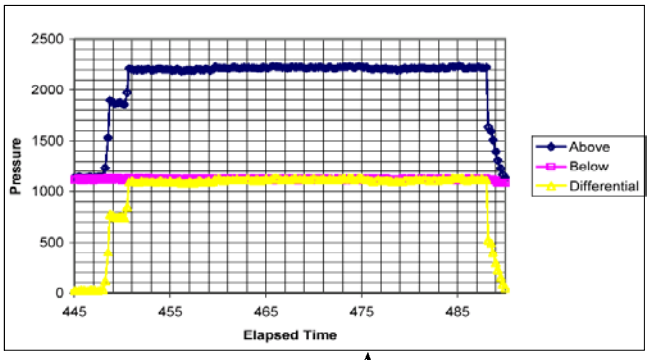

Fig. 4H—Third cycle of 550º F and ΔP1050 psi.

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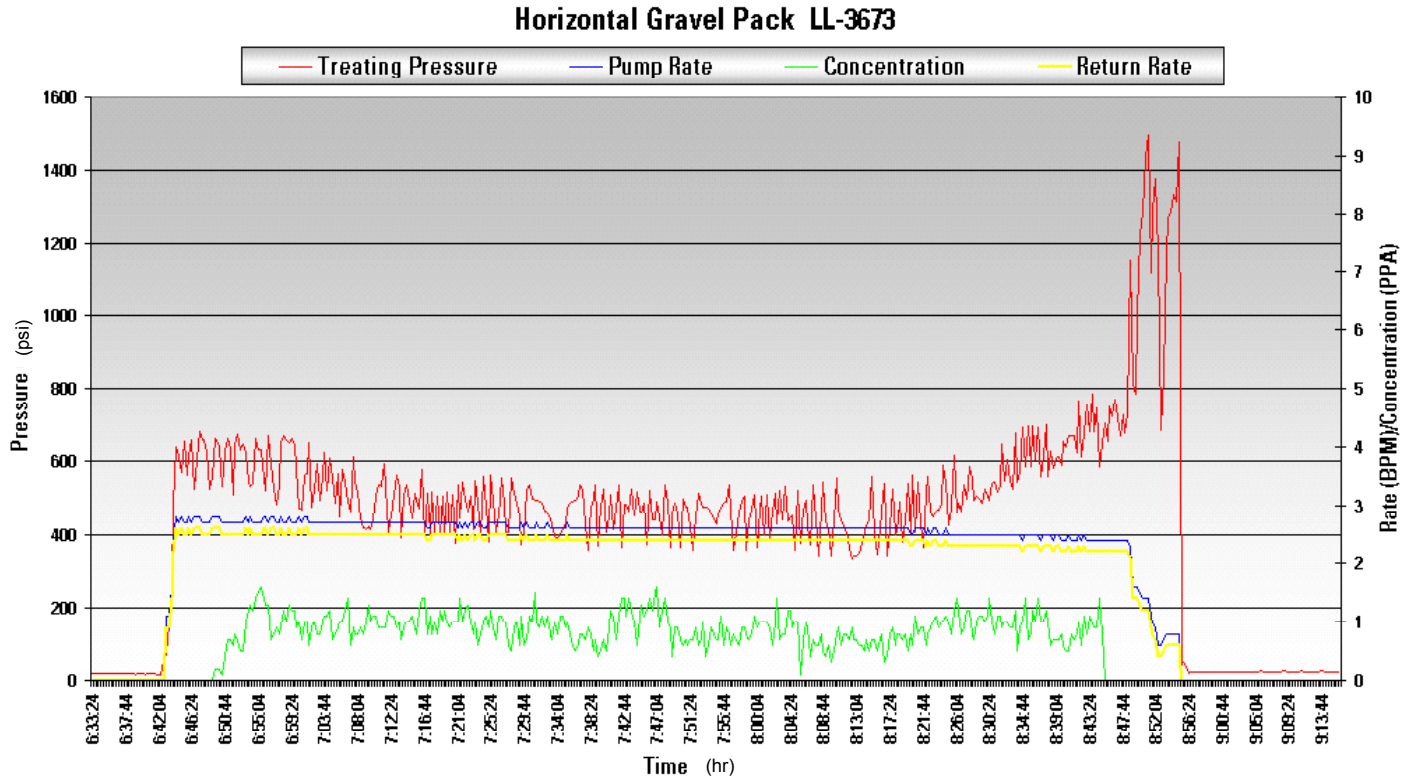

Fig. 5—Pump chart of well LL-3673.

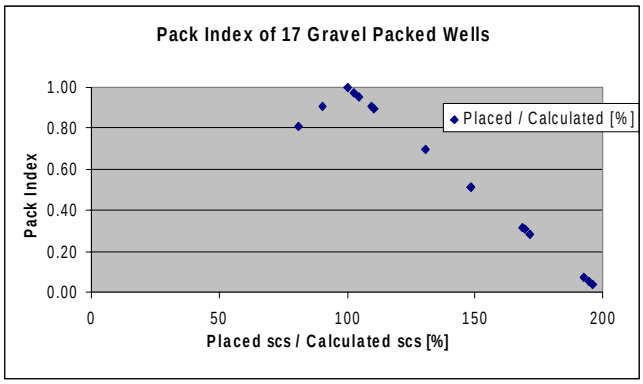

Fig. 6A—Gravel-pack index of 17 wells; placed sacks/calculated sacks versus the pack index.

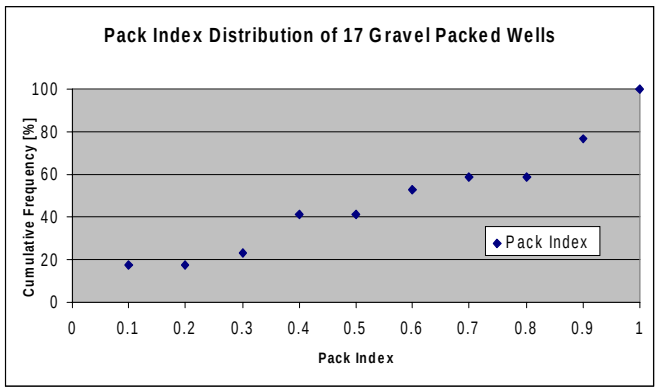

Fig. 6B— Gravel-pack index distribution of 17 wells; pack index versus cumulative frequency.

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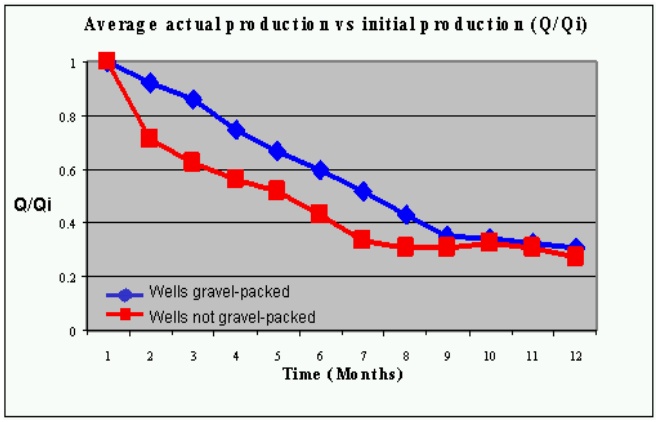

Fig. 7A—Average declining production curves for gravel-packed and nongravel-packed wells.

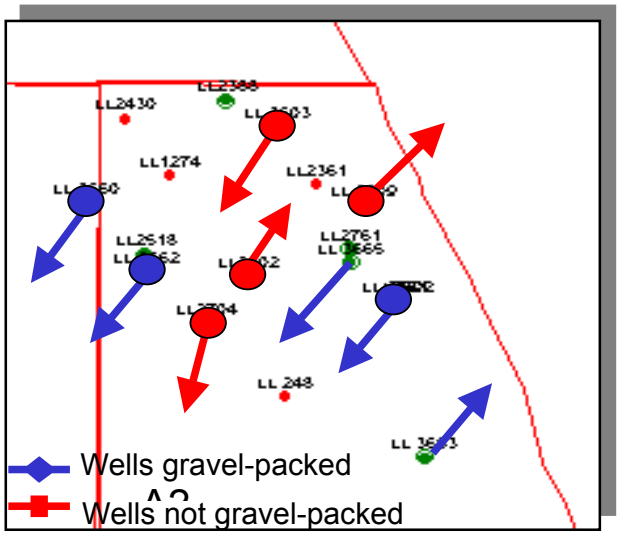

Fig. 7B—Map with gravel-packed wells and nongravel-packed wells in Block A-282.

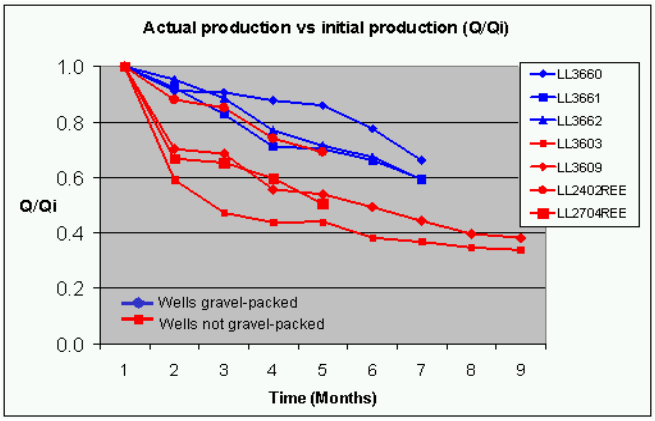

Fig. 7C—Production results of gravel-packed versus nongravel-packed wells in Block A-282.

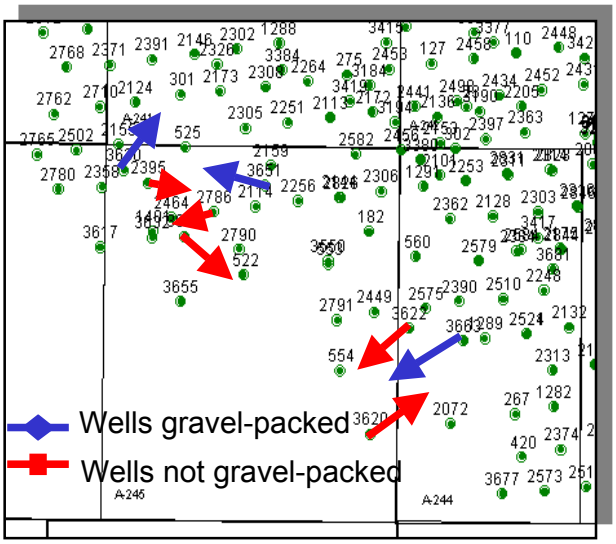

Fig. 7D—Map with gravel-packed wells and nongravel-packed wells in Blocks A-244 and A-245.

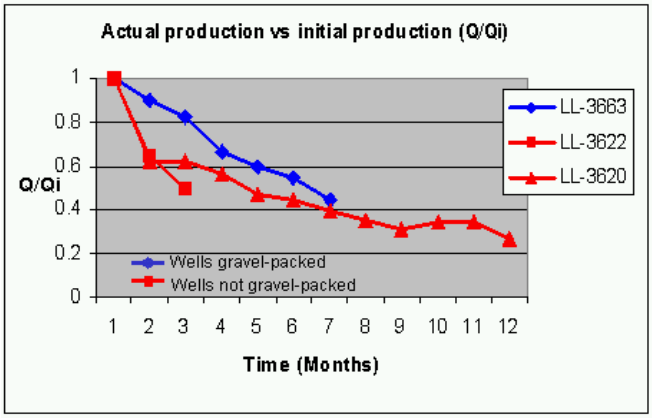

Fig. 7E—Production results of gravel-packed versus nongravel-packed wells in Block A-244.

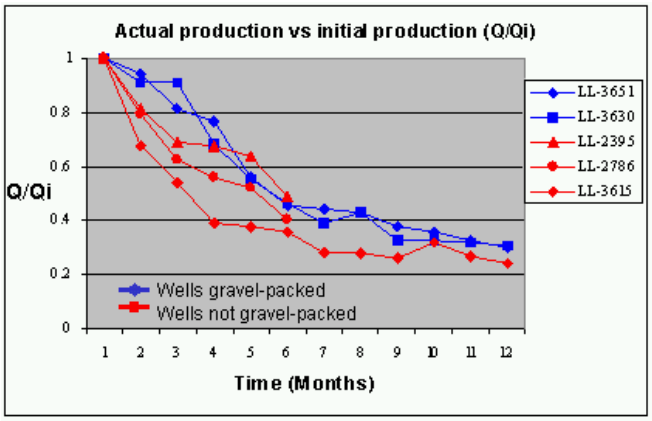

Fig. 7F—Production results of gravel-packed versus nongravel-packed wells in Block A-245.

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