



SPE 39433

Case History in Achieving High Rate Producers in Sub Sea Gravel Packed Completions

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This paper was prepared for presentation at the 1998 SPE International Symposium on Formation Damage Control held in Lafayette, Louisiana, 18–19 February 1998.

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Abstract

The Zafiro Field, offshore Equatorial Guinea, was developed as a fast track project with production coming onstream in August, 1996 to an FPSO, less than two years from the field discovery. Downhole gauges with surface readout on the FPSO gave continual monitoring of well performance during early production from the field. These subsea wells, which required sand control, were targeted to produce at rates of 8000 bopd. Early wells made this target with Productivity Indices (PI's) of 6 to 33 bopd/psi. However the data also showed high post completion skin damage when compared to skins measured immediately after TCP operations. This real time data allowed continual improvements to be made in completion designs. This paper is a case history of these design changes which more than doubled PI's, yielding producers capable of 14,000 bopd. Design changes included a move to openhole completions where possible, new screen configurations, fluid studies for optimizing gelled fluids to transport sand in high angle and horizontal openhole completions, filter cake removal in openhole completions, and acid stimulation.

Introduction

The Zafiro Field is located in west Africa approximately 40 miles offshore Equatorial Guinea (Fig. 1) in water depths ranging from 425 to 2000 feet. The discovery well, Zafiro 1, was tested in March 1995 by Mobil (75%) and partner United Meridian Corporation (25%). The field is being developed on a fast track basis with subsea wells tied in to a Floating Production, Storage, and Offtake vessel (FPSO). First pro-

duction was brought onstream 25th August, 1996. Field production exceeded 90,000 bopd in November, 1997.

The discovery well penetrated 119 net feet of highly permeable clean oil bearing sands in the Intra Qua Iboe formation. Bottomhole pressure of 2488 psia was recorded at a datum of -5225 feet subsea; static bottomhole temperature was recorded to be 170 °F.

Subsequent wells showed the reservoir to be highly stratified with permeability thickness varying considerably from well to well.

Wells were targeted to make 8000 bopd each. A sonic sand detector was used to assist in determining a maximum sand free rate from the Pliocene age sand. Flow tests during rig work showed that maximum sand free rates were too low to meet the targeted 8000 bopd per well without gravel packing to control sand production.

Early Design

Early wells were vertical, cased with 9-5/8" production casing throughout the pay intervals. Wells were shot with tubing conveyed 7" OD guns against an open choke, 500 psi underbalanced, at 12 shots per foot.

With the exception of the first two Zafiro gravel packs, perforations were not washed. Instead the wells were flowed continually after gun detonation for three or more hours to clean up perforation tunnels. Pre-gravel pack flow tests at ~ 2000 bopd followed by a pressure buildup, yielded slightly negative skin values and indicated this method of cleanup was effective.

Early wells used gravel packing equipment and materials readily available in west Africa, namely 8 gauge stainless wirewrapped screen and 40/60 sand with HEC as the carrying fluid. HEC was also used as loss circulation material (LCM) when fluid losses were encountered. Shunts attached to the wirewrapped screens to give an alternate path for transporting sand were introduced after the first two gravel packs. Sand stratification coupled with gross length of completion intervals, greater than 100 feet, were the major factors in having wirewrapped screens with shunts to minimize voids in the pack.^{1,2}

Downhole gauges with surface readout onboard the FPSO were run on all wells to obtain real time data as the wells were produced or shut in. Not only did the downhole gauges serve as a means to solve reservoir management issues³, it allowed early analysis of the completion design and the ability to respond quickly to any changes deemed necessary.

Early Results

When the early Zafiro wells came onstream in August and September of 1996, all Zafiro wells (No's 1-4) were capable of making the 8000 bopd target. Downhole gauges run with the completion gave the opportunity for well performance to be monitored early-on and design changes made accordingly. It was observed that skin damage was higher than desired, ranging from 13 to 23. Although skins of > 20 are common in the industry^{4,5}, it was felt these skins could be reduced.

Much discussion centered around the pros and cons to change procedures back to washing perforations versus whether or not to omit HEC from the system. HEC as documented by others⁶ could be damaging to the formation. The skin of + 23 on Zafiro 1 where perforations were washed prior to gravel packing hinted that HEC was part of the problem.

Fluids Testing on Zafiro Cores

Fluids testing with both carrying fluids and LCM was initiated on Zafiro cores to determine their effects on the Zafiro formation. Return permeabilities using HEC, a viscoelastic surfactant-based fluid (VSBF), NaCl, and CaCO₃ with a bio-polymer pill were conducted at the Mobil lab.

It was found in the fluids study (Table 1) that as a carrying fluid, both NaCl and VSBF gave the highest return permeabilities (73% to 77%) at static bottomhole temperatures. HEC with breaker exhibited only a 33 % return permeability.

As a loss circulation material, CaCO₃ with the bio-polymer pill exhibited only 19% return permeability, increasing only to 48% after 7-1/2% HCl acid was introduced. The VSBF, although viscous, has high leakoff properties and is not designed to control loss circulation. It was therefore decided to incorporate a flapper valve into the gravel pack bottomhole assembly when feasible to minimize fluid loss to the formation after gravel packing. It was also decided to minimize the amount of HEC pill that is spotted when losses were severe enough to require a loss circulation pill after perforating or should the flapper valve fail after gravel packing.

Other Considerations Leading to New Design

During a TCP operation in the Opalo 2 well, a low order detonation occurred with 7" OD guns in the hole. Fishing attempts were unsuccessful and the well was redrilled.

It was decided to no longer run 7" OD guns due to

associated mechanical risks. There were no 6" OD guns available at the time of completion and consequently 4-1/2" guns were used to perforate this 55 degree well.

HEC was not used as a carrying fluid and a flapper valve was incorporated so that no HEC was spotted after the gravel pack. Yet this well experienced extremely high skin (+70). Analysis indicated that the smaller gun, laying on the low side of the 9-5/8" casing, did not effectively perforate the upper side of the 9-5/8" and the smaller hole sizes did not allow enough 40/60 sand to be put away during gravel packing. The majority of the skin is attributed to convergence of flow on the low side of the well resulting from this inefficient perforation job. The results of Opalo 2 pointed to the need to omit perforations when possible, i.e., design for openhole gravel pack completions.

New Design Parameters and Potential Problems

New design parameters called for openhole completions when possible. Also since some of the sands were less than twenty feet thick, higher angle wells, even horizontal, were preferred to expose more sand to the wellbore. A minimum 500 feet of horizontal section in the Zafiro sand was desired. Applying nodal analysis using existing tubular sizes, the horizontal length began to reach diminishing returns at 1200 feet. Design for the first horizontal openhole completion was 500 feet.

Due to expected longevity of the wells, coupled with the high cost of subsea well intervention, prepacked screens were not considered. Plugging and subsequent production losses attributed to prepack screens over time⁷ was considered when making this decision. It was decided that the high angle and horizontal wells would need to be gravel packed. Prepacked screens would be available but used only as backup should mechanical or hole problems warrant their use.

It has been known that horizontal wells could be successfully gravel packed with a high rate water pack.⁸ However, due to pit volume limitations on the rig, it was desired to use a non-damaging viscous slurry pack. Previous fluids testing indicated the VSBF had enough viscosity to carry sand at Zafiro bottomhole treating temperatures and at pump rates < 5 BPM.

Shunt tubes would need to be used to eliminate voids but would need protection when running the bottomhole assembly to bottom. A special shrouded screen (Fig. 2) was developed to achieve this protection. Basically a typical 8 gauge stainless steel screen wrapped on 4" base pipe, fitted with four shunt tubes was built and inserted into a 7" OD perforated shroud then welded in place. The 7" OD outer shroud not only served as protection when running in hole, it provided centralization of the screen and standoff from the openhole wall. This standoff allowed for more gravel pack sand to be placed between the screen and formation. It also minimized any plugging tendencies from filter cake embed-

ding in the screen when running the screen on the low side of the openhole.

Use of oil base mud has been very successful in drilling the Zafiro wells. Fluids tests run with oil base mud in a gravel pack simulator indicated plugging would be a problem if the openhole were left with the oil base mud filtrate in place prior to gravel packing.

It was decided that for horizontal wells, a 12-1/4" pilot hole would be drilled using MWD to verify that the targeted sand had been encountered. A string of 9-5/8" casing would be set above the target zone, the oil base mud system would be swapped out to a drill-in fluid more compatible with gravel packing, and the horizontal section drilled.

Testing was done on a water base gelled drill-in system using CaCO_3 as the bridging material. This system was found to form a very thin filter cake ($\sim 1/8"$) with a low lift-off pressure (42 psig).

A post gravel pack acid job consisting of ~ 20 gal/ft of 7-1/2% HCL with iron sequestering agent and clay stabilizer, spotted with coil tubing, would be required to effectively dissolve and remove the CaCO_3 filter cake and pass through the gravel pack.⁹ Stress strain analysis on Zafiro cores had indicated that hole collapse may result if the openhole was acidized prior to gravel packing.

Surface testing was conducted using shunts in a horizontal mode with gravel transported via a gelled system (Fig. 3). Early results were pessimistic, but it was found that low density gravel would achieve a gravel pack. Further testing showed that after changing hole sizes in the shunts and optimizing the hole spacing successful results could be achieved with regular gravel. Results of the testing have indicated that 2000 feet or longer horizontal wells can be gravel packed with gelled system when the proper hole sizes in the shunts are used.¹⁰

Field Results With New Design Criteria

Openhole Horizontal Completions. Three horizontal openhole completions have been drilled, completed and put on-stream to date. All three wells used the water based gelled CaCO_3 drill-in fluid, the VSBF carrying fluid, low density (S.G. = 1.7) artificial 40/60 sand, and shrouded shunted screen bottomhole assembly with flapper. These three wells, even though drilled in areas of the field that exhibited lower permeability thickness, are producing in excess of 10,000 bopd each with less than 500 psi drawdown. A typical drawing of the downhole configuration can be seen in Figure 4.

Zafiro 5: 508 ft. This near horizontal has 508 feet of 8-1/2" openhole beginning with 82 degrees and tapering off to 75 degrees, chasing a 30 feet thick sand that was dipping downward at 10 to 12 degrees. The well was completed and put onstream in February, 1997. The initial slurry was pumped at 1.5 to 5 bbls per minute, using 25% excess low density

sand over the calculated volume required. A screenout was not obtained. A top job was performed with no problems and a total of 64% excess sand was pumped. The post acid job was spotted with coil tubing from the toe to heel then squeezed into the formation.

This well has produced up to 12,000 bopd and is produced on a regular basis at 10,000 bopd. The initial post gravel pack PI of the well is 47.3 with a horizontal skin of 3.0. The horizontal permeability thickness, k_{ph} , is 35,000 md-ft.

Zafiro 10: 855 ft. This horizontal openhole section (908 ft) was drilled at 81 to 91 degrees. A 992 feet shrouded screen assembly was run into the well. Sluffing shales prevented getting the assembly to bottom; 855 feet of the assembly was run into the openhole section with the remaining screen in the 9-5/8". The well was gravel packed with low density sand with 43% excess sand being pumped. The well produces in excess of 10,000 bopd with an initial post gravel pack PI of 68.1. The measured k_{ph} is only 11,400 md-ft and horizontal skin is 0.3.

Zafiro 13: 611 ft. This horizontal openhole section was drilled at 87 degrees. Again sluffing shales prevented getting to bottom with the bottomhole screen assembly. 611 feet of the 1000 feet assembly was run in the openhole section. The well was gravel packed with 75% excess low density sand. The well exhibited an initial post gravel pack PI of 23.3 and produces 10,000 bopd. The measured k_{ph} is 37,000 md-ft and horizontal skin is 3.8.

Openhole Near Vertical Completions. Near vertical openhole completions differed from the horizontal wells in that the entire section was drilled with oil base mud. The pay section was next under-reamed using a water base gelled system. CaCO_3 was used only if loss circulation was encountered during under-reaming. When CaCO_3 was used, a post gravel pack acid job using 7-1/2% HCL, 25 to 50 gal/ft was administered. The same gelled system without CaCO_3 was used for cleanout sweeps during under-reaming operations. Regular sand was used in the gravel packing. One or two joints of shrouded screen were used in the bottomhole assembly to act as a centralizer; regular screens with shunts were used throughout the remainder of the assembly.

Zafiro 11: 235 ft straight openhole. This well had 9-5/8" set in a highly stratified section of the Zafiro sand with the cleanest part of the sand near the bottom of the hole. Shale sluffing was encountered during under-reaming to 14-3/4". Difficulty in keeping the hole clean during trips with drill pipe gave justification to the running of a prepacked screen. Indeed, only 10% of the sand had been put away before a screenout occurred during the gravel pack operation. The

well produced at an initial rate of 9500 bopd with an initial post gravel pack PI of 28.1 and a kh of 140,000 md-ft. Skin damage of 12.9 in this high permeability well can be partially attributed to the plugging of the prepacked screen. The well produces at approximately 10,000 bopd.

Opalo 3: 78 feet of 14 degree openhole. Opalo 3 had 9-5/8" set immediately above the clean sand and no shale sluffing problems were encountered during under-reaming. The well was gravel packed with 23% excess sand. This well which had a measured kh of 37,500 md-ft, had an initial post gravel pack PI of 87.7. Skin damage was 1.3. The well produces around 10,000 bopd but has been beamed up to produce near 14,000 bopd for a short period of time.

Opalo East 1: 158 feet straight openhole. This well has yet to be tied in to the FPSO. It was gravel packed upon drilling in order to conduct multi-rate testing and bottomhole sampling for full evaluation. The well was under-reamed to 14-3/4" using water base gelled system with CaCO₃ viscous sweeps during the operation. Post gravel pack PI for this high permeability well (kh of 233,000 md-ft) was 61.7. Skin damage was 11.4. However, the well was not acidized since the well was suspended pending flowline installation.

Topacio 3: 60 feet of near vertical hole. Shale sluffing problems arose in Topacio 3 as 9-5/8" was set well above the clean part of sand. The original 8-1/2" hole was cemented and a new 8-1/2" hole sidetracked just below the 9-5/8" shoe. Since shale sluffing problems increase with time, it was decided not to under-ream the new 8-1/2" hole. The well was gravel packed with 84 % excess sand. The initial post gravel pack PI was 22.8. The measured kh was 46,000 md-ft. Skin damage was 5.2.

Observations

One yardstick commonly used to determine how efficient a well completion to be is the Productivity Index (PI). However, since PI's are effected by kh and skin, PI's alone in non-homogeneous reservoirs can be deceiving. For this reason, both PI's and PI/Kh, bopd/psi/darcy-ft, were compared for the Zafiro completions (Figs. 5 and 6).

Conclusions

1. Openhole gravel packed completions can yield higher producibility than cased hole gravel packed wells.
2. Fluids studies on field cores can pay dividends by aiding in the selection of optimal fluids used during completions.
3. Several hundred feet of horizontal openhole can be successfully gravel packed using viscoelastic surfactant-based fluids in conjunction with shunted screens.
4. Use of shunted screens and viscoelastic surfactant-based fluids minimize pit volume requirements on the rig for long interval jobs.

5. Gravel packing high angle and horizontal wells is superior to running prepacked screens when long life completions are desired.

6. Minimizing fluid loss to the formation, either during post perforating or post gravel pack operations aids in minimizing skin damage.

7. Additional fluids testing and other work to prevent shale sluffing is required for Zafiro completions.

Acknowledgments

The authors would like to thank the Mobil drilling supervisors Will Billings, James Menard, Keith Renard, and Bob Simon for their field support. In addition, the authors would like to thank the staff of Mobil E&P Technology, Dowell Schlumberger, US Filter/Johnson Screens, and Lloyd Jones & Associates.

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Table 1-Return Permeability Tests of Carrying Fluids and LCM Pills Run on Zafiro Cores at BHT

Type Fluid	Return Permeability Thru Core
NaCl	73%
3% KCL & NaCl	76%
CaCO ₃ Biopolymer Pill	19%
CaCO ₃ Biopolymer Pill followed by 7-1/2% HCL	48%
Viscoelastic Surfactant-based fluid	77%
HEC without breaker	28%
HEC with breaker	33%

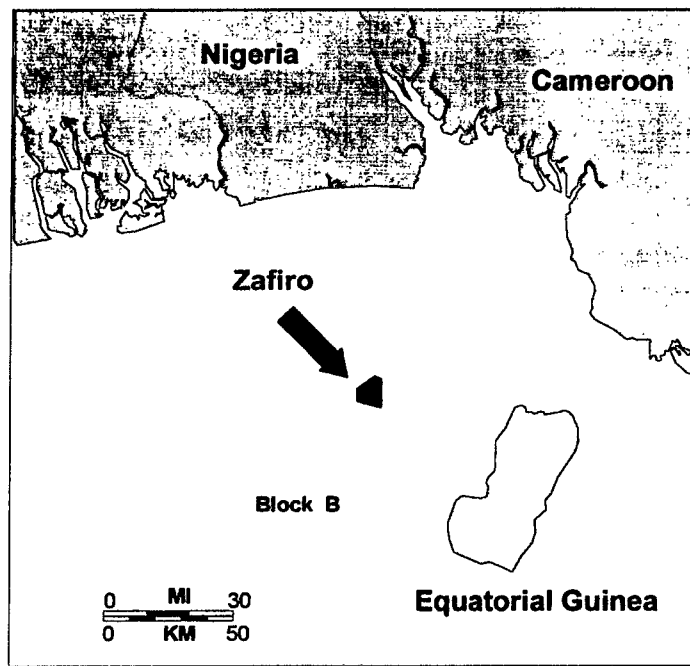


Fig 1- Map of the Zafiro Field

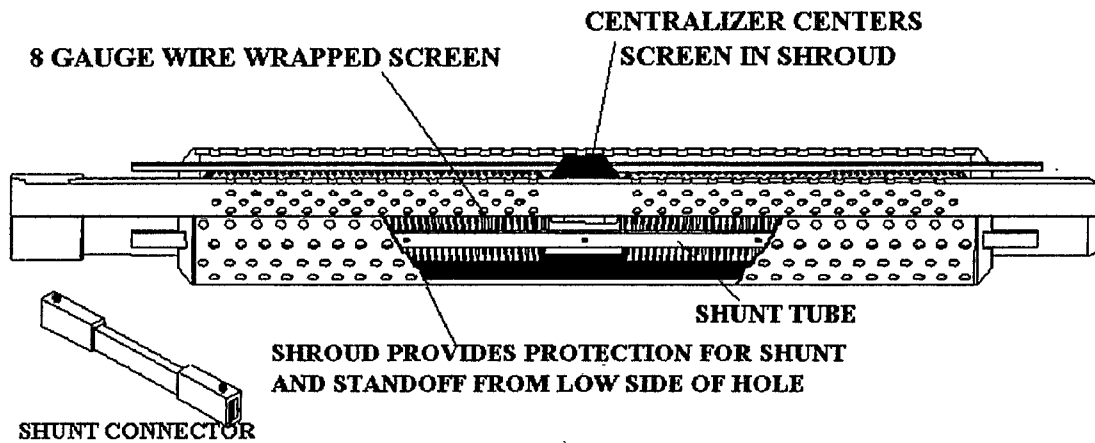


Fig. 2- Shrouded screen with shunt tubes



Fig. 3 -Surface tests performed with shunts in horizontal mode and slotted plastic pipe used as the formation with high leak-off. Flowed into the the liner and then down the shunt tube. Resulted in 500 ft completely packed with one shunt.

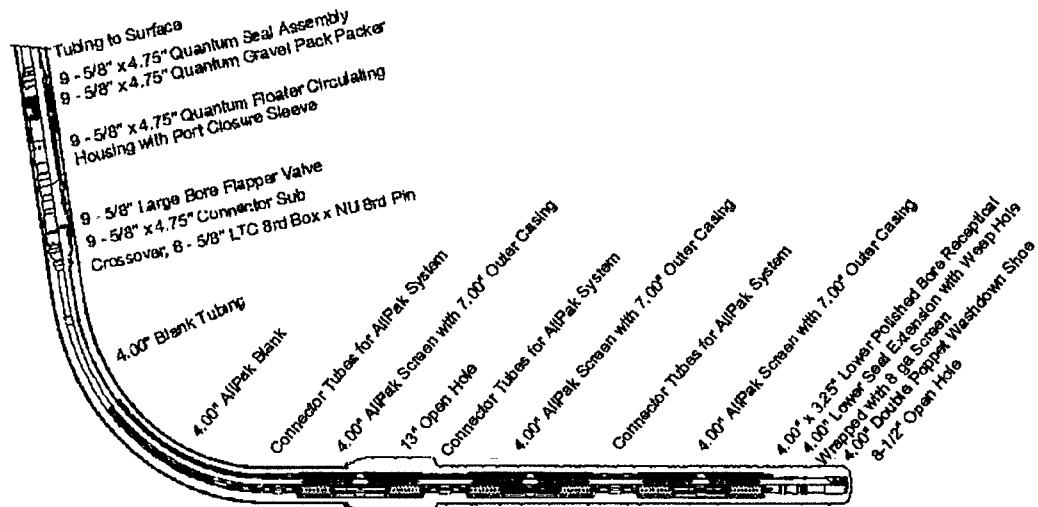


Fig. 4 - Typical Mobil Equatorial Guinea Openhole Gravel Pack Bottomhole Assembly

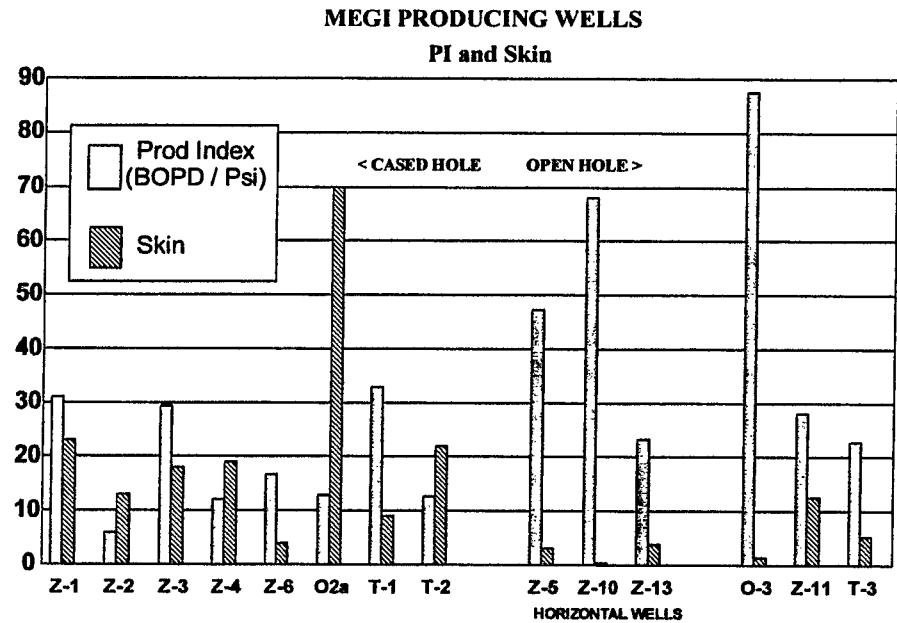


Fig. 5- Productivity Index and Skin for MEGI Producing Wells

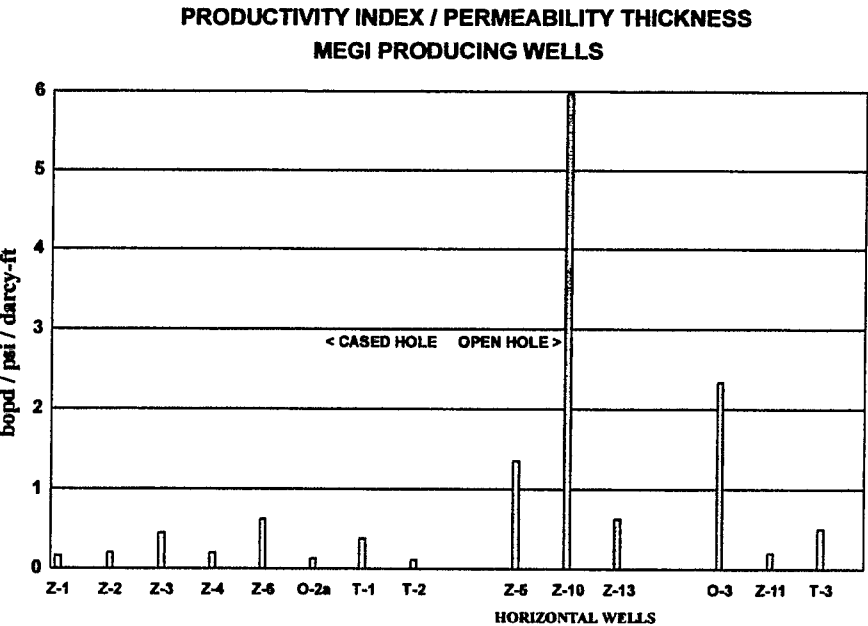


Fig. 6 - Productivity Index/Permeability Thickness for MEGI Producing Wells