



Key Drilling and Completion Concerns in Horizontal Wells

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Abstract

Horizontal wells have been widely used in the industry for the last 10 years. In this time drilling and completion techniques have evolved from simple barefoot completions to more complex completions utilizing downhole sand exclusion. This paper will present key learnings from design, execution and evaluation of a wide range of horizontal wells completed with and without downhole sand control.

The paper will discuss essential well design issues from drilling fluid selection and maintenance guidelines, to determining the need for downhole sand control, to determining the effect of alternative completion techniques on well productivity. Analytical relationships will be used to describe the interplay between drilling and completion operations and well flow performance. Field case histories will also be presented to demonstrate the practicality of the design guidelines presented.

Introduction

A range of horizontal drilling and completion techniques have been developed over the past 10 to 15 years to meet design and implementation challenges. In general, horizontal well designs have become more complex to accommodate increasingly complex completion designs. Early horizontal wells were generally designed for simple barefoot completions with little regard for drilling fluid composition, sand production or completion pressure loss. With time these simple drilling and completion designs were revised to accommodate sand production from weak sandstone reservoirs and to allow stimulation of low permeability reservoirs. In sand producing areas, operators and service companies developed techniques for predicting formation failure potential and began to design wells capable of preventing large-scale formation collapse and associated uneconomic sand production. These sand exclusion completions required well designs to become much more sophisticated with specialized drill-in fluids, expensive sand exclusion screens and clean-up treatments. Similarly, isolation and stimulation requirements drove well designers toward more complex cased hole designs allowing oilfield perforators to shoot past damage zones and connect the wellbore to the

reservoir. Critical review of the various design techniques indicates that several key design elements dominate well flow performance for each type of horizontal well.

This paper will review key drilling and completion design features needed to provide a horizontal well capable of producing reserves effectively and without undue pressure loss. While reservoir characterization provides the basis for all well designs, the process of selecting the best well length and type of completion for a given reservoir is beyond the scope of this paper. The interested reader is directed to references 1 through 6. This paper will instead assume a fully characterized reservoir and focus on drilling and completion parameters under the control of well design and field implementation personnel. The discussion will be subdivided into separate sections for each of the following well/completion types:

- Simple Barefoot Completion
- Open Hole Completion requiring Stand-Alone Sand Control Screen or OH Gravelpack
- Cased Hole Perforated Completion

Reservoir Characterization

As noted above, reservoir properties will be assumed for the well design discussions which follow. All of the wells will be placed in a reservoir with the following basic properties:

$K_h=100$ md to oil

$K_h/K_v=1$

$H=150$ ft with well located 10 ft from top of reservoir= 140 ft above Oil/Water Contact

The reservoir is supported by a strong bottom water drive, providing steady-state flow conditions. Formation strength and failure characteristics will be allowed to vary to provide a need for different completion types.

Reservoir fluid properties are as follows:

$u=0.5$ cp

$B=1.25$ rb/stb

The well is produced at a pressure above the bubble point in all cases.

Using Goode & Kuchuk's relation⁵ for steady-state flow from a reservoir underlain by a strong aquifer, this combination of reservoir properties results in reservoir pressure losses for flow to an undamaged/unstimulated horizontal well as shown in Figure 1, Effect of Well Length on Reservoir Pressure Loss.

As shown, longer well lengths require less reservoir pressure loss than shorter wells. For a 2000 ft well length, reservoir pressure loss is 4.01 psi per 1000 STB/day of production. At a target rate of 20,000 STB/day, total reservoir pressure loss will therefore be 80 psi. If the well can be completed without damage this 80-psi reservoir pressure loss will equal the total drawdown required for the well at the target 20,000 STB/day rate.

The rate normalized pressure loss values noted above (4.01 psi/MSTBPD=80 psi/20,000 STBPD) can be converted to well productivity by noting that a well's productivity index, PI, is equal to rate divided by drawdown (Q/DP), the reciprocal of rate normalized pressure loss (DP/Q). Results are shown in Figure 2, Effect of Well Length on Productivity.

For the remainder of the paper, we will look at the effect of drilling and completion design elements on the reservoir characterized above. Pressure losses resulting from different drilling and completion design decisions will create additional, non-reservoir, pressure losses, whether positive in the case of damage or negative in the case of stimulation. To simplify comparisons between alternative design cases, a 2000 ft horizontal section will be drilled through the reservoir in all cases.

Completion Evaluation

The effectiveness of a well design can be reviewed in a number of ways such as cost, cost per unit recovery (i.e.: \$/bbl, \$/boe or \$/MMSCF) or productivity. While cost is an important measure of overall well performance, productivity generally provides the best gauge of completion design benefit. Calculation of productivity for a range of alternative completion designs allows the project engineer to rank desirable features and determine the most cost-effective design for a given well.

A simple method for rating completion performance and its effect on overall well productivity is flow efficiency:

$$FE = DP_{\text{reservoir}} / (DP_{\text{reservoir}} + DP_{\text{skin}}) = Q_{\text{actual}} / Q_{\text{zeroskin}}$$

As shown, flow efficiency relates total pressure loss due to flow to the well to an idealized pressure loss for flow through the reservoir only where both pressure losses

are calculated at a constant flow rate. This pressure loss efficiency is equivalent to a flow rate efficiency relating the actual flow rate for a given drawdown to an idealized flow rate for an undamaged/unstimulated (i.e.: zero skin) wellbore. The flow efficiency therefore shows the effect of completion pressure loss on potential well rate and productivity. For the reservoir characterized above, a 2000 ft long horizontal well requires 80 psi of pressure drawdown to flow 20,000 STB/day. If completion pressure loss (i.e.: DP_{skin}) is 0 psi then this well will have a flow efficiency of 1.0 and will have high productivity. If, instead of 0 psi, completion pressure loss at 20,000 STB/day is 80 psi then the well will have a flow efficiency of 0.5, half of the zero-skin flow efficiency noted above. While the 0.5 flow efficiency well can deliver 20,000 STB/day if total well drawdown is 160 psi, corresponding to 80-psi reservoir pressure loss plus 80-psi completion pressure loss, rate will drop to 10,000 STB/day if drawdown is reduced to 80 psi.

This simple example shows how the pressure and rate flow efficiency relations are used in determining the flow performance of a well, and more particularly the flow performance of a completion. Clearly, high completion pressure losses are bad and a completion providing a lower flow efficiency completion is less desirable than one providing a high flow efficiency.

Flow efficiencies can also be calculated using dimensionless pressure loss terms HWGF and Skin (S) as shown below:

$$FE = DP_{\text{reservoir}} / (DP_{\text{reservoir}} + DP_{\text{skin}})$$

Where :

$$DP_{\text{reservoir}} = [141.2 * Q * u * B / (K_h * H)] * HWGF$$

$$DP_{\text{skin}} = [141.2 * Q * u * B / (K_h * H)] * (H/L) * (K_h / K_v)^{1/2} * S$$

Giving:

$$FE = DP_r / (DP_r + DP_s) = HWGF / (HWGF + (H/L) * (K_h / K_v)^{1/2} * S)$$

For the 2000 ft horizontal well situated in the reservoir described above, Goode & Kuchuk's relation⁵ for steady-state flow from a reservoir underlain by a strong aquifer provides a Horizontal Well Geometric Factor (HWGF) of 0.682.

Flow efficiency, pressure loss and skin terms will be used in the following discussion to determine the productivity benefit of a given design or operation. Productivity index values will also be used, allowing the reader to equate rate gains with reductions in completion pressure loss.

Well Design Cases

As noted earlier, the simplest well design is comprised of a horizontal section completed barefoot. This simple design case will be reviewed first and then followed with increasingly complex designs.

Simple Barefoot Completion

Key drilling and completion design considerations that affect the flow performance of a simple openhole, barefoot, completion are mud design and wellbore clean-up.

Mud Design: While important for all wells, mud design is especially important for wells that will be completed openhole. The filtercake formed during the drilling process has a very low permeability and if not removed will create very high completion pressure losses during production. This high pressure loss can lead to low flow efficiency and low productivity.

Mud cake permeability can be estimated from API fluid loss data. Typical results are provided in Figure 3, Mud Cake Permeability. As shown, mud cake permeabilities are extremely low. While these low permeabilities are desirable during the drilling phase when fluid loss control is important, low mud cake permeabilities become a hindrance during production when the goal is to deliver produced fluids from the reservoir to the well with low pressure loss. For radial flow to the wellbore, the mud cake permeabilities and thicknesses noted above can be used to calculate a dimensionless pressure loss or skin effect as shown in Figure 4, Skin Effect due to Mud Cake.

As shown, the dimensionless pressure loss, skin, due to mud cake is very high. If the mud cake is left intact, high pressure losses due to mud cake skin will reduce flow efficiencies to extremely low levels, effectively preventing production from the well. Figure 5, Correlation of Mud Cake Skin to Pressure Loss, shows how much pressure loss can occur if 20,000 STB/day is flowed through the typical mud cake described above. The graph shows that the pressure required to flow 20,000 STB/day=10 STB/day/ft of wellbore length through intact mud cake is so high as to prohibit economic production from a well: graphed mud cake pressure loss ranges from 5,000 psi to 50,000 psi. These high mud cake skin pressure losses result in very low flow efficiencies as shown in Figure 6: Effect of Mud Cake Skin on Flow Efficiency.

From this information it is clear that the mud cake must be removed. This can be performed by use of a mud cake clean-up treatment or by designing the mud cake to break down or lift-off with production. The benefit of mud cake removal is shown in Figure 7, Skin due to Flow

Convergence to Holes in Mud Cake. As shown, even limited mud cake removal significantly reduces skin. Figure 7 shows that intact mud cake=0% mud cake removal results in a skin of +2934. Removal of 0.01% of the mud cake by small equally spaced holes lowers skin to +58, while removing 1% of the mud cake reduces skin to +0.4. At 10% mud cake removal skin is +0.004 and, of course, mud cake skin is zero at 100% mud cake removal. If there are no other damage effects, these skin values result in the following flow efficiencies:

MCreoval= 0%	S=+2934	FE=0.003
MCreoval=0.01%	S= +58	FE=0.145
MCreoval= 1%	S= 0.4	FE=0.959
MCreoval= 10%	S= 0.004	FE=0.999
MCreoval=100%	S= 0	FE=1.000

The final mud design parameter which must be considered in design is the mud filtrate which will leak off into the formation through the mud cake. Review of data from a number of core studies⁷⁻¹⁰ shows that mud filtrates can reduce near-wellbore permeability values anywhere from 0% ($K_{mf}/K_r=1$) to near 100% ($K_{mf}/K_r=0$) with the median value for both oil-based and water-based mud systems providing a K_{mf}/K_r value of roughly 0.5. This is shown in Figure 8, Comparison of Mud Filtrate Return Permeability Data. The mud filtrate return permeability data noted above can result in skin values as shown in Figure 9, Skin due to Mud Filtrate Invasion.

From the above discussion it can be seen that it is important to design mud systems to build effective filter cakes during drilling operations but be easily removed prior to production. For best results, the mud should be designed for low spurt and low fluid loss during drilling. This will limit invasion of mud particles into the formation and minimize mud filtrate invasion. The mud filtrate should be designed to minimize near-wellbore permeability impairment (i.e.: provide high K_{mf}/K_r). The mud cake must also be easily removable by production or via a wellbore clean-up treatment.

Due to the uncertainty in predicting pore sizes for non-homogeneous reservoirs, the most efficient drill-in fluid systems will contain a wide particle size distribution based on the most probable range of pore sizes. Additionally, the drill-in fluid should contain a sufficiently high concentration of bridging solids to minimize the impact of drill solids on subsequent clean-up treatments. Studies^{11,12} have shown that properly designed mud systems should include a wide range of mud particle sizes to reduce spurt volumes and minimize loss of mud solids to the formation. In well-designed drill-in fluid systems spurt losses can be reduced to very low levels and mud solid invasion of the formation limited to distances less than a centimeter^{13,14}. To enhance clean-up, the filter cake formed by the mud solids should also be soluble in a clean-up fluid. Similarly, mud filtrate

should be selected to minimize K_{mf}/K_r reduction.

If these guidelines are followed a very low skin, high productivity well can be attained. Typical mud design values are as follows:

Spurt Loss < 2 cc using 2.0" diameter ceramic disc
 Total Fluid Loss < 10 cc/30 mins using 2.0" ceramic disc
 Soluble Bridging Solids > 35 lbs/bbl
 Non-Soluble Drill Solids < 3%
 MBT < 5 l/BBL
 $K_{mf}/K_r > 0.75$
 Mud Cake Removal > 10%

If these mud design values are used completion performance and well productivity will be maximized. This is shown in Figure 10, Horizontal Well Inflow Performance: Barefoot Completion, where total pressure loss required to produce the target rate of 20,000 STBPD is graphed for various mud clean-up and mud filtrate values. As shown, total pressure loss, corresponding to the sum of both reservoir and completion pressure loss, approaches reservoir only pressure loss as mud cake clean-up approaches 10% and $K_{mf}/K_r = 1$.

With skin related pressure losses reduced to near zero values, well productivity will be maximized as shown in Figures 11 and 12: Horizontal Well Inflow Performance: Barefoot Completion Flow Efficiency and Barefoot Completion Productivity Index.

Open Hole Completion requiring Stand-Alone Sand Control Screen or Openhole Gravelpack

Key drilling and completion design considerations that affect the flow performance of an openhole completion with a stand-alone screen or gravel pack are mud design and sand exclusion design.

Mud Design: The guidelines discussed for a barefoot completion should also be followed for an openhole sand control completion. However, the need for a clean-up treatment becomes more important as direct flowback of the mud solids will be restricted by the sand exclusion media, whether gravel or screen.

A number of studies have shown that mud solids do not readily flow back through gravel or screen^{15,16}. This fact can be readily seen in the generally low productivity of openhole sand control completions which do not use clean-up treatments and the correspondingly large improvements that these wells show after pumping post-completion treatments^{17,18,19}.

Sand Exclusion Design: In addition to effective mud design, openhole sand exclusion completions also require effective sand exclusion design. This can be as

simple as sizing a stand-alone screen to prevent unacceptable formation solids production to as complex as sizing a gravelpack/screen combination to filter out large formation particles while allowing mud solids and small formation grains to be produced²⁰.

For best results, the largest possible screen should be run in the hole to minimize the hole/screen annular distance and reduce friction due to flow along the inside of the screen. In most cases this will result in a stand-alone screen design, except where a gravelpack is required to prevent large-scale formation grain movement.

A comparison of the effect of using different screens in an 8-1/2" wellbore is provided in Figures 13 and 14. Figure 13, Effect of Hole/Screen Annular Permeability on Horizontal Well Inflow Performance, shows the effect of screen size on completion pressure loss and well productivity. As shown, use of larger screen minimizes completion pressure loss and results in maximum productivity. As noted above, use of smaller screens will reduce well productivity. This is caused by additional hole/screen annular radial flow distance and by friction due to flow along the screen's base pipe. Of the total pressure difference noted above, the amount of friction is provided in Figure 14, Effect of Screen Base Pipe ID on Axial Flow Friction.

In summary, open hole sand exclusion completions should be designed using the following design parameters:

Spurt Loss < 2 cc using 2.0" diameter ceramic disc
 Total Fluid Loss < 10 cc/30 mins using 2.0" ceramic disc
 Soluble Bridging Solids > 35 lbs/bbl
 Non-Soluble Drill Solids < 3%
 MBT < 5 lbs/bbl
 $K_{mf}/K_r > 0.75$
 Mud Cake Removal > 10%
 $K_{annulus}/K_r > 10%$
 Maximum Screen ID and OD

To achieve these parameters, especially Mud Cake Removal > 10% and $K_{annulus}/K_r > 10%$ will generally require use of a drill-in fluid and some sort of acid clean-up.

Cased Hole Perforated Completion

Key drilling and completion design considerations that affect the flow performance of a cased hole perforated completion are mud design and perforation design.

Mud Design: The guidelines discussed for a barefoot completion provide a useful starting point for cased hole perforated completion designs. In particular, the spurt and total fluid loss values should be followed, however,

soluble mud solids and clean-up treatments become unnecessary as the perforations will bypass the mud cake laid down during drilling. The dominant mud effect will be depth of mud filtrate invasion and permeability loss in the filtrate invaded region. Depth of filtrate invasion will be minimized through use of the low spurt and total fluid loss values discussed above. The level of permeability impairment in the filtrate invaded zone can be minimized through selection of a mud system which maximizes K_{mf}/K_r values.

Perforation Design. As in conventional well designs, the key to effective perforated completion performance in horizontal wells is perforation length. Longer perforations provide better productivity than shorter perforations as shown in Figure 15, Effect of Perforation Length on Well Productivity. As shown, well productivity increases sharply for perforation length increases from 2" to 10". After perforation length exceeds 10" the rate of productivity gain slows, however, productivity continues to rise with length increases.

A second perforation design feature which affects well productivity is the condition of the wellbore at the time of perforating. As discussed in H.O. McLeod's paper²¹ perforating while in an underbalanced condition minimizes crushed zone damage and maximizes well productivity. McLeod showed that the degree of perforation crushed zone damage could be correlated to perforating conditions with the most damage suffered when perforating overbalanced in high solids muds. These effects can be seen in Figure 16, Effect of Perforating Conditions on Well Productivity. Perforation damage effects will be exacerbated by deep penetration of damaging mud filtrate as shown in Figure 17, Effect of Perforating Conditions on Well Productivity, where K_{mf}/K_r is reduced to 0.5 from the previous graph.

As a result, perforating conditions and mud design go hand-in-hand for cased hole perforated completions.

Perforating Design Recommendations:
 Select Perforations with $L_p > 12"$
 Select Moderate Perforating Density = 6 SPF
 Perforate in Filtered Brine
 Perforate in an Underbalanced Condition if Possible

Field Case Histories

This section of the paper will review several field cases histories to show the applicability of the design elements noted above.

Mud Design/Mud Cake Removal Example

In this example a well is drilled into a stable formation using a water-based drill-in fluid system with calcium carbonate bridging solids. During reservoir drilling, the drill-in fluid's carbonate solids loading is allowed to drop

to low levels and the reactive drill solids is allowed to rise to high levels. This results in poor mud cake properties and very low well productivity. This low productivity can only be improved by working over the well and pumping an aggressive heated-acid treatment. A productivity comparison is provided in Figure 18: Mud Cake Removal Example.

Openhole Completions with Stand-Alone Screens

A series of wells are drilled using the same water-based drill-in fluid with calcium carbonate bridging solids. All wells are completed in weak sandstone reservoirs with sand-exclusion screens to prevent sand production. Some of the wells are acidized to remove mud cake damage and provide a high permeability hole/screen annulus. Other wells are not acidized, allowing the mud cake to break-up and flow back through the screen as the formation fails. A productivity comparison is provided in Figure 19. As shown, the wells completed with acid clean-up provide significantly higher flow efficiencies.

Cased Hole Perforated Completion

This example well is drilled and a liner cemented across the reservoir. The well is perforated overbalanced in unfiltered brine resulting in a large crushed zone skin. The well is later re-perforated underbalanced to increase productivity. Results are shown in Figure 20.

Summary

As shown in the Well Design discussions above, different types of horizontal well completions are sensitive to different design features. Use of an integrated design methodology taking account of reservoir characterization, completion flow analysis, laboratory testing and productivity post-audits is necessary to provide high performance horizontal wells^{17,22}.

Conclusions

- Different completion types are controlled by different design parameters.
- Openhole, barefoot, completions are most sensitive to mud design and mud cake clean-up.
- Openhole wells completed with stand-alone sand screens are sensitive to mud cake clean-up and hole/screen annular permeability.
- Cased hole perforated completions are sensitive to perforation design and perforating conditions.
- Use of the design methodology and guidelines provided in this paper can prevent high completion skins and productivity loss in horizontal wells.

Nomenclature

API=American Petroleum Institute
B=volume factor, bbl/STB
DP =pressure loss, psi
e=absolute pipe roughness, inches
FE=flow efficiency, dimensionless
ID=internal diameter, inches
H=reservoir vertical thickness, ft
HWGF=horizontal well geometric factor, dimensionless
K=permeability, md
L=horizontal well completion length, ft
L_p=perforation length in formation, inches
MC=mud cake
PI = productivity index, STB/day/psi
Q=flow rate, STB/day
S=skin factor, dimensionless
SPF=shots per foot
u=viscosity, cp

subscripts:

c=crushed zone
h=horizontal
mc=mud cake
mf=mud filtrate
r=reservoir
v=vertical

References

- Joshi, S.D.: **Horizontal Well Technology**, PennWell Books, Tulsa, Oklahoma, 1991.
- Giger, F.M. et al: "The Reservoir Engineering Aspect of Horizontal Drilling," SPE 13024.
- Renard, G. and Dupuy, J.G.: "Influence of Formation Damage on the Flow Efficiency of Horizontal Wells," SPE 19414.
- Kuchuk, F.J., Goode, P.A., Brice, B.W., Sherrard, D.W., Thambynayagam, R.K.M.: "Pressure Transient Analysis and Inflow Performance of Horizontal Wells," SPE 18300.
- Goode, P.A. and Kuchuk, F.J.: "Inflow Performance of Horizontal Wells," SPE Reservoir Engineering, August 1991.
- Babu, D.K. and Odeh, A.S.: "Productivity of a Horizontal Well," SPE Reservoir Engineering, November 1989.
- Shaw, J.C. and Chee, T.: "Laboratory Evaluation of Drilling Mud Systems for Formation Damage in Horizontal Wells", SPE 37171, presented in Calgary Alberta, November 1996.
- Longeron, D.G., Alfenore, J., Salehi, N. and Saintpere, S.: "Experimental Approach to Characterize Drilling Mud Invasion, Formation Damage and Cleanup Efficiency in Horizontal Wells with Openhole Completions", SPE 58737, presented at 2000 International Symposium on Formation Damage Control, Lafayette, La. February 23-24, 2000.
- Davidson, J.M. et al: "Oil-Based Muds for Reservoir Drilling: Their Performance and Cleanup Characteristics", SPE 72063 published in SPE Drilling and Completions Journal, June 2001.
- ConocoPhillips' Internal Laboratory Reports
- Abrams, A.: "Mud Design to Minimize Rock Impairment due to Particle Invasion", JPY, May 1971.
- Burnett, D.B. and Hodge, R.M.: "Laboratory and Field Evaluation of the Role of Drill Solids in Formation Damage and Reduced Horizontal Well Productivity," SPE 37125 presented at the 1996 SPE International Conference on Horizontal Well Technology.
- Thomas, B. and Sharma, M.M.: "Distribution of Mud Induced Damage Around Horizontal Wellbores," paper SPE 39468 presented at the 1998 SPE International Symposium on Formation Damage Control held in Lafayette, Louisiana, February 18-19.
- Burnett, D.B.: "Wellbore Cleanup in Horizontal Wells: An Industry Funded Study of Drill-In Fluids and Cleanup Methods," paper SPE 39473 presented at the 1998 Formation Damage Control Symposium held in Lafayette, Louisiana, February 18-19.
- Hodge, R.M.; Augustine, B.G., Burton, R.C.; Sanders, W.W. and Atkinson, D.J.; "Evaluation and Selection of Drill-in Fluid Candidates to Minimize Formation Damage," SPE 31082 presented at the International Symposium on Formation Damage Control, Lafayette, Louisiana, February, 1996. SPE 31082 later revised and presented in the SPE Drilling & Completions Journal, December, 1997.
- Pitoni, E. et al: "High Productivity Open Hole Gravel Packs in Depleted Permeable Sands", SPE 38157 presented at the 1997 SPE European Formation Damage Conference, the Hague, Netherlands, June 2-3, 1997.
- Burton, R.C. and Hodge, R.M.: "Drilling and Completion of Horizontal Wells Requiring Sand Control," SPE 52812.
- Munro, C. et al: "Stimulating Depleted HP/HT Sand Screen Completions Using Coiled Tubing", SPE 74807.
- MacCulloch, D.J. et al: "Damage Removal in Screened Horizontal Wells", SPE 81732.
- Hodge, R.M., Burton, R.C., Constien, V., and Skidmore, V.: "An Evaluation Method for Screen-Only and Gravel Pack Completions," paper SPE 73772 presented at the 2002 SPE International Exhibition and Symposium on Formation Damage Control held in Lafayette, Louisiana, February 20-21
- McLeod, H.O.: "The Effect of Perforating Conditions

- on Well Performance”, JPT, January, 1983.
22. Burton, R.C., Davis, E.R., Hodge, R.M., Gilbert, T., Stomp, R., Abdelmalek, N. and Bailey, M.: “Subsea Development of Low-Pressure Gas Reservoirs Using High Performance Well Designs”, SPE 74365 presented at the SPE International Petroleum Conference & Exhibition, Villahermosa, Mexico, February, 2002.

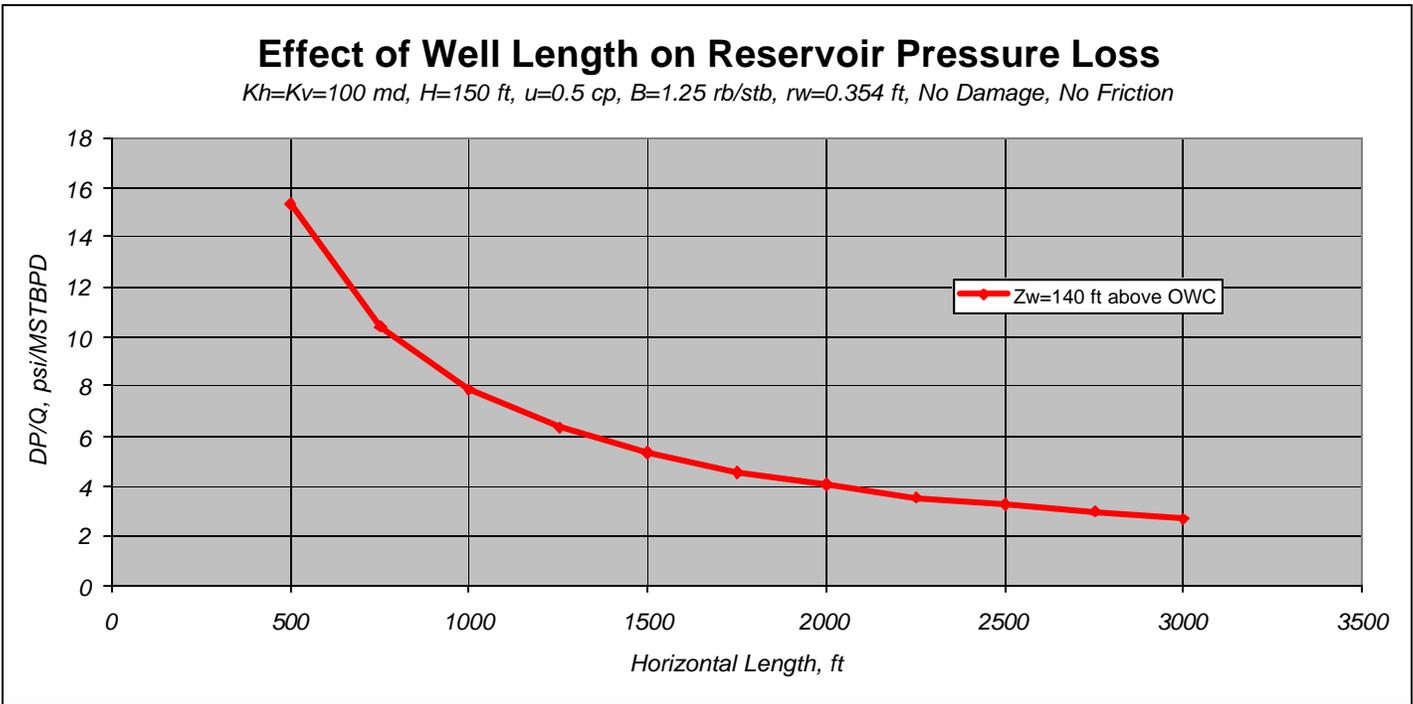


Figure 1

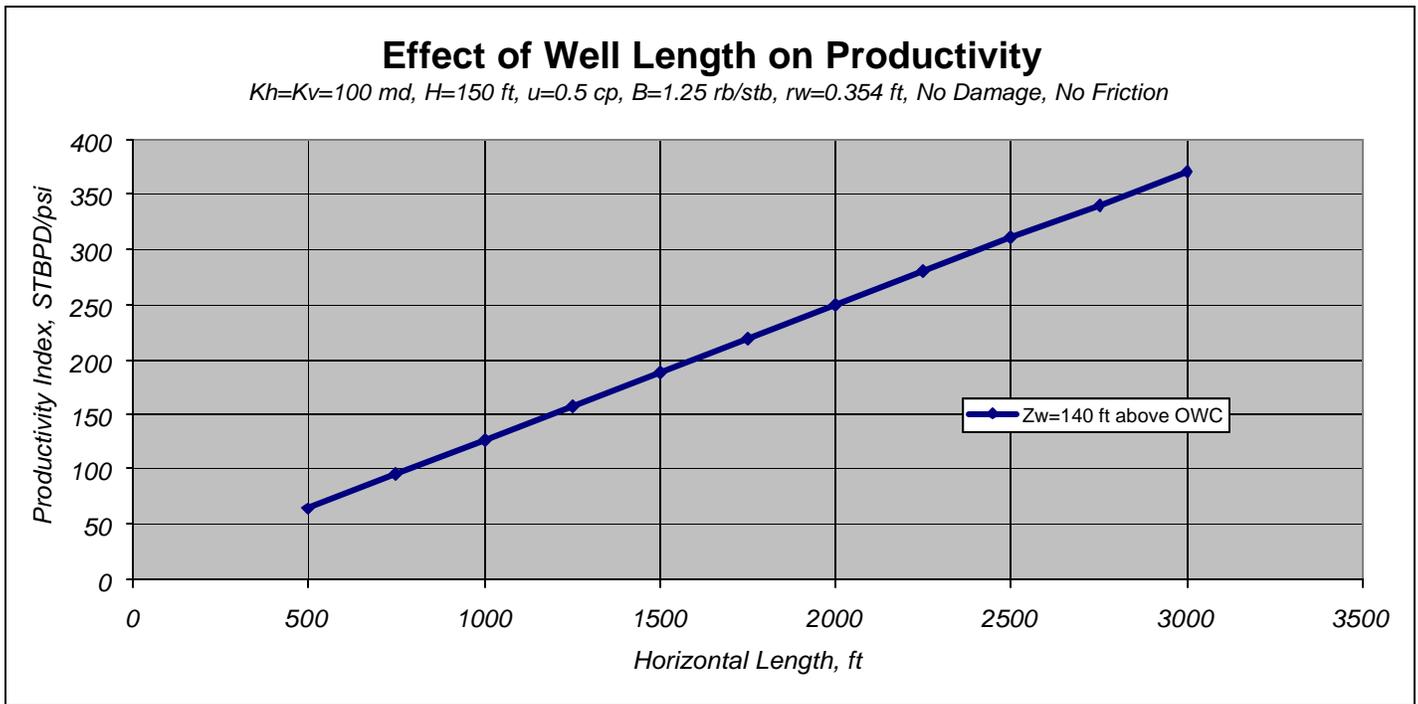


Figure 2

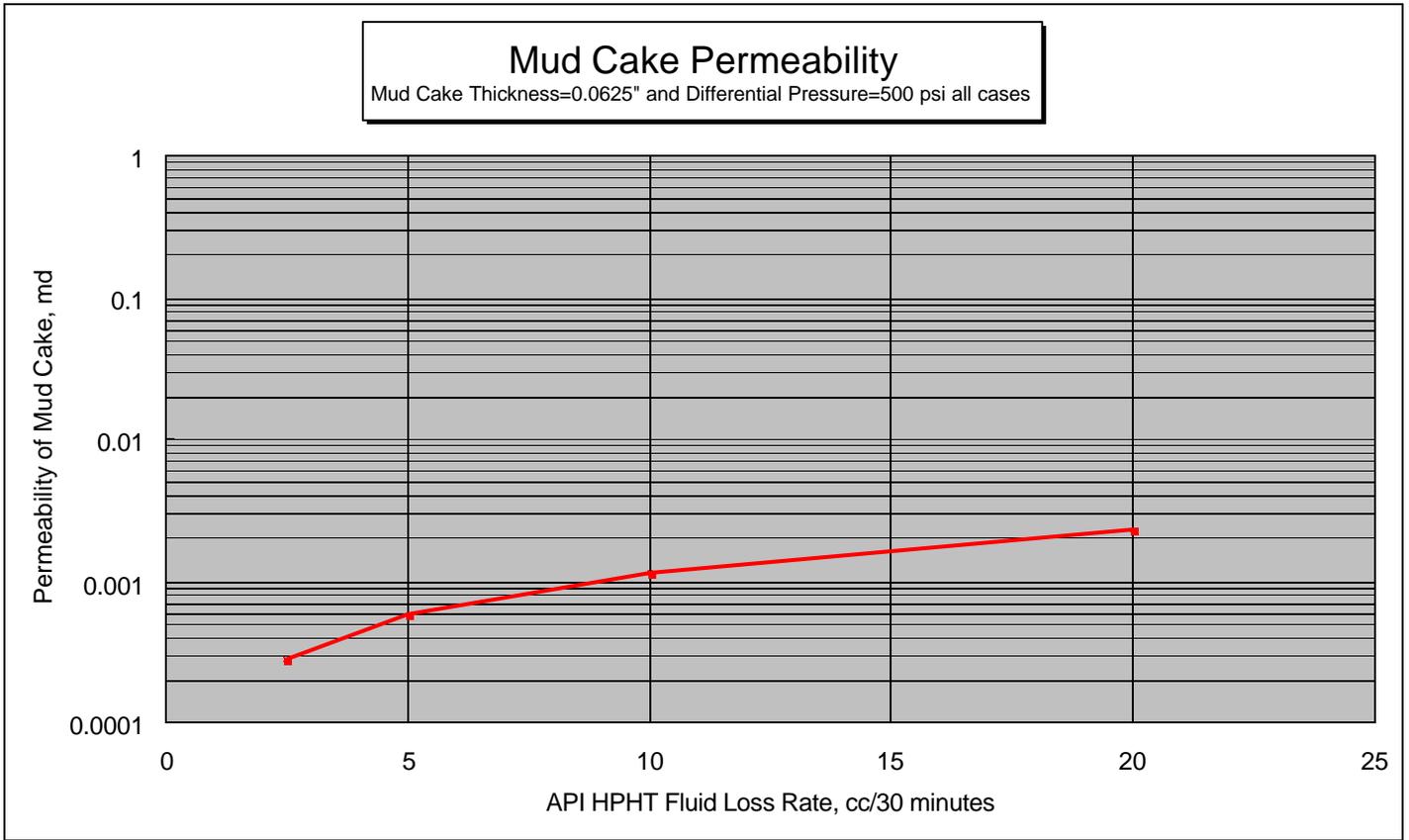


Figure 3

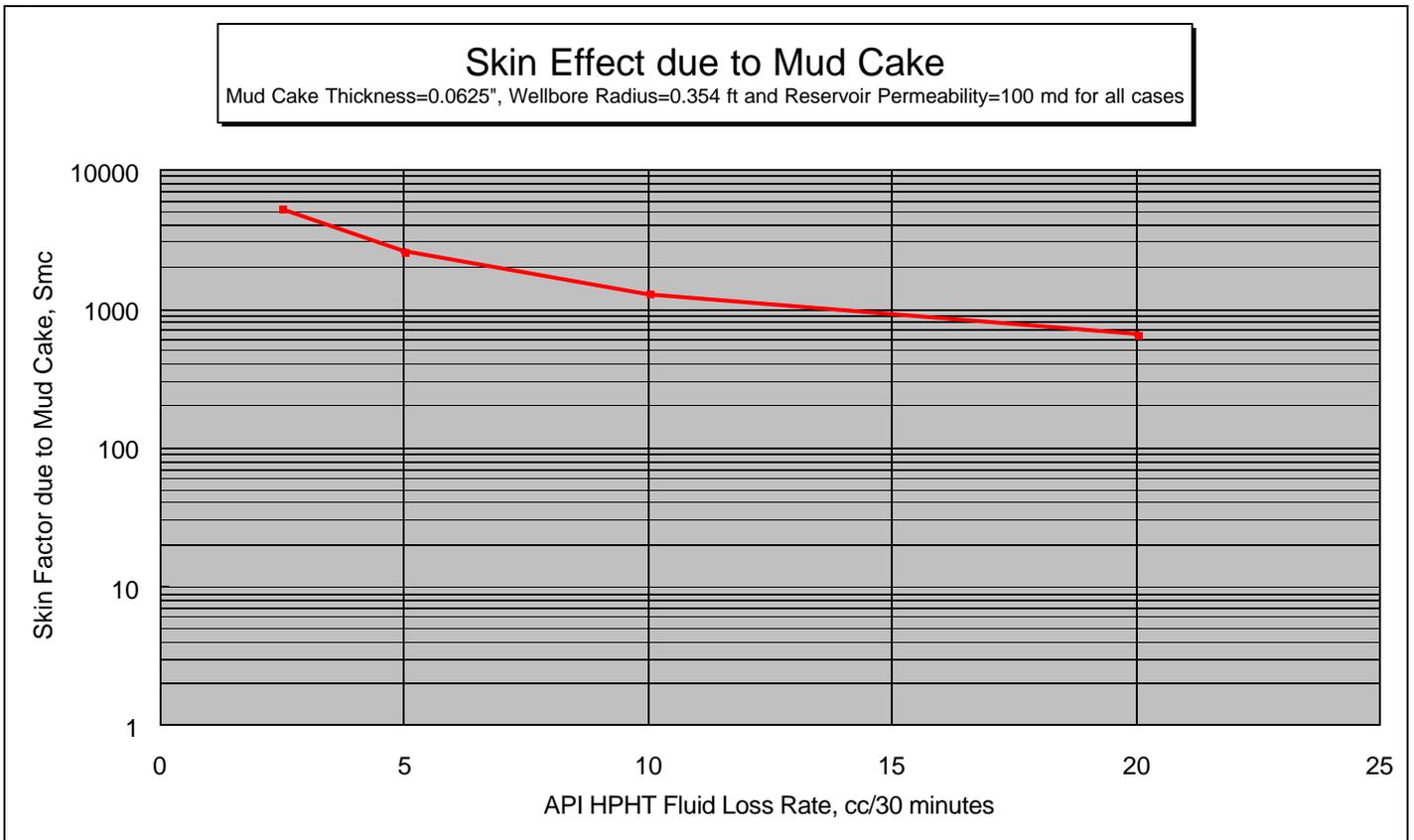


Figure 4

Correlation of Mud Cake Skin to Pressure Loss

$DP = [141.2 * Q * u * B / (K * L)] * S_{mc}$ with: $Q = 20,000$ STB/day, $u = 0.5$ cp, $B = 1.25$ rb/stb, $K = 100$ md, $L = 2000$ ft

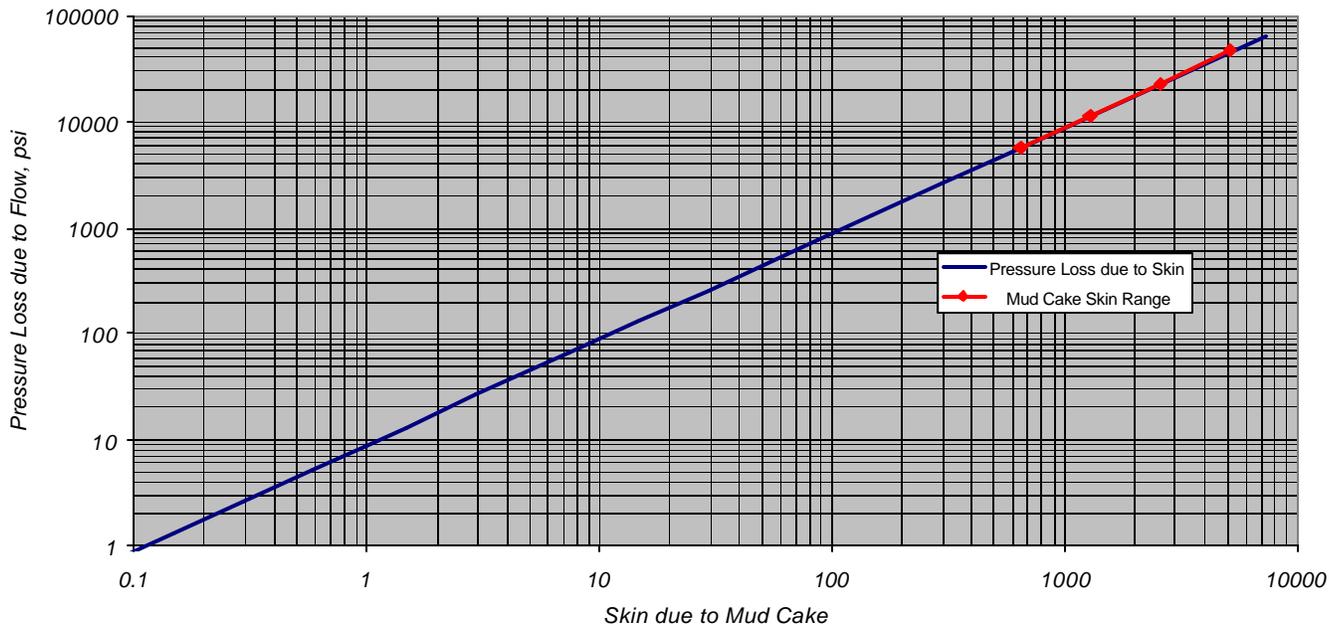


Figure 5

Correlation of Mud Cake Skin to Flow Efficiency

$Flow\ Efficiency = DP_{reservoir} / (DP_{reservoir} + DP_{skin})$ with: $DP_{reservoir} = 80$ psi and $DP_{skin} = 141.2 * Q * u * B / (K * L) * S_{mc}$

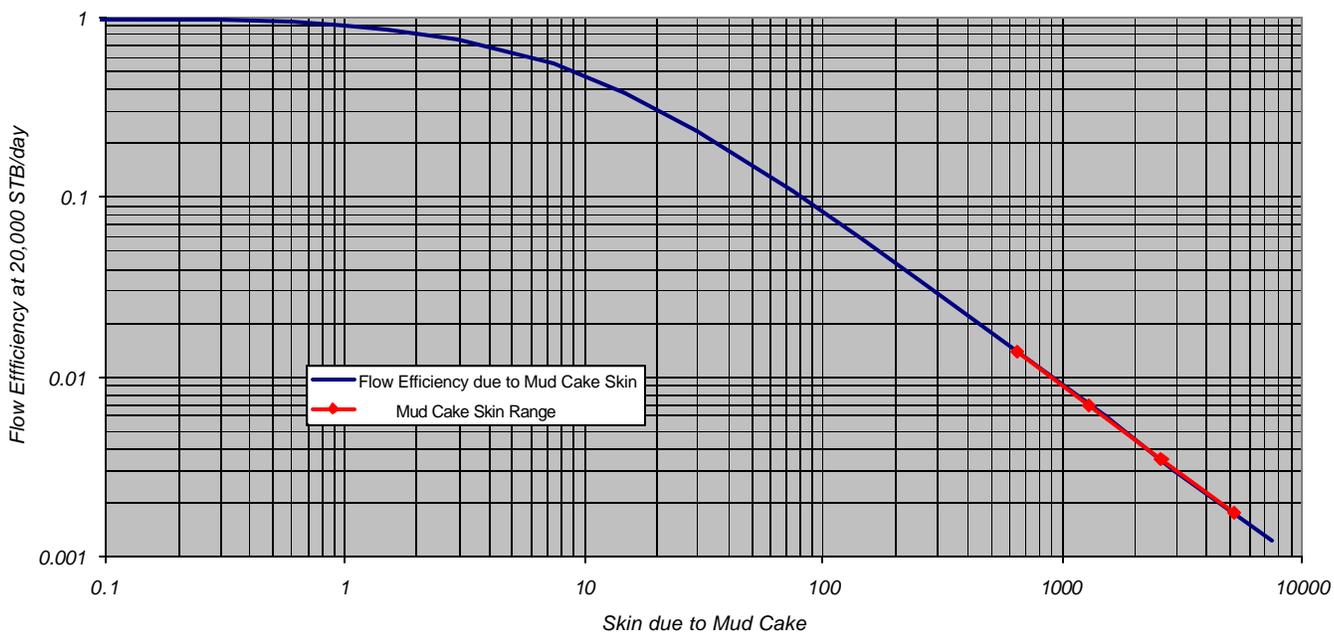


Figure 6

Skin due to Flow Convergence to Holes in Mud Cake

$K_{mc}=0.0005$ md, $K_r=100$ md, $K_{mf}/K_r=1$ and $r_w=0.354$ ft for all cases

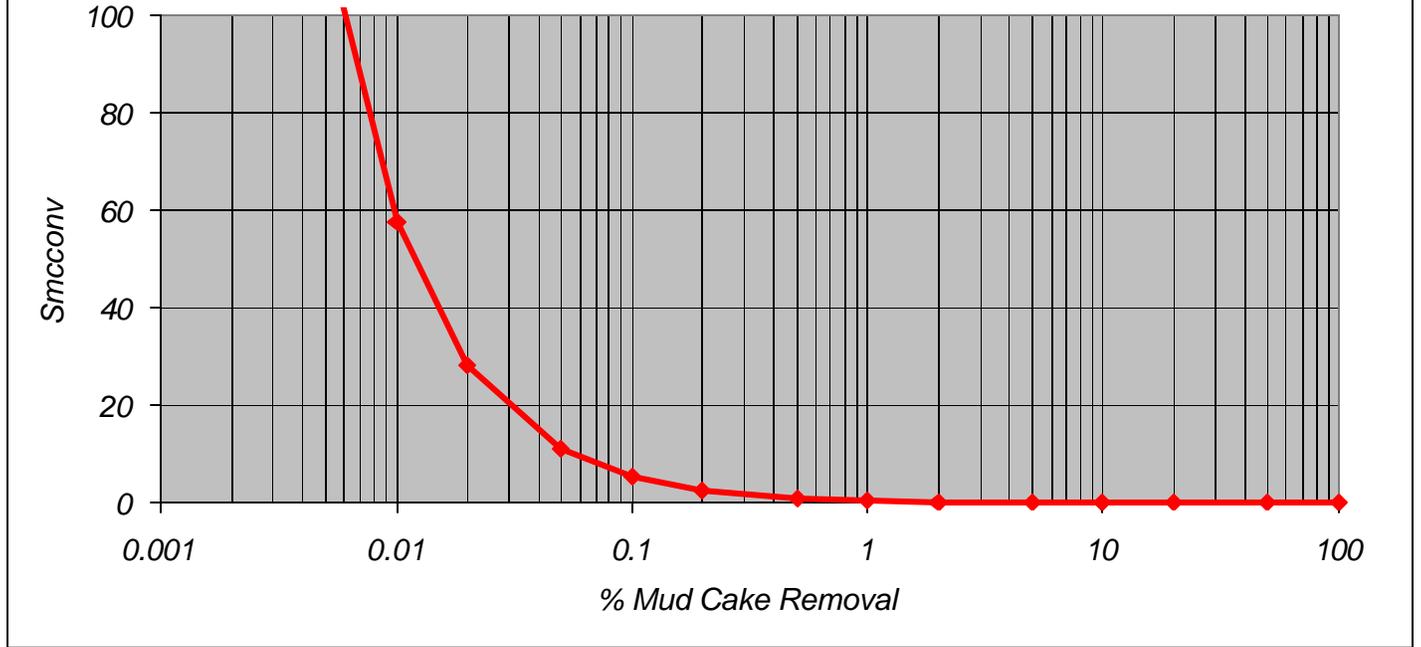


Figure 7

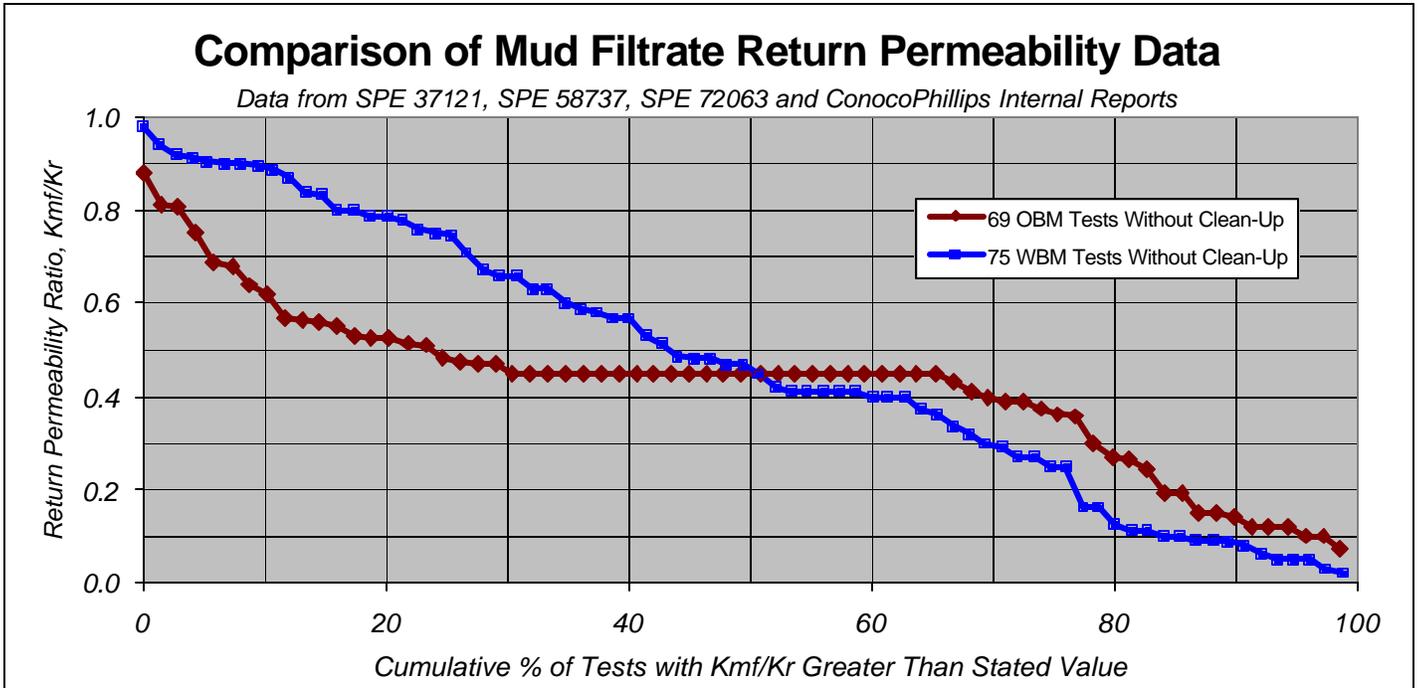


Figure 8

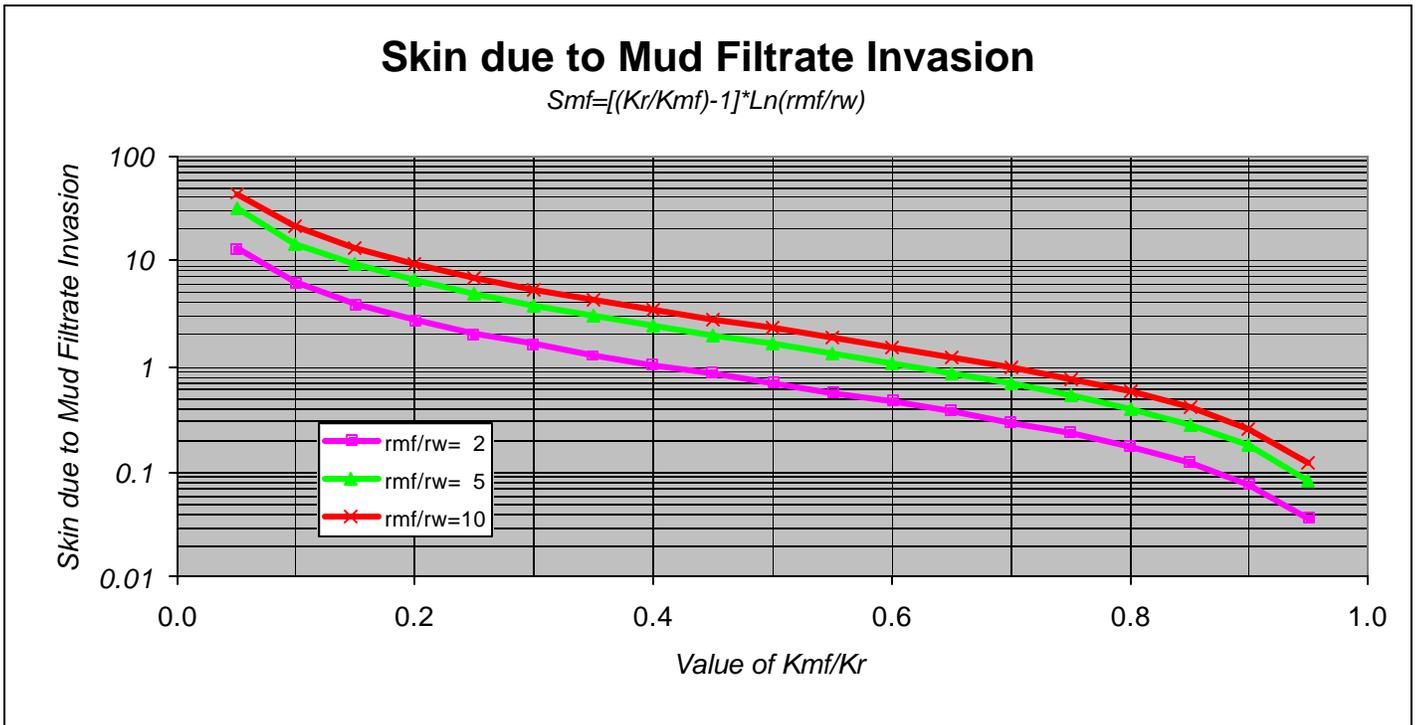


Figure 9

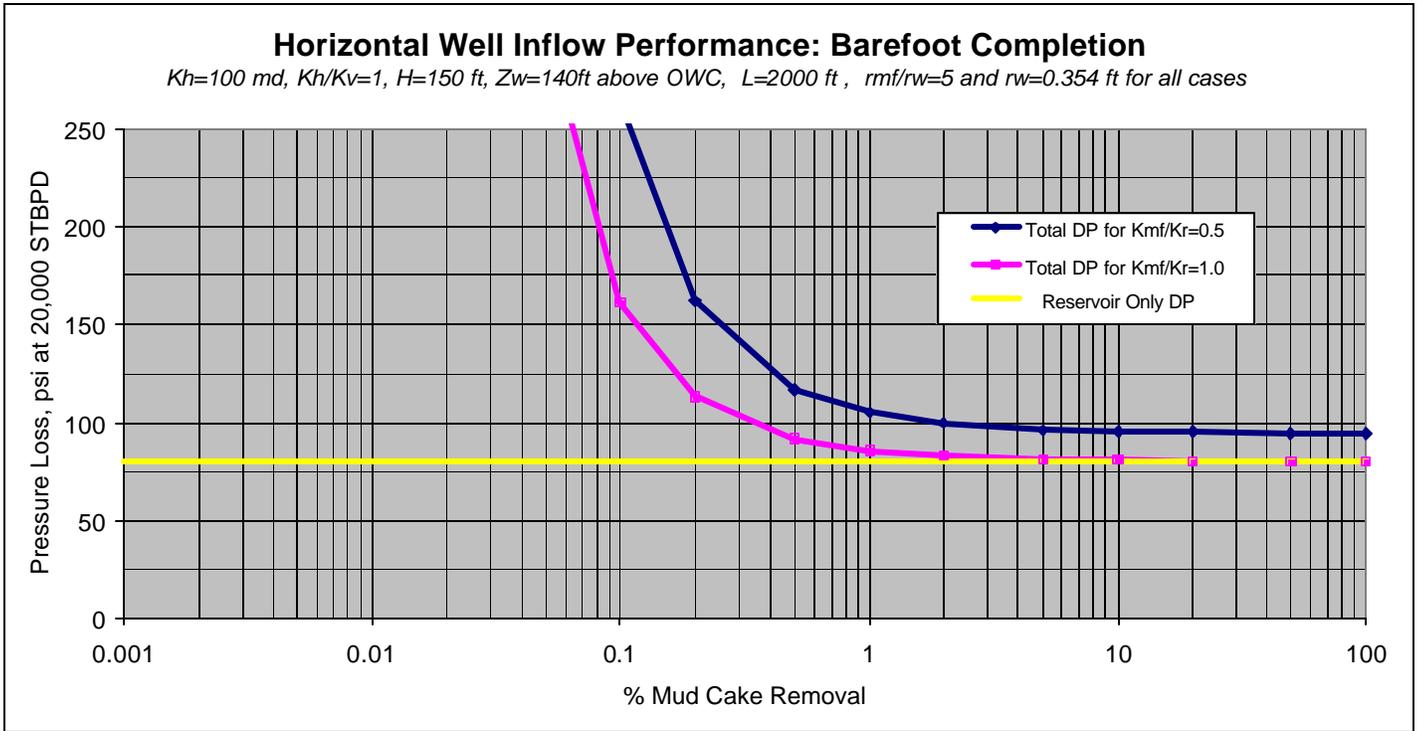


Figure 10

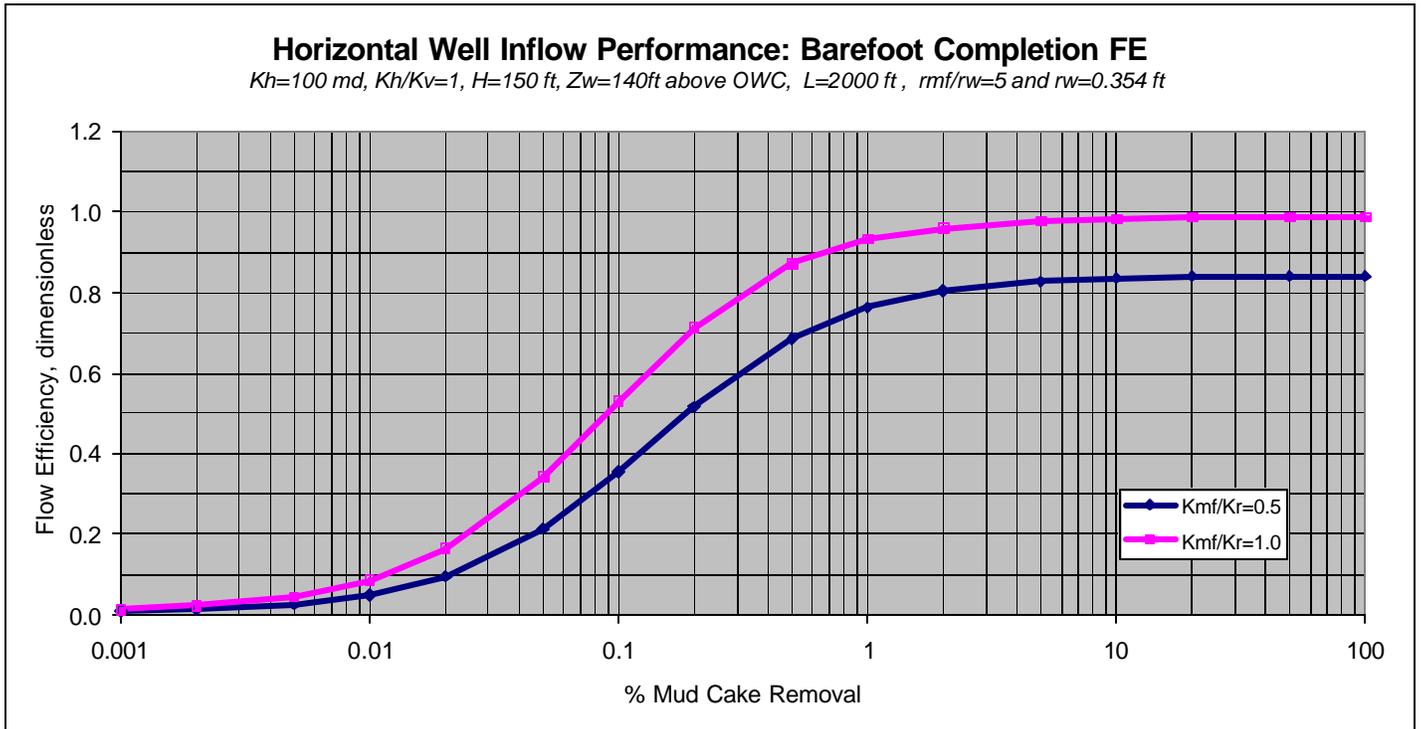


Figure 11

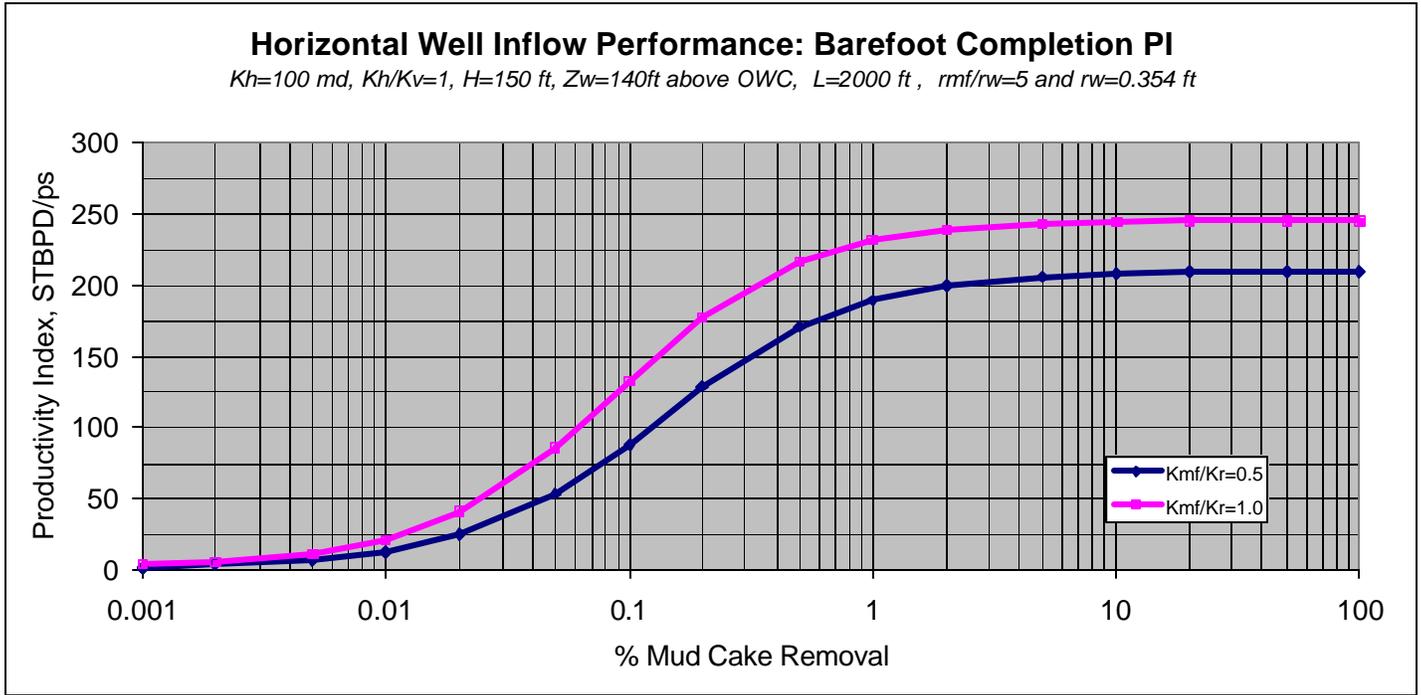


Figure 12

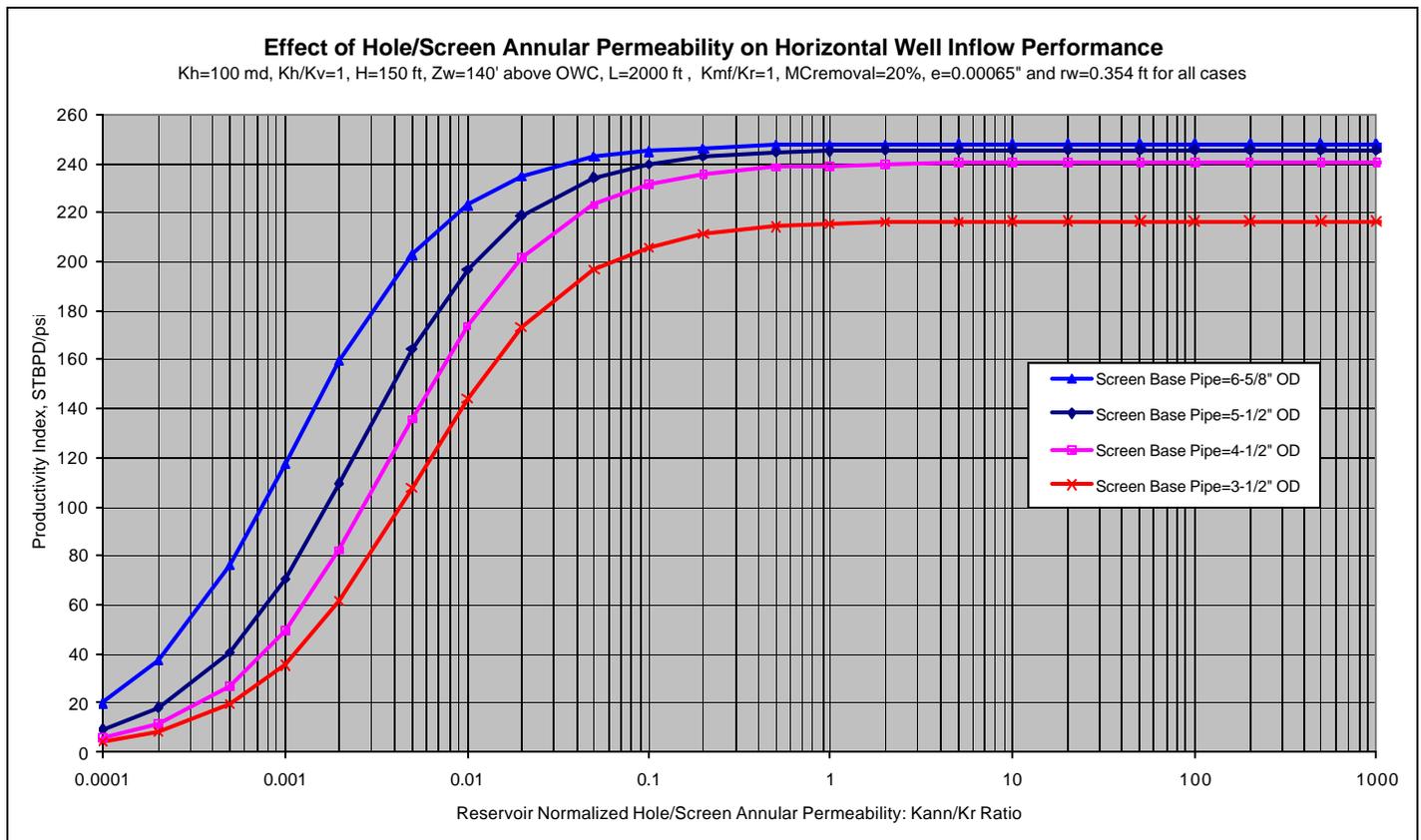


Figure 13

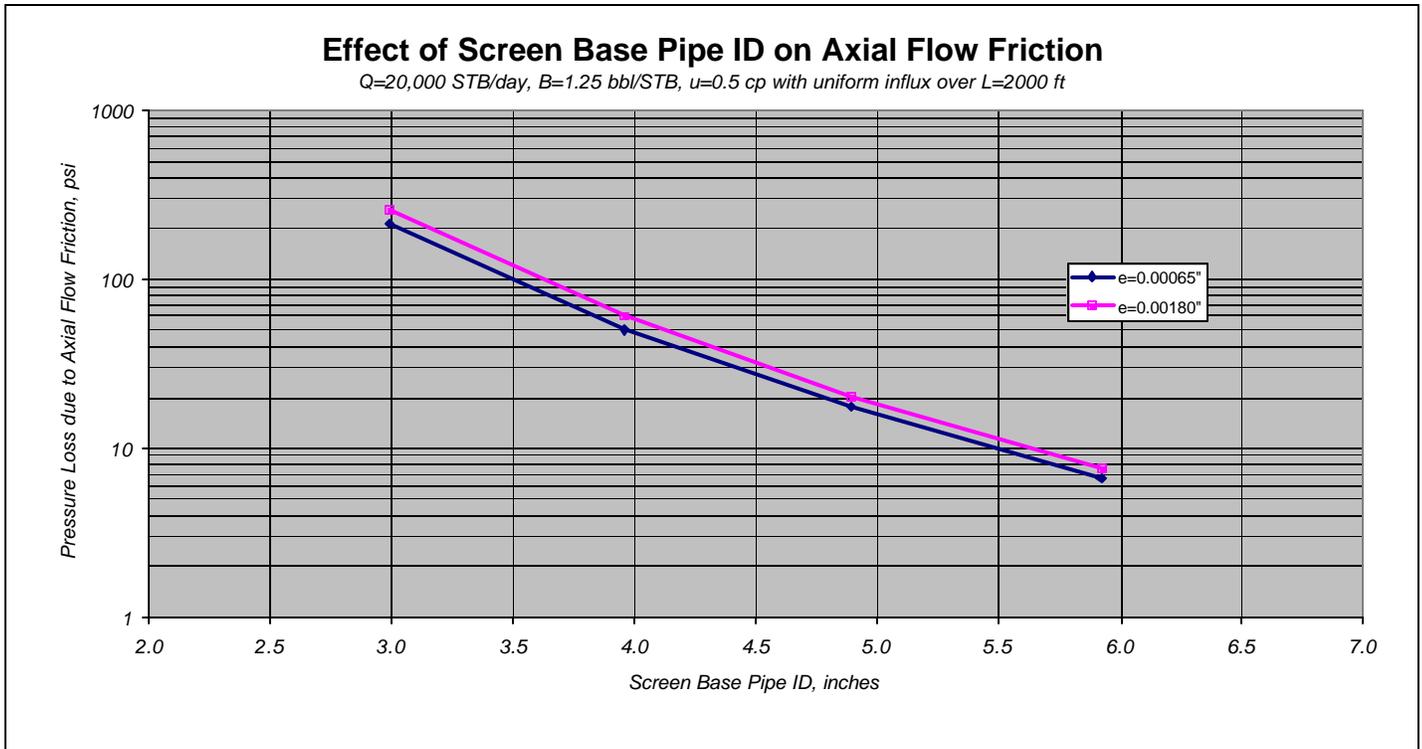


Figure 14

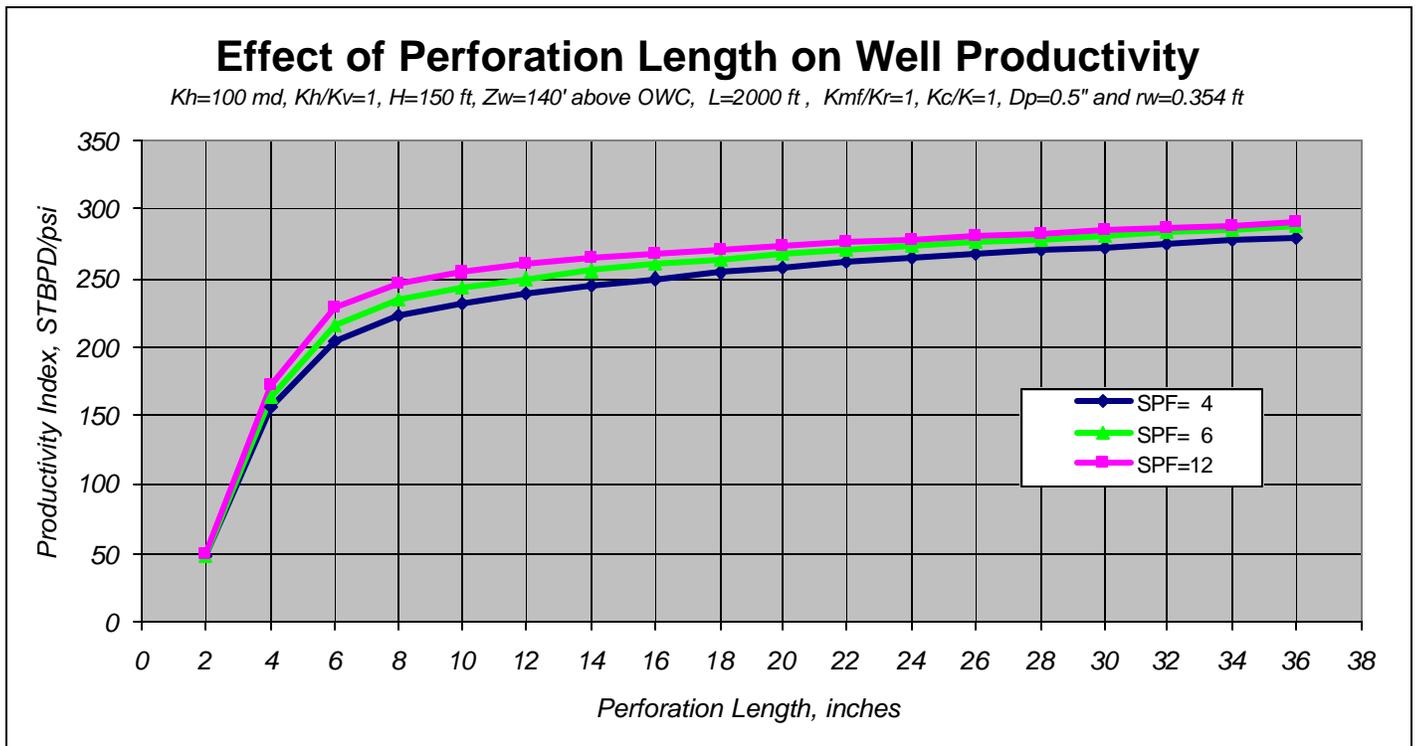


Figure 15

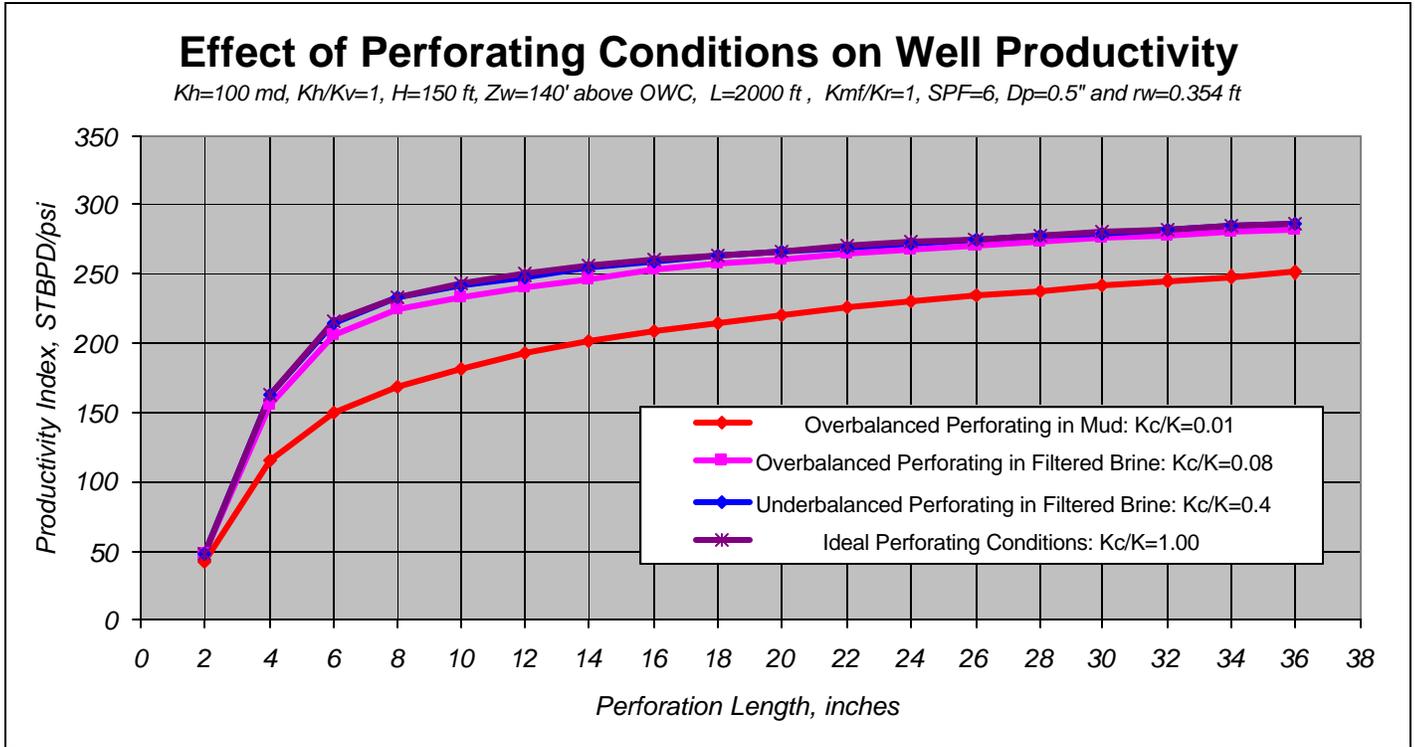


Figure 16

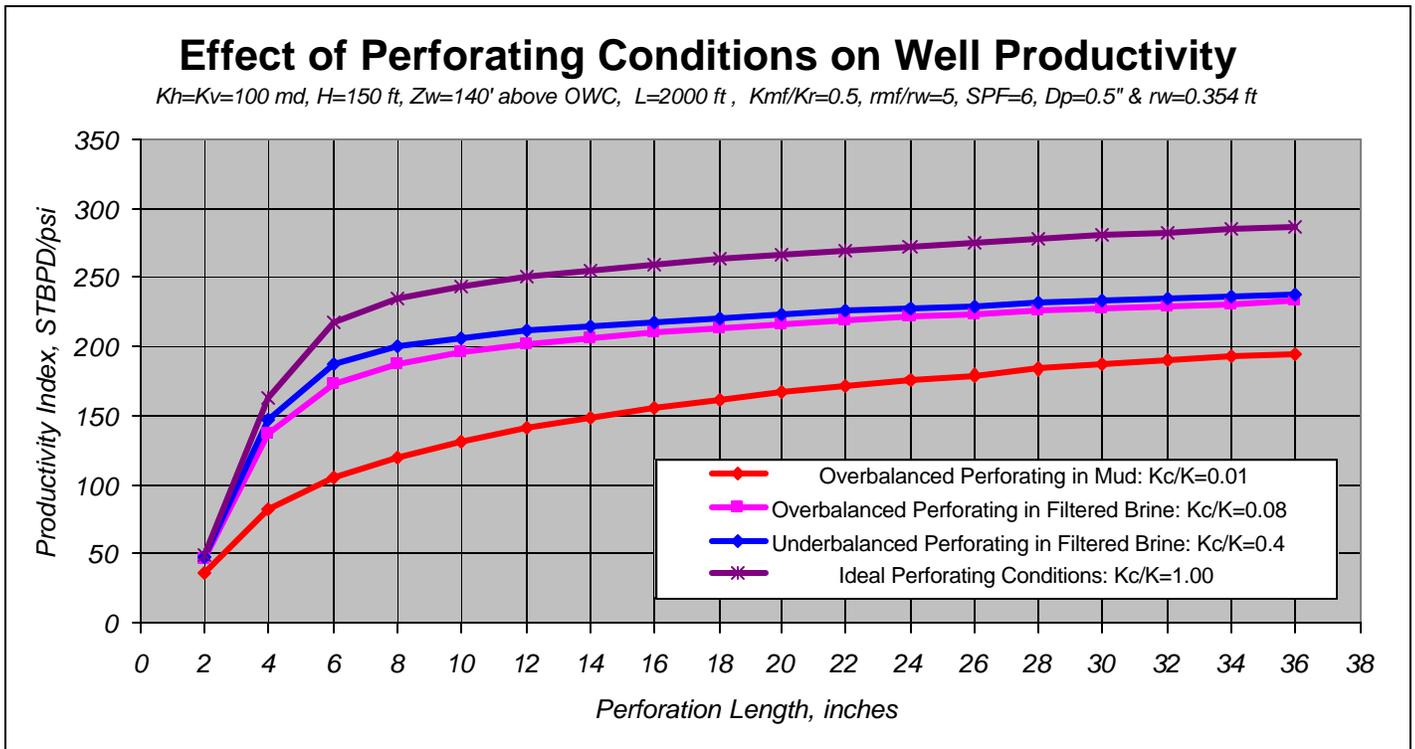


Figure 17

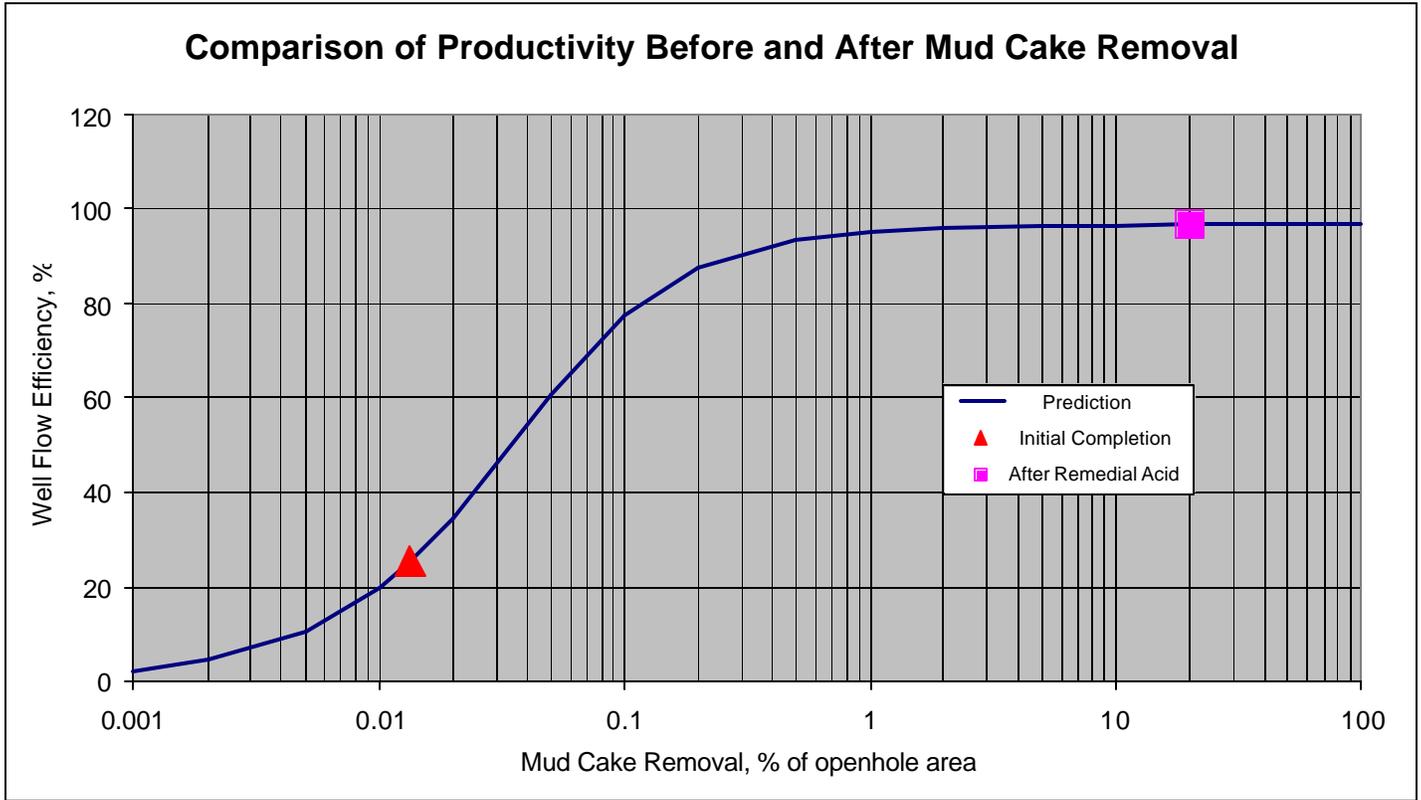


Figure 18

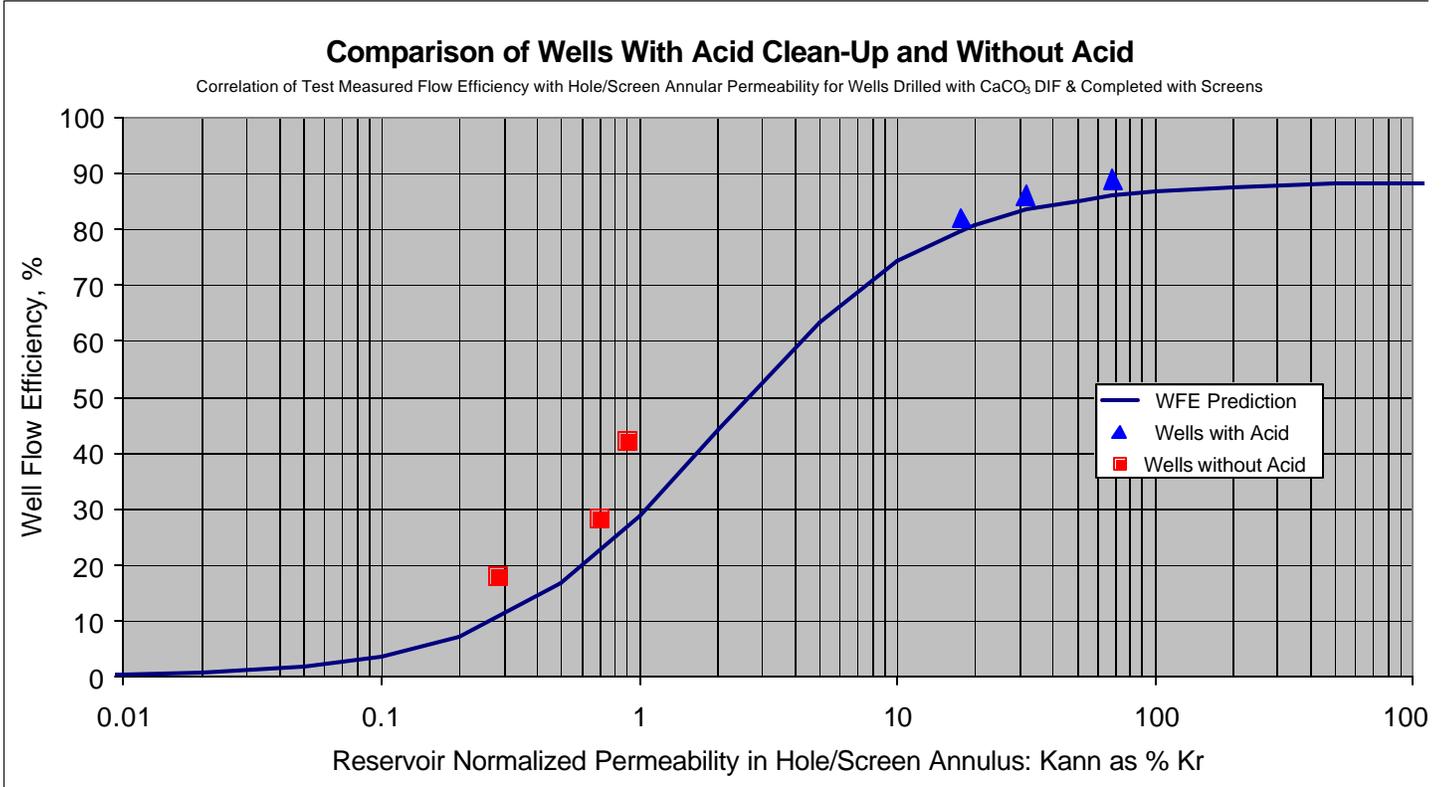


Figure 19

Effect of Perforating Conditions on Well Performance

Kc/K for Overbalanced Perforating=0.01-0.03 and Kc/K for Underbalanced Perforating=0.30 to 0.50

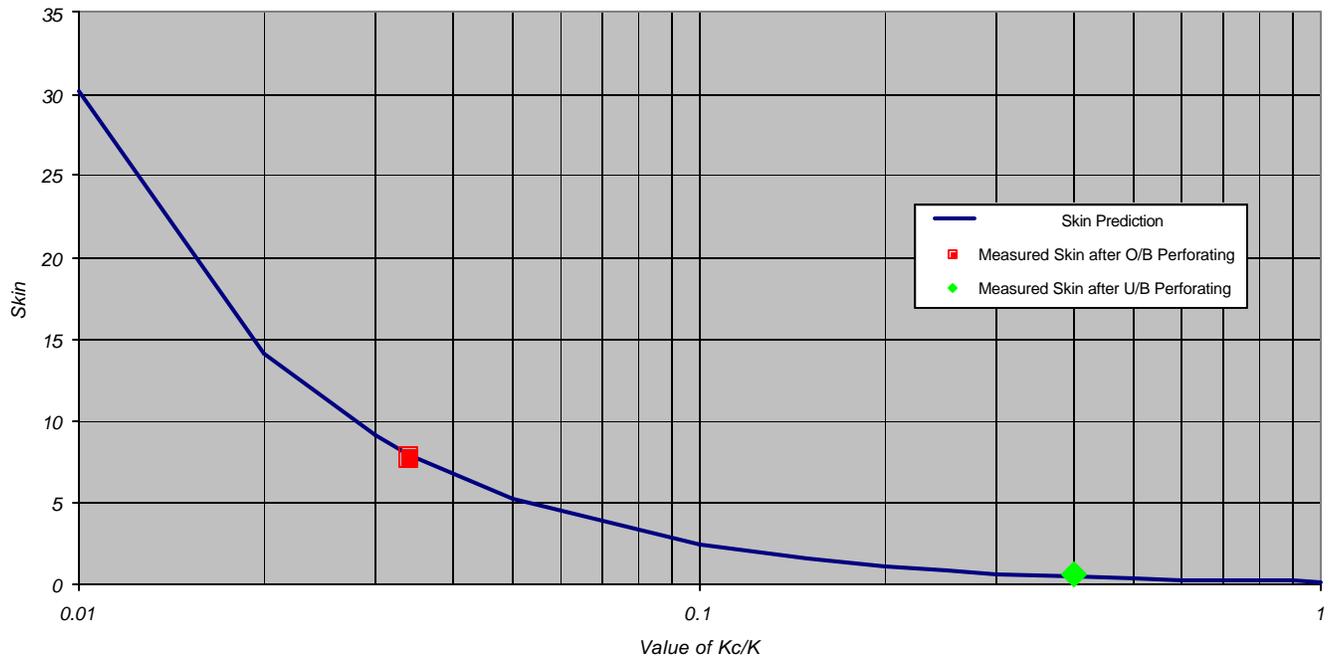


Figure 20