Optimization of Horizontal Well Completion (Position, Length and Perforation Scenarios)

by

Abdullah M. Al-Gahtani

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING

December, 1997

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

OPTIMIZATION OF HORIZONTAL WELL COMPLETION
(Position, Length and Perforation Scenarios)

BY

Abdallah M. Al-Gahtani

A Thesis Presented to the
FACULTY OF THE COLLEGE OF GRADUATE STUDIES
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
In

PETROLEUM ENGINEERING

December 1997

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

KING FAHAD UNIVERSITY OF PERTOLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA
COLLEGE OF GRADUATE STUDIES

This thesis, written by
MR. ABDALLAH MUUBARAK AL-GAHTANI
Under the direction of his thesis committee, and approved by all its members, has been presented to and accepted by the Dean of the Graduate School, in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in PETROLEUM ENGINEERING.

Thesis committee:

Habib Menouar
Dr. Habib Menouar
Thesis Advisor

A. A. Almajed
Dr. Abdul-Aziz Al-Majed
Member

A. Kaabi
Dr. Abdul-Aziz Al-Kaabi
Member

A. A. Almajed
Dr. Abdul-Aziz Al-Majed
Department Chairman

Dr. Abdallah Al-Shehri
Dean, College of Graduate Studies

DEDICATION

TO MY PARENTS AND WIFE

Whose blessing and praying have been greatly instrumental
in achieving this work.

ACKNOWLEDGMENTS

I wish to express my sincere appreciation and gratitude to my Thesis Chairman, Dr. Habib Menouar for his valuable guidance and assistance in this thesis. I am also very thankful to other members of my thesis committee, Dr. Abdul-Aziz Al-Majed and Dr. Abdul-Aziz Al-Kaabi for their suggestions. I would also extend my appreciation to KFUPM for offering the graduate study program.

I would like to thank Dr. Abdul-Aziz Al-Shuaibi from Math Department for his assistance in developing analytical solutions for horizontal well productivity and numerical modeling

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ملخص الرسالة

اسم الطالب : عبد الله مبارك عبد الهادي القحطاني
عنوان الرسالة : تحديد الاتمام الأمثل للآبار الأفقية
حقل التخصص : هندسة البترول
تاريخ الشهادة : ديسمبر ١٩٩٧م .

كما هو معلوم فإن الآبار الأفقية أكثر انتاجاً للزيت من الآبار العمودية وذلك لتعرضها لمساحة أكبر من طبقات الأرض الحامله للزيت. لذا ، من المفترض أن تكون الآبار الأفقية الأكثر طولاً أكثر انتاجيه من الآبار القصيرة منها. لكن ذلك لا ينطبق على الآبار المغطاه بإطار حديدي وأسمنت ومثقوبة جزئياً في أماكن مختارة. حينئذ تكون إنتاجية البئر معتمدة على طول وتوزيع الثقوب في ذلك الجزء من البئر وليس من المؤكد أن تزيد انتاجية البئر بنفس زيادة طول الأماكن المفتوحة في ذلك الجزء .

تدل الخبرة في حقول الزيت على أن الآبار الأفقية ممكن أن تكون محدودة الانتاج بسبب طول الجزء الأفقي منها نظراً للضغط المفقود بسبب احتكاك الزيت مع الاطار الأفقي للبئر. ذلك يكون جلياً في الآبار المحفوره في الطبقات الأكثر مساميه حيث من الممكن أن يكون الضغط المفقود داخل البئر مساوياً للضغط المطلوب لانتاج الزيت من داخل الطبقة .

هذا البحث يناقش تأثير طول الجزء الأفقي من البئر وكذلك طول وتوزيع الأماكن المفتوحة لطبقات الزيت في ذلك على انتاجية البئر . لهذا الغرض فقد تم تطوير برنامج باستخدام الحاسب الآلي مبني على الحلول التحليلية للآبار الأفقية لتحديد تأثير تلك العوامل على انتاجية الآبار الأفقية وقد تم اختبار هذا البرنامج بمقارنة نتائجه مع انتاجية الآبار الموجودة في الحقول .

بعد القيام بتشغيل البرنامج واعتبار المتغيرات التي تؤثر على انتاج الآبار الأفقية (مثل طول وتوزيع الأماكن المفتوحة في الجزء الأفقي من البئر ، انتاجية البئر ولزوجة الزيت المنتج) ، فقد تم القيام بتطوير علاقة لتحديد انتاجية الآبار الأفقية المفتوحة جزئياً في أماكن مختارة . كما تم تطوير علاقه أخرى لتحديد الطول الأمثل للجزء الأفقي من البئر .

درجة الماجستير في العلوم
جامعة الملك فهد للبترول والمعادن
الظهران ، المملكة العربية السعودية
ديسمبر ١٩٩٧م

THESIS ABSTRACT

NAME: ABDALLH M. AL-GAHTANI

TITLE: OPTIMIZATION OF HORIZONTAL WELL COMPLETION

DEPARTMENT: PETROLEUM ENGINEERING

Due to the large exposure to the reservoir, horizontal wells may be several times more productive than vertical wells. Hence, longer horizontal wells are expected to be more productive than shorter wells. This assumption is valid for openhole completions, however, it may not be always the case for cased, cemented, and partially perforated wells where the productivity of the well becomes a function of length and distribution of perforated intervals. The productivity of a horizontal well may not increase with increasing well length and perforation percentage of the horizontal section. Field experience with horizontal wells has shown that the productivity of a horizontal well may be restricted by frictional losses obtained in longer horizontal sections espicially for wells drilled in high permeability reservoirs where frictional losses in the horizontal section may be comparable to the pressure drawdown across perforations.

In this work the effect of horizontal well length as well as the length and distribution of perforated intervals on horizontal well performance are studied. A computer program based on analytical solution of the flow performance of partially perforated horizontal wells has been developed and tested against field data. An extensive number of computer runs to study the influence of the main parameters affecting the performance of horizontal wells have been conducted. Those parameters were the length, the perforated length fraction, the reservoir permeability and the fluid viscosity. A correlation has been developed to describe the performance of partially perforated horizontal wells by comparison to openhole wells. Another correlation to estimate the optimum horizontal well length, beyond which the contribution of horizontal wellbore to the production rate is negligible, is also presented.

MASTER OF SCIENCE DEGREE
KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
Dhahran, Saudi Arabia
December 1997

hapter 1

INTRODUCTION

In the last decade, drilling of horizontal wells has gained wide acceptance as a viable option to maximize the return on investment due to the enhanced productivity horizontal wells offer. As the technology matures, horizontal wells have become an established way of oil and gas recovery. Horizontal wells made it possible to develop previously uncommercial reservoirs. The success of horizontal wells is attributed to their high productivity, as compared to conventional wells, and to their numerous applications in oil fields.

The principal application of horizontal wells is to increase the well productivity via increased contact with the reservoir rock. Increasing the area of contact with the reservoir will result in augmenting the productivity index of the well. Typically, horizontal wells offer productivity indices four times higher than vertical wells penetrating the same reservoir. That relative productivity increase is more pronounced in thin reservoirs. Increasing the area of contact with the reservoir will also result in increasing the area of the fluid influx flow toward the wellbore and that will decrease the fluid influx velocity, which help mitigate the water/gas coning. Another application of horizontal wells has been to place the borehole in a direction that intersects several of the existing natural vertical fractures or isolated productive zones, which might otherwise be bypassed. Horizontal wells are most productive in cases where the ratio of vertical to horizontal permeability is high. Horizontal wells may have different applications depending on the type and shape of reservoir or in situations where vertical well drilling is not feasible.

To date, the majority of horizontal wells have been completed as open holes. If the drain hole must be cased, slotted liners, preperforated liners or prepacked screens may be used. More recently, as the technology of horizontal wells has matured, there has been a clear industry trend toward cemented completion or selective completion using External Casing Packers (ECP).

From the reservoir viewpoint, horizontal wells proved successful. However, recent experience with horizontal wells has revealed that the wellbore pressure drop, due to frictional losses in their long horizontal sections restricts the high productivity of these wells.

This study has been undertaken to provide insight about some of the parameters that control the productivity of horizontal wells namely: well length and diameter, perforation length and distribution and reservoir permeability and dimensions.

Chapter 2

LITERATURE REVIEW

A considerable amount of work has been published on various aspects of horizontal wells, including transient flow models, stabilized flow models productivity indices, and coning and cresting behavior. Although these models have provided insight into the behavior of horizontal wells, they have generally been based on the assumption of well being a line sink with a uniform flux boundary condition at the well and an infinite conductivity. Hence, any impact of fluid flowing within the wellbore on the well's inflow performance was neglected. This aspect of well modeling has not received much attention in the literature, particularly the effect of well completion on its performance.

Several authors have presented formulae for determining the productivity index of horizontal wells, Jh, in a variety of geometries. All methods, however, assume that only a single section of the well is open to production.

Despite the belief that horizontal wells are appropriate only in tight reservoirs, a survey of the literature review shows that horizontal well applications concern as well with high permeability reservoirs. The problem of optimizing the production of horizontal wells has two facts: the first one is related to the productivity index of the formation and the second one is related to the multiphase flow in the horizontal well. Both topics have received some attention in the literature. Several papers have been published on pressure transient behavior and productivity of horizontal wells. Giger *et al.*[1] reported the productivity of horizontal wells by using the steady-state equations for flow into horizontal wells presented by Borisov[2]. Goode and Thambynayagam[3] presented an excellent paper on pressure drawdown and buildup analysis of horizontal wells in anisotropic media. Their well, finite in length, is perpendicular to the linear barriers that are no-flow boundaries, and these boundaries are parallel to the y-axis. The well lies on the x-axis and the y-axis is infinite. They presented an analytical expression in closed form for the pressure drop for both the drawdown and buildup. One shortcoming of this model is that if the well lies parallel to the linear barriers, the result given must be modified. Most work dealing with horizontal-well problem uses the instantaneous Green's function technique developed by Gengarten and Ramey[4] to solve 3D isotropic diffusivity equation. Daviau *et al.*[5] analyzed horizontal wells of uniform flux and/or infinite conductivity in the wellbore, with wellbore storage and skin. Kuchuk *et al.*[6,7] Dealt with horizontal wells with and without a gas cap on top or an aquifer at the bottom in the infinite x and y directions. They also discussed the inflow performance in terms of pressure difference between reservoir and wellbore for a horizontal well producing from a closed rectangular region. They used finite Fourier transforms to solve the anisotropic problem for the line-source case. A solution published by Joshi[8] deals with flow in vertical planes perpendicular to the well axis at early time, and in horizontal planes at late time. The three-dimensional problem is broken into a series of two-dimensional problems. The solution is sought by means of potential theory in fluid mechanics. Babu and Odeh[9], using Green's function and Newman's product method applied the intersection of the three infinite source planes in a bounded reservoir. This results in an instantaneous source point. A uniform flux solution and no-flow boundaries were assumed. Goode *et al*[10] presented a general solution for the pseoudosteady state pressure drop of a horizontal well producing from a rectangular region of uniform thickness. Their solution is also applicable for a well bounded above and below by no-flow barriers and for cases of constant pressure boundary as in gas cap reservoirs. Probably one of the most important paper directly related to this topic has been presented by Goode *et al*[11]. In this paper a theoretical solution of the inflow performance in the case of partially perforated horizontal wells is presented. This solution is derived in two steps. First, the horizontal well is simulated by a set of vertical fractures corresponding to the perforated intervals. These fractures are assumed to penetrate the whole vertical cross section of the reservoir. Second a skin factor compensating for the horizontal well penetration in the vertical direction is used to complete the procedure. This method is a result of an elegant mathematical procedure using successive integral transforms (Laplace and Fourier).

This solution is presented in the form of a normalized productivity index by reference to the open-hole solution. This study shows that the more the perforated intervals are spread over the horizontal section, the higher the productivity index. Also the effect of length of the perforated intervals on the normalized productivity index for different reservoir thickness is presented. In general, the well flowing pressure is taken as the average pressure existing in the middle of the horizontal section of the well and no pressure drop is assumed between the toe and the heel of the well.

Several authors conducted analytical or experimental studies to investigate different aspects of flow behavior in horizontal wells. Dikken[12] examined the effect of pressure drop in the horizontal well on the overall performance of the well. He presented an analytical solution that links a single-phase turbulent liquid flow in a horizontal wellbore to an isothermal reservoir flow, and predicts the frictional pressure gradient along the wellbore. Constant productivity index per unit bore length and constant well and reservoir characteristics were assumed. The author examined the effects of a non-negligible pressure drop in the horizontal well on the overall performance of the well. This effect is most likely to be significant in the case of large flow rates where turbulent flow regimes may prevail. The results showed that the augmentation of production rate with increasing wellbore length levels off quickly after the well length reaches a certain critical value. He concluded that the reduced drawdown caused by the turbulent flow along the wellbore may result in the total production rate reaching a certain critical value as a function of wellbore length. This means an optimal length exists for which little additional production results from extending the horizontal well.

Brice[13] tested the frictional pressure drop in horizontal wellbores. He concluded that reservoir simulators do not predict the pressure drop in the wellbore if they are not corrected for diameter due to perforation in the production liner to represent actual flow conditions.

Islam and Chakma[14] presented a physical model based on experimental results that describe multi-phase flow in a horizontal wellbore. They observed that multiphase flow in horizontal wells should be treated differently from multiphase flow in normal horizontal pipelines. They suggested a numerical method to analyze fluid flow in a horizontal well. Their work confirmed the previous results presented by Dikken[12] and shows that friction losses in horizontal wells cannot be ignored. The presence of perforations along the horizontal section complicates furthermore any modeling of the flow in horizontal wells. This paper proves the need for a rigorous treatment of the flow in horizontal wells even in the case of low viscosity oil. However, the interaction between the flow behavior in the wellbore and the reservoir was not taken into account.

Suzuki *et al*[15] has also examined the effect of perforations on multiphase flow in horizontal wells. In their paper, the authors simulated the effect of such perforations in the laboratory. They used a flow test unit designed specifically for this purpose. They also proposed a theoretical model to describe two phase flow in perforated horizontal wells. These authors claim that both experimental and theoretical results were in agreement and it was important not only to take into account the effect of perforations in evaluating multiphase flow in horizontal wells but also to consider the reservoir interaction with the horizontal well behavior.

Ozkan *et al.*[16] presented a semi-analytical model coupling wellbore and reservoir single-phase liquid flow, and incorporating the effect of laminar and turbulent flow patterns in the wellbore. In another paper Novy[17] examined the effect of friction forces on horizontal well rates. He presented charts of oil rates versus length to show when frictional losses can be considered significant. A region in these charts is safe when oil rate losses due to frictional forces do not exceed 10%. This paper is in fact a generalization of Dikken's paper[12]. It is based on a simplified productivity index equation describing the flow from the formation to the horizontal well coupled with a Poiseuille type theoretical relation between the pressure drop and the flow rate. This study concerns both oil and gas wells. Cases where friction can be assumed negligible are identified using field data published in the literature. The author shows that even for 4" diameter horizontal wells, pressure losses can be considered negligible for most gas wells. This is not the case for some oil wells, where even for an 8" diameter tubing, the pressure drop could be significant. Other conclusions are as follows: The pressure drop in the horizontal section of the well over the drawdown pressure should not exceed 10 to 15% to avoid flow rate loss.

Ihara *et al.*[18] have conducted experimental and theoretical investigations on the subject using large-scale test facility. These test facilities closely simulate the interaction between a horizontal well and a reservoir, and enable to acquire data on pressure drop and liquid hold-up. Although good agreement was found between the data and the physical model proposed by them, the model showed a discrepancy from the data at downstream where fluid velocity was relatively high. The model was combined with a single-phase inflow performance relationship to study horizontal well productivity.

Landman and Goldthorpe[19] presented a mathematical model that couples pressure-flow rate relationship for each of a specified number of perforations with a wellbore pressure drop model that treats the perforated well as a pipe manifold containing T-junctions. However, the flow was assumed to be single phase and turbulent within the wellbore.

Seines *et. al*[20] analyzed the importance of friction pressure losses within the completed section of the horizontal well under some reservoir conditions in planning horizontal wells in the Troll field . They studied the phenomena with subsequent three-phase reservoir simulator. However, they did not address the effect of perforations distribution along the completed section.

Ihara *et al.*[21] conducted an experimental and theoretical investigation on the effect of frictional pressure drop on the performance of a horizontal well. They used both small-scale and large-scale test facilities. They proposed a model that uses the IPR approach and mechanistic model for wellbore hydraulics.

To mitigate the frictional effects, Brekke *et al*[22] developed an innovative approach of placing a string at the heel of the well. The purpose of the string is to distribute the fluid flow, thereby minimizing the pressure losses. The performance of the stringer was examined using a horizontal well simulator. A field test on the North Sea wells verified the simulation results and succeeded in reducing the frictional losses. They also found that the optimal stringer length to be 28% of the horizontal wellbore length regardless of the drawdown and well length.

Asheim *et al.*[23] proposed a frictional factor correlation for wellbore pressure drop calculations, which include acceleration pressure losses due to continuous fluid influx along the wellbore. Yuan *et al.*[24] investigated the flow behavior in a horizontal pipe with fluid injection from a single injection point in the pipe wall and from multiple injection points with different perforation densities. They developed a new correlation for predicting frictional losses in horizontal wellbores.

The mechanistic model, however, may not necessarily mimic the actual flow in horizontal wellbores because it assumes constant flow rate through each perforation and does not account for the interaction of the wellbore and the reservoir. In addition, the types of fluid and flow regime in fluid flow were not considered. The fluid flow studies have shown that the frictional effects are exacerbated during two-phase flow. Furthermore, the models that were used were laboratory-scale test models much smaller than in real life. In addition, the validity of those models was not checked using actual field data. In all these studies, however, the emphasis was on evaluating the frictional losses per say, but not the impact this may have on the loss of productivity due to horizontal pressure drop. Clearly, effort had to be made on simulating the whole horizontal well, distribution of perforation, and reservoir systems as realistically as possible. Not considered by the foregoing studies are the influence of well completion scenario on the inflow performance as well as the well bore hydraulics, and the interaction of these two parameters considering two-phase flow with different flow regimes. Moreover, no guidelines have been publisheed for completion optimization of horizontal wells from the production-engineering viewpoint.

Chapter 3

RESERVOIR ENGINEERING ASPECTS OF HORIZONTAL WELLS

One of the distinguishing features of horizontal wells as compared to conventional ones is the relatively long well length that penetrates the reservoir and allows more exposure to the reservoir, as well as selective production. For a given reservoir thickness, the productivity index of a horizontal well, J_h, is a direct function of the horizontal section length. However the incremental gain in reservoir contact area in a thin reservoir is much more than in a thick reservoir. As a result the increase of the productivity index of a horizontal well is more pronounced in thin reservoirs than in thick reservoirs compared to a vertical well penetrating the same reservoir as presented by Joshi[8]. This makes horizontal wells more appropriate for thin reservoirs. Reservoir anisotropy, which is characterized by the horizontal to vertical permeability variations K_h/K_v, may have similar effect as the increase of reservoir thickness. Reducing the K_h/K_v value will have the same effect on the incremental gain in a horizontal well as increasing the reservoir thickness by the same ratio. The productivity ratio increase J_h/J_v is shown in fig.'s 1& 2.

In a horizontal well that is cased and selectively perforated, the productivity index calculations are different. The fluid flow convergence toward these open intervals is taken into account. An analytic formulae which can be used to determine the inflow performance in a horizontal well with several open intervals placed arbitrarily along the drilled length of the well was recently presented by Goode & wilkinson[11].

Those solutions suggest that the productivity index of a partially completed horizontal well will increase with increasing perforation length. However, that increase is not linear and may level out after a certain length of perforation depending on the reservoir thickness and characteristics. Moreover, it was shown that for thick and high permeability reservoir, having 60% of the horizontal section length perforated will result in obtaining 90% of the productivity index of an openhole horizontal well penetrating the same formation. Results of these solutions are shown in fig 3.

The effect of near-wellbore damage can be incorporated into the calculations of the productivity index of a horizontal well. The solutions apply to a horizontal well under steady-state flow conditions assuming an elliptical drainage area. For that reason, the equivalent skin has to be multiplied by the scaled aspect ratio (I_{ani} h/L). Comparing the steady-state solutions for vertical and horizontal well, the effect of near-wellbore damage is more detrimental because it is multiplied by the scaled aspect ratio. The skin effect may easily have a value as high as 10 to 20. The effect of near-wellbore damage on horizontal wells is depicted in fig. 4. As shown on the graph, the slope of the horizontal well productivity index decline is steeper, indicating the relatively larger detrimental impact of skin. Another conclusion we can draw from this graph is that fully stimulated vertical well may outperform damaged horizontal well at reasonable skin effect value.

Chapter 4

STATEMENT OF PROBLEM

Due to the large exposure to the reservoir, a horizontal well may be several times more productive than a vertical well drilled in the same formation. Hence, longer horizontal wells are expected to be more productive than shorter wells. However, that may not be always the case and a major uncertainty is how the productivity of a horizontal well would increase with increasing well length and perforation percentage of the horizontal section. Field experience with horizontal wells have shown that the productivity of a horizontal well may be severely restricted by frictional losses obtained in longer horizontal sections. Wells suffering from this are those drilled in high permeability reservoir where frictional losses in the horizontal section may be comparable to the pressure drawdown across perforations. From the reservoir-engineering standpoint, horizontal wellbore is treated as an infinite conductivity fracture; i.e. the pressure drop along the well length is negligible. Although this may be a good assumption in situations where the pressure drop along the horizontal section is small compared to that in the reservoir, in practice, a pressure drop from the upstream end is essential to maintain fluid flow within the horizontal section.

Unlike conventional wells, the open intervals to flow in horizontal wellbores are relatively extensive. However, If the well is selectively completed, the productive length of the well may no longer be the drilled length. The productivity of the well will be affected by the total length of the open intervals to flow and their distributions along the horizontal section. Moreover, the horizontal well productivity is drastically reduced with the near-wellbore damage causing additional pressure drop in the formation, as explained earlier. Hence, having additional pressure drop in the wellbore will aggravate the problem. A major uncertainty is whether the production of the well will increase with increasing the horizontal section of the well. Economics aside, these facts imply that longer horizontal wells are more productive and horizontal wells should be drilled as long as possible. However, increasing the well length will increase the frictional losses in the horizontal wellbore, which in turn will increase the backpressure at the reservoir rendering some portion of that wellbore unproductive.

As the technology matures, the issue of the effect of frictional losses on the performance of horizontal wells becomes more conceived. As more wells are being drilled and more experience with horizontal wells is gained, the fact of the frictional losses having the potential of seriously impairing the productivity of horizontal wells has been established. Nowadays, it is a common practice to consider wellbore hydraulics in planning development of oil field utilizing horizontal drilling.

Fluid flow in horizontal completion systems are controlled by two opposing forces, namely the driving force which is the pressure drawdown in the reservoir, that is the difference between the reservoir pressure and wellbore pressure, and the resistance force which is the frictional pressure losses from the point of inflow to the heal end of the well. As a result, the wellbore pressure is increasing toward the upstream of the wellbore and that will reduce the pressure drawdown on the sand face causing a reduction in the fluid influx into the wellbore. The wellbore pressure profile is depicted in fig. 5 &6.

Hence, an equilibrium between the driving force and the resistance force has to be reached in order to maintain fluid flow in that section. If the flowing pressure gradient within the wellbore is comparable to the drawdown, no flow can occur beyond a particular distance from the start of the horizontal section (the heel end). Friction can thus reduce productivity. Systems likely to suffer from this effect include those with low drawdown in high permeability formations, and long horizontal section wells with small diameters.

Modeling of fluid flow in horizontal wells has not been given much attention in literature. Moreover, no study has been reported that couples the inflow performance of partially completed horizontal wells with fluid flow in the wellbore. Both the flow behavior in a horizontal wellbore, and its interaction with the reservoir, have been recognized as one of the unsolved, yet most important problem in production engineering. Neither the pressure drop-flow rate behavior in horizontal section nor the interaction with the reservoir has yet been clarified.

In this research, the effect of well length, length and selection of perforated intervals on the performance of horizontal wells are examined. The approach is to combine the inflow performance of the reservoir to the outflow performance of the horizontal section of the well to obtain the overall performance of the horizontal well. This research will quantify the influence of the inter-related production parameters of horizontal wells: the driving force (the inflow performance) and wellbore hydraulics (the outflow performance). A semi-analytical approach is used to carry out this work. The inflow performance will be determined using analytical equations whereas the outflow performance will be calculated using pressure drop empirical correlations. This is accomplished using a computer program that couples the theoretical solution of the productivity index, presented by Goode[11], to an empirical multiphase model of the flow in the horizontal section of the well. From the results, two correlations were developed that can relate the performance of a partially completed well to the performance of the open-hole completion, and to calculate the optimum well length for different reservoir characteristics and well configuration.

Chapter 5

FLOW MODELING IN HORIZONTAL WELLBORES

Although a large body of literature was devoted to predicting the behavior of both single phase and multiple phase flow in horizontal wellbores, flow modeling in horizontal wellbores is still a subject of research due to the complexity of flow, effect of fluid influx & variation, effect of length & distribution of perforated intervals, and the interaction of wellbore to reservoir which makes it different from flow in pipelines and vertical wells.

Many authors have studied modeling of fluid flow in horizontal wells. Until recently, the effect of frictional losses on the performance of horizontal wells has not been given much attention.

5.1 INFLOW PERFORMANCE

Analytical solutions suggest that the inflow performance of a horizontal well is proportional to the length of the horizontal wellbore. However, for a well that is cased, cemented, and selectively perforated that may not apply. The drilled section length may not be the only parameter characterizing the well productivity. The inflow performance depends also on the length and distribution of the perforated intervals along the horizontal wellbore.

Goode, et al[11], has presented one important paper directly related to this topic. In this paper a theoretical solution of the inflow pressure in the case of partially perforated horizontal wells is presented. This solution is derived in two steps. First, the horizontal well is simulated by a set of vertical fractures corresponding to the perforated intervals. These fractures are assumed to penetrate the whole vertical cross section of the reservoir. Second a skin factor compensating for the horizontal well penetration in the vertical direction is used to complete the procedure. This method uses a mathematical procedure based on successive integral transforms (Laplace and Fourier).

This solution is presented in the form of a normalized productivity index by reference to the open-hole solution. This study shows that the more the perforated intervals are spread over the horizontal section, the higher the productivity index. Also the effect of length of the perforated intervals on the normalized productivity index for different reservoir thickness is presented. In general, the well flowing pressure is taken as the average pressure existing in the middle of the horizontal section of the well and no pressure drop is assumed between the toe and the heel of the well.

The analytical solutions of the performance of partially perforated horizontal wells suggest that a considerable amount of productivity is lost because of partial perforation. However, it is possible in some cases for a partially perforated horizontal well to attain 90% of the inflow performance of the openhole potential.

The analytical solutions of the performance of partially perforated horizontal wells are shown in appendix.

5.2 OUTFLOW PERFORMANCE

Horizontal wells are assumed to perform like an infinite conductivity fracture of the same length and height, which assumes no pressure drop along the wellbore and hence constant fluid influx from reservoir, is obtained. This may be a valid assumption in openhole wells with large diameters and short lengths where all the horizontal wellbore section is exposed to flow. The constant pressure along the horizontal wellbore can be a reasonable assumption when the horizontal wellbore pressure drop is very small as compared to reservoir pressure drawdwon. In contrast, if the pressure drop along the horizontal wellbore is significant as compared to the pressure drawdown, the pressure drop can not be ignored. This is especially true in the case of highly productive reservoirs with limited pressure drawdown, small wellbore diameter, and horizontal wells produced at high GOR and/or high water cut.

The effect of frictional losses is more pronounced in horizontal welbores that are cased, cemented, and selectively perforated where the fluid may enter the wellbore at various locations along the horizontal well length. The distance between perforations may not be sufficient to achieve a stabilized velocity profile. In other words, the length and distribution of the perforated intervals along the horizontal wellbore affect the wellbore hydraulics. However, in long horizontal wells with large diameters, the disturbance of flow by fluid influx from perforations may not be significant. This makes the use of conventional pipeflow pressure correlations for calculating the frictional losses along the horizontal wellbore legitimate.

Experience with horizontal wells revealed that frictional losses in horizontal wellbores may not be significant. However, they do affect the performance of the well. The frictional losses in horizontal welbores are wellbore-related phenomena and function of flow rates in a manner analogous to the non-Darcy skin factor in gas wells. Wells that are likely to suffer from that effect are those with long horizontal wellbores and small diameter wells with high viscous fluid and high flow rate. Field data showed that horizontal wells completed with 2000' of 7" liner and producing as much as 20 MSTBD may have frictional losses of 3 to 5 psig at the most. Field example is shown in fig. 7.

The horizontal wellbore is considered like a pipe manifold with N-junctions distributed along the wellbore as depicted in fig. 8. The pressure drop in each segment due to friction, change in kinetic energy, and change due to well inclination is calculated using pressure drop empirical correlations[25]

5.3 OVERALL PERFORMANCE

Depending on the backpressure at the heel of the horizontal wellbore, an interaction between the inflow and outflow will take place that would determine the overall performance of the well. The length and distribution of the perforated intervals along the horizontal wellbore influence that interaction.

As mentioned earlier, the frictional losses in horizontal wellbores may not be significant. However, the issue here is not the magnitude of the frictional losses in horizontal wellbores but the effect of length & distribution of perforated intervals on inflow/outflow performance of the horizontal well and its effect on the overall performance of the well.

A computer model has been developed to handle the calculations involved. This program consists of two parts: The first part concerns the estimation of the productivity index based on the perforations distribution and the reservoir and fluid characteristics. The second part relates to the iterative process for computing both the fluid flow rate and pressure distribution along the horizontal section of the well.

The productivity index solution as a function of distribution and length of perforated intervals as suggested by Goode[11] is used to describe the reservoir flow performance. This solution is valid for an open-hole horizontal well. The primary advantages of this type of solution are that it describes in detail the fluid flux from the reservoir to the horizontal section of the well. The method consists of dividing the horizontal section of the well using a finite difference approach. The flux in each grid of the horizontal section is guessed and a pressure drop is estimated at each block. The calculations are repeated using an iterative process until a fairly accurate fluid production and pressure distribution evaluation is reached. The flow chart for that program is presented in fig. 9 .

A certain number of utility programs are used in order to complete these computations such as the definition of flow regimes, estimation of viscosity, gas gravity, compressibility and so forth. In this regard, the main program presents some flexibility in the sense that it can incorporate future developments for handling the different process variables in the system. The inflow and outflow performances are coupled. Starting with an initial pressure at the upstream of the well, the flow rate from the first set is calculated using the inflow performance. Proceeding to the next segments, the pressure and rate are updated along the horizontal section. Non-uniform fluid influx is expected due to pressure gradient along the horizontal section.

Understanding the fluid flow behavior in horizontal wellbores is crucial to designing the optimal well characteristics of length and diameter.

In order to check the validity of the method, the computer program has been run to simulate four actual cases of horizontal wells. Data relevant to these four cases is presented in table 1. The flow rate distribution along the horizontal section of the well as computed by the program has been checked against the flowmeter measurements in each case and plotted in figures 10 through 17. As shown in these figures, the simulation of the flow rate is fairly accurate.

The results of wellbore modeling are compared to field data and the pressure-rate relation in each perforated segment, obtained from the model, is compared to the actual data.

Chapter 6

PARAMETRIC STUDY

The results obtained showed that the performance of a cased, and perforated horizontal well can be affected by the perforated length fraction, total length, tubing diameter and reservoir permeability on the horizontal well performance are studied in this section. Results were presented in Ref. 26.

6.1 Effect of perforated intervals position

Considering a 2000 ft horizontal well in a 4 darcy permeability reservoir, five computer runs have been performed to study the effect of the position of the perforated sections on the rate. In the first run, it is assumed that a portion of 20% of the well length is perforated at the toe of the horizontal well. In the second run, it is assumed that the next 20% have been perforated and so on. In the last run the 20% section located at the heel of the horizontal well is perforated. The reservoir characteristics used for all these runs are similar to case 1. The results, which are, presented in figure 18 show that the position of the perforated section has a significant effect on the production rate. Depending on the case where the horizontal well is perforated near the toe or near the heel the rate can be multiplied by a factor of more than two. For instance at a flowing pressure of 2900 psig, the rate can reach 25000 STBPD when the well is perforated at the heel instead of 12000 STBPD for the same well perforated at the toe. At a flowing pressure of 2800 psig, the production rate gain can be even higher, 150% approximately.

6.2 Effect of perforated intervals percentage

In another set of experiments, the perforated length fraction has been varied from 20 to 80%. Figures 19 to 22 show such experiments for a 1000-ft horizontal well and different tubing diameters. Two observations can be made. First, for a small tubing diameter, 0.3 ft, the production rate gain resulting from increasing the perforated section from 20% to 80% does not exceed 20 to 25% while this increment reaches 75% in the case of a 0.6 ft tubing. The second observation is that for small tubing diameters, the rate increment resulting from increasing the perforated section beyond 40% is not significant.

Similar experiments have been conducted for 2000 and 3000 ft horizontal wells. The results, which are presented in figures 23 to 26 and figures 27 to 30 successively, show a similar trend. A close examination of figures 23 and 26 which describe for instance the behavior of a 2000 ft well, show that for small diameter tubing's, longer perforated sections do not lead necessarily to higher production rates and may even result in poor well performances for lower flowing pressures. This shows the increasing role of friction forces and illustrates the fact that high friction losses can go against an efficient production of the well. The comparison of figures 27 to 30 related to a 3000-ft horizontal well confirms this fact for small diameter tubing. It also confirms the same observation made previously, which is; the rate increment is not significant beyond 40% perforated length.

6.3 Effect of Well Length

Some of the results generated in the previous sections are presented in Figures 31 to 34 to illustrate the effect of the total well length on the production rate. These figures show clearly that for a small tubing diameter, 0.3 ft, the friction forces are so important that a 1000-ft horizontal well can lead to better performance than a 3000 ft well. For a 0.6-ft tubing diameter, figure 34 shows that the production rate increment is negligible for horizontal well length larger than 2000 ft.

6.4 Effect of Reservoir Permeability

In another series of experiments, the effect of reservoir permeability is examined. Since the higher the reservoir permeability, the higher the ratio $\Delta P_{friction} / \Delta P_{formation}$, the question is what is the sensitivity of the well performance to the combination of reservoir permeability and tubing diameter.

Figures 35 to 46 illustrate this sensitivity. It can be observed from these figures for instance that, regardless of the horizontal well length and the tubing diameter, the production rate increases proportionally to the reservoir permeability. More importantly, a close examination of these figures reveals the crucial role of the ratio $\Delta P_{friction} / \Delta P_{formation}$. Comparing figure 35 to 43, it can be observed for instance, that the performance of a 1000 ft and a 3000 ft horizontal well are very similar for a small tubing diameter of 0.3 ft when the reservoir permeability is 1 darcy. On the other hand, For a reservoir permeability of 7 darcies, the performance of a 3000-ft horizontal well is reduced over the 1000 ft well for the same tubing diameter of 0.3 ft. The reason is that the increase of friction forces due to longer horizontal section leads to less production in the heel region, which results in lower performance. This does not happen for larger diameter tubing as it can be seen from the comparison of figures 38 to 46.

6.5 Effect of Solution GOR

In the last series of experiments, the effect of solution GOR is examined. The results are presented in fig.'s 47 through 49. The results indicated that the increase of solution GOR value reduces oil viscosity and hence reduce frictional losses. This will increase production rate. Going for longer length of wellbore will increase the productivity index, however it will increase frictional losses and as a result it will reduce the effect of solution GOR as indicated by comparing fig.'s 47&49.

Chapter 7

OPTIMIZATION OF WELL COMPLETION

7.1 Optimization approach

The type of formation dictates the well completion. Very often, the horizontal wells need to be cased and perforated. It is important in this case to know how much of the horizontal length should be perforated and where to locate the perforations. That would involve two parts: on one hand, the completion scenario that will yield high productivity index, and on the other hand, it will yield the minimum frictional losses possible. The key element of the well completion success from the production point of view is to have the configuration that makes more production with less frictional losses. Examining different perforation scenarios can attain this.

As mentioned earlier, the analytical solution showed that the productivity index of a partially perforated well will increase with the perforation length. However, that increase is not linear and may level out after certain length of perforation depending on reservoir thickness and characteristics. Moreover, it was shown that for thick and high permeable reservoir, having 60% of the horizontal section length perforated will result in obtaining 90% of the productivity index of an open hole horizontal well penetrating the same formation.

The definition of optimum horizontal section of a well completed in high permeable reservoir, comes from the observation that the production rate of a horizontal well increases to a certain limit and starts flattening out and may not increase with increasing the well length. This is the optimum well length as supported by the derivative curve in fig. 50.

Different reservoir permeabilities, from 1 to 7 darcys were studied to show the effect of the inflow on the overall performance of the horizontal wells. Results presented in figure 51 suggest that high permeability reservoirs deliver more production. Moreover, in high permeable reservoirs, more frictional pressure losses are expected as shown in figure 52. The plot shows that as more frictional losses are created in the horizontal wellbore, more back pressure is exerted at the sand face and the wellbore pressure at the end of the wellbore levels out and becomes comparable to the reservoir pressure. As a result, the flow rates obtained at the end of the wellbore in different reservoir permeability are comparable. Further more, the majority of the flow is obtained near the heel of the wellbore as shown in fig. 51.

To generalize the results, several hundreds of runs were conducted considering different parameters namely reservoir dimension (L_x, h) and permeability, fluid properties (u) and well completion parameters (L_w, D_w, N_p, L_p). A comparison of the productivity indices of those runs versus the productivity indices of similar well dimension completed as an open hole is presented in figure 53. The results obtained support the fact that the productivity index of horizontal wells is reduced because of partial perforation. Figure 54 is showing a comparison of the flow rates obtained in those runs where the horizontal wells are partially-perforated cases compared to the open hole cases. The effect of partial penetration and the frictional pressure losses have not been considered. The results showed that the productivity of partially perforated horizontal wells is adversely affected by those two factors and a deviation from the open-hole performance is observed. The two trends obtained here are true for the two casing diameters considered 4-1/2" & 7". It shows also that the 7" is less affected by the frictional losses. However, the influence of partial perforation is still in effect.

7.2 Optimization correlations

To account for that deviation due to frictional losses and partial perforation, a correlation was developed to relate the performance of partially perforated horizontal wells to the performance of the wells if completed as open hole. This is basically a measure of the completion efficiency. Two models were developed to describe the performance of horizontal wells partially perforated and frictional pressure losses. The first one concerns the reduction of performance due to partial perforation and frictional losses. The other one concerns optimum well length. The coefficients of the correlations were obtained using non-linear regression analysis. System outputs are listed in appendix.

7.2.1 Well performance prediction

Model 1:

$$R = 0.9236222302.\ (J_{hp}/J_{ho})^{0.1988473001}.u^{09}.D^{.29}.L_w^{-.004455}.K_h^{-.062}$$

Model 2:

$$R = 0.75529.\ (L_{pt}/L_w)^{-.22}.(L_w/L_x)^{-.20965}.u^{09}.D.^{29}.L_w^{-.004455}.K_h^{-.062}$$

Where ;

$Q_o = J_{ho} \cdot (P_r\text{-}P_{heel})$

$Q_p{=}R\ .\ Q_o$

To test the accuracy of that correlations, a number of runs were done using both the computer program calculations and the correlations. The results are presented in fig. 55 and that shows that the results obtained from correlations are fairly matching the calculated results.

MODEL 2:

Optimum Well Length

Another correlation was developed to estimate the optimum well length beyond which, little additional production will result from extending the horizontal well.

$$L_{Optimum} = 20649.2\ .\ K_h^{-0.238598822}.u^{.241627047}.D^{.734163232}$$

The correlation was used to calculate the optimum well length for different cases. The coefficients of the correlations were obtained using linear regression analysis. System outputs are listed in tables 2 to 4. These correlations were presented in Ref. 27.

Results compared with the optimum well length obtained that would yield the maximum production rate using the computer program are presented in fig. 56.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn:

- Friction in horizontal wells is important to consider when the reservoir permeability is large.
- The perforated intervals and the location of these perforations directly affect the performance of horizontal wells.
- 20% of the length perforated at the heel yields twice the production of the same fraction perforated at the toe.
- 20% of the length perforated uniformly across the well yields 3 to 4 times the production of the same fraction perforated at the toe of the horizontal well
- For given reservoir conditions, there is an optimum well length that yields maximum oil production.
- For homogenous reservoirs considered in the study, 2000' of horizontal section is the optimum well length.

- The performance of a horizontal well is affected by the well length, as well as the length and distribution of the perforated intervals.

- In a 4-1/2 inch casing horizontal section, the rate of increase in production rate due to increasing the horizontal section is low for wells with horizontal sections longer than 2000'
- Different well completions may perform similarly.
- Longer horizontal wells yield higher productivity index but not necessarily higher production rates
- It's important to consider wellbore hydraulics when designing the well completion.
- In highly permeable reservoirs, longer horizontal wells do not necessarily achieve higher production rates.

For future study, further investigation on the effect of vertical permeability on the performance of horizontal wells is recommended.

BIBLIOGRAPHY

1. **Giger, F., Reiss, L.H., and Jourdan, A.**:" The Reservoir Engineering Aspects of Horizontal Drilling," paper SPE 13024 presented at the 1984 SPE Annual Technical Conference and Exhibition, Houston, Sept. 16-19.

2. **Borisov, Yu. P.**: Oil Production Using Horizontal and Multiple Deviation Wells, Nedra, Moscow (1964) (Translated into English by J. Straus, Philips Petroleum Co., Bartlesville, OK).

3. **Goode, P.A. and Thambynayagam, R.K.M.**:" Pressure Drawdown and Buildup Analysis of Horizontal Wells in Anisotropic Media," SPE 14250 Presented at the 60th Annual Technical Conference and Exhibition of The Society of Petroleum engineers Las Vegas, NV Sept. 22-25 1985.

4. **Gringarten, A. C. and Ramey, H. J., Jr.**, "The Use of Source and Green's Functions in Solving Unsteady-Flow Problems in Reservoirs," SPEJ (Oct. 1973) 285-96: Trans., AIME, 267.

5. **Daviau, F., Mouronval, G., and Bourdarot, G.,** " pressure Analysis for Horizontal Wells," SPE paper 14251, Sep. 1985.

6. **Kuchuk, F.J.**: " Well Testing and Interpretation for Horizontal Wells," JPT (Jan. 1995) 36-41. Kuchuk, F.J. et al.: " Pressure Transient Behavior of Horizontal Wells with and without Gas Cap or Aquifer," SPEFE (March 1991).

7. **Kuchuk, F.J., Goode, P.A., Brice, B.W. and Sherard, D.W.**: " Pressure Transient Analysis and Inflow performance for Horizontal Wells," Paper SPE 18300, presented at the 63 rd SPE Annual Conference, Houston, Texas, Oct. 2-5, 1988.

8. **Joshi, S. D.**: "Augmentation of Well Productivity with Slant and Horizontal Wells," *JPT*, June 1988.

9. **Babu, D. K. and Odeh, A. S.**,"Productivity of Horizontal Wells," SPE Paper 18298, October 1988.

10. **Goode, P.A. and Kuchuk, F.J.**:" Inflow performance of Horizontal wells," SPERE (Aug. 1991).

11. **Goode, P.A. And Wilkinson, D. J.**: " Inflow Performance of Partially -Open Horizontal wells," JPT (Aug. 1991) 983-987

12. **Dikken, B.J.**: "Pressure Drop in Horizontal Wells and Its Effect on Production Performance," Jour. Pet. Tech., (Nov. 1990) pp. 1426-1433

13. **Brice, B. W.**: "Production Impacts on Δp Friction in Horizontal Production Wells," Paper SPE 23666. Presented at SPE Second Latin American Petroleum Engineers Confereance, II LAPEC, Caracas, Venezuela, (March 1992)

14. **Islam, M.R. and Chakma A.**: " Comprehensive Physical and Numerical Modeling of a Horizontal Well," SPE 20627 presented at 65th Annual Technical Conference of the SPE, New Orleans, Louisiana, Sep. 23-26,1990.

15. **Suzuki, K.**:" Influence of Well Bore Hydraulics on Horizontal Well Pressure Transient Behavior" Japan Oil Development Co., LTD

16. **Ozkan, E. et al.**: "Effect of Conductivity on Horizontal Well Pressure Behavior," Paper SPE 24683, presented at SPE 67th Annual Technical Conference and Exhibition, Washington D.C., (October 1992).

17. **Novy, R.A.**: " Pressure Drop in Horizontal Wells: When Can They Be Ignored?" Paper SPE 24941, presented at the 67th SPE Annual Conference, Washington, DC, Oct. 4-7, 1992.

18. **Ihara, M., Brill, J.P. and Shoham, O.**:" Experimental and Theoretical investigations on Two-phase Flow in Horizontal Wells," Paper SPE 24766 Published in the 67th SPE Annual Technical Conference and Exhibition, Washington DC (Oct. 1992).

19. **Land, M.J. and Goldthorpe, W.H.**: " Optimization of Perforations Distributions for Horizontal Wells," SPE 23005 presented at the SPE Asia Pacific Conference, Perth, Australia, Nov. 4-7,1991.

20. **Seines, K. et al.**: " Considering Well Friction Effects in Planning Horizontal Wells," JPT (Oct. 1993) 994-1000.

21. **Ihara, M., Koji Yanai and Shingo Takao**: "Two Phase Flow in Horizontal Wells," SPE Production and Facilities, November 1995.

22. **Brekke, K.**: " New and Simple Completion Methods for Horizontal Wells Improve the Production in High Permeability, Thin Oil Zones", Paper SPE 24762 presented at the SPE 67th Annual Conference, Washington, DC, Oct. 4-7, 1992.

23. **Asheim, H., Kolnes, J., and Oudeman, P.**:" A Flow Resistance Correlation for Completed Wellbore," *Petroleum Science and Engineering*, 8(1992), pp. 97-104.

24. **Yuan, H., Sarica, C., and Brill, J. P.**:" Effect of Perforation Density on Single Phase Liquid Flow behavior in Horizontal Wells," Paper SPE 37103 presented at the 1996 International Conference on Horizontal Well Technology, Calgary, Alberta, Nov. 18-20, 1996.

25. **Beggs, H.D. and Brill, J.P.**," A Study of Two Phase Flow in Inclined Pipes," Jour. Pet. Tech. (May 1973) pp. 607-617.

26. **Al-Qahtani, A. M., Menouar, H., and Al-Majed, A.**:" Effect of Length and Distribution of Perforated Intervals on Horizontal Wells Rates," Paper SPE 37112 presented at the 1996 International Conference on Horizontal Well Technology, Calgary, Alberta, Nov. 18-20, 1996

27. **Al-Qahtani, A. M., and Menouar, H.**:" New correlations for Optimizing Horizontal Wells Completions," Paper SPE 37768 presented at the 1997 Meddle East Oil Show, Bahrain, March 18, 1997

APPENDIX

The analytical solution of the performance of partially perforated horizontal wells

$$J = \frac{7.08 \text{ x } 10^{-03} K_{H}h}{\mu B_o \left(p_{ID} + s^{*}_{m} \right)}$$

$$p_{ID} = S_{zD} + p_{xyD}$$

$$p_{xyD} = \frac{2\pi L_y}{L_x} \sqrt{\frac{K_x}{K_y}} \left(\frac{1}{3} - \frac{y_w}{L_y} - \frac{y_w^2}{L_y^2} \right) + \frac{2 L^2_x}{\pi^2 L^2_p} \sum_{n=1}^{\infty} \frac{Z_n}{n^3} \left(\sum_{i=1}^{n_p} \cos \frac{n\pi x_i}{L_x} \text{ x } \sin \frac{n\pi L_i}{L_x} \right)^2$$

Where

$$Z_n = \left\{ 1 + \exp(-2\alpha_n L_y) + \exp(-2\alpha_n Y_w) + \exp\left[-2\alpha_n \left(L_y - y_w \right) \right] \right\} \Big/ \left[1 - \exp(-2\alpha_n L_y) \right]$$

$$\alpha_n = \frac{n\pi}{L_x} \sqrt{\frac{K_x}{K_y}}$$

$$L_p = \sum_{i=1}^{n_p} L_i$$

$$S_{zD} = \frac{h}{2L_p} \sqrt{\frac{K_x}{K_z}} \left[-\ln \left(\frac{2\pi r'_w}{h} \sin \frac{\pi z_w}{h} \right) - \frac{n_p h}{L_p} \sqrt{\frac{K_x}{K_z} \left(\frac{1}{3} + \frac{z_w}{h} + \frac{z^2_w}{h^2} \right)} \right] + 2 \sum_{k=1}^{\infty} F^{*}_{w}(\beta_k) \cos^2 \frac{k\pi z_w}{h}$$

Where

$$r'_w = \frac{1}{2} \left(1 + \sqrt{\frac{K_z}{K_y}} \right) r_w$$

$$\beta_k = \frac{\pi^2 k^2}{h^2} \frac{K_z}{K_x}$$

$$F^*{}_w(\beta_k) = \frac{1}{L^2{}_p} \int_{\sqrt{\beta}}^{\infty} \frac{du}{\sqrt{u^2-\beta}} \frac{1}{2u^2} \sum_{i=1}^{n_p} \left[\exp(-2uL_i) + 4\sum_{j\langle i} \exp(-u|x_i - x_i|) \,.\, \sinh uL_i \, \sinh \, uL_j \right]$$

This equation can be written in the form,

$$F^*{}_w(\beta_k) = \frac{1}{2L^2{}_p} \int_{\sqrt{\beta}}^{\infty} \frac{\exp(-a)}{\sqrt{u^2-\beta}} \frac{1}{u^2} \, du$$

Let

$$u = \frac{\beta}{\chi} \Rightarrow \chi = \frac{\beta}{u}, \quad du = \frac{-\beta}{\chi^2} d\chi$$

as u goes from $\sqrt{\beta}$ to ∞ , χ goes from $\sqrt{\beta}$ to 0

$$F^*{}_w(\beta_k) = \frac{1}{2L^2{}_p} \int_{\sqrt{\beta}}^{0} \frac{\exp\left(-a\dfrac{\beta}{\chi}\right)}{\sqrt{\left(\dfrac{\beta}{\chi}\right)^2 - \beta}} \frac{1}{\left(\dfrac{\beta}{\chi}\right)^2} \left(\frac{-\beta}{\chi^2}\right) d\chi$$

$$F^*{}_w(\beta_k) = \frac{1}{2\beta L^2{}_p} \int_{0}^{\sqrt{\beta}} \frac{\exp\left(-a\dfrac{\beta}{\chi}\right)}{\dfrac{\sqrt{\beta}}{\chi}\sqrt{\beta-\chi^2}} d\chi$$

Let

$$\chi = \sqrt{\beta}\cos(\omega) \Rightarrow d\chi = -\sqrt{\beta}\sin(\omega)\, d\omega$$

as χ goes from 0 to $\sqrt{\beta}$, ω goes from $\frac{\pi}{2}$ to 0

$$F^{*}{}_{w}(\beta_k) = \frac{1}{2\beta L^{2}{}_{p}} \int_{\frac{\pi}{2}}^{0} \frac{\exp\left(-a \dfrac{\beta}{\sqrt{\beta}\,\cos(\omega)}\right)}{\dfrac{\sqrt{\beta}}{\sqrt{\beta}\,\cos(\omega)} \sqrt{\beta - \beta \cos^{2}(\omega)}} \left(-\sqrt{\beta}\,\sin(\omega)\right) d\omega$$

$$F^{*}{}_{w}(\beta_k) = \frac{1}{2\beta L^{2}{}_{p}} \int_{0}^{\frac{\pi}{2}} \frac{\cos(\omega)\ \exp\left(-a\,\sqrt{\beta}\ \sec(\omega)\right)}{\sqrt{\beta}\ \sqrt{1-\cos^{2}(\omega)}} \left(-\sqrt{\beta}\,\sin(\omega)\right) d\omega$$

$$F^{*}{}_{w}(\beta_k) = \frac{1}{2\beta L^{2}{}_{p}} \int_{0}^{\frac{\pi}{2}} \cos(\omega) \exp\left(-a\,\sqrt{\beta}\ \sec(\omega)\right)\, d\omega$$

$$F^{*}{}_{w}(\beta_k) = \frac{1}{2\beta L^{2}{}_{p}} \int_{0}^{\frac{\pi}{2}} \cos(\omega) \sum_{i=1}^{n_p} \left[\begin{array}{l} \exp\left(-2\sqrt{\beta}\,\sec(\omega) L_i\right) + \\ 4 \displaystyle\sum_{j \langle i} \left[\begin{array}{l} \exp\left(-\sqrt{\beta}\ \sec(\omega)\ |x_i - x_i|\right). \\ \sinh\left(\sqrt{\beta}\ \sec(\omega). L_i\right). \\ \sinh\left(\sqrt{\beta}\ \sec(\omega).\ L_j\right) \end{array}\right] \end{array}\right]$$

Nomenclature

R	ratio of production rate of partially-perforated to openhole, (Q_p/Q_o)
Q_o	Production rate of openhole wells, bbls/day.
Q_p	Production rate of partially-perforated well, bbls/day.
K_v	vertical permeability ,L^2, md
K_h	horizontal permeability , L^2 , md
J_{HP}	productivity index of partially perforated horizontal well , bbl/day/psi
J_{HO}	productivity index of openhole horizontal well , bbl/day/psi
L_x	length of horizontal drainage area , ft .
L_w	horizontal section length , ft .
L_{pt}	length of perforated section , ft
D_w	wellbore diameter , ft .
u	wellbore fluid viscosity , cp .
$L_{opt.}$	Optimum well length, ft.
h	formation thickness
B_o	oil FVF, RB/STB
h_D	dimensionless formation thickness, $(h/L_x)\sqrt{k_x/k_z}$, md
k_{He}	effective horizontal permeability, $\sqrt{k_x k_y}$, md
L_i	half-length of open segment *i*, ft
L_p	sum of open half-lengths, $\sum_{i=1}^{np} L_i$, ft
L_x	length of *x* side of drainage region, ft
L_y	length of *y* side of drainage region, ft
$L_{1/2}$	half-length of fully open well, ft
n_p	number of open sections
P_{ID}	dimensionless inflow pressure
P_{ssD}	dimensionless steady-state pressure
P_{xyD}	dimensionless pressure drop in x,y plane
r_{ew}	wellbore radius of equivalent vertical well, ft
S_m	mechanical skin
S_{zD}	addition skin from partial penetration
x,y,z	directional coordinates, ft
x_i	distance from center of segment *i* to left boundary at x=0, ft
x_w	distance from left boundary at to reference point on well, midpoint between open extremities, ft
y_w	distance of well from boundary at y=0, ft
z_w	distance of well from boundary at z=0, ft

Subscript

D	Dimensioless
o	Openhole
p	Partially-perforated
h	Horizontal
v	Vertical
w	Wellbore
pt	Perforated total
x	Horizontal alongr wellbore
Y	Horizontal perpendicular to wellbore
z	vertical

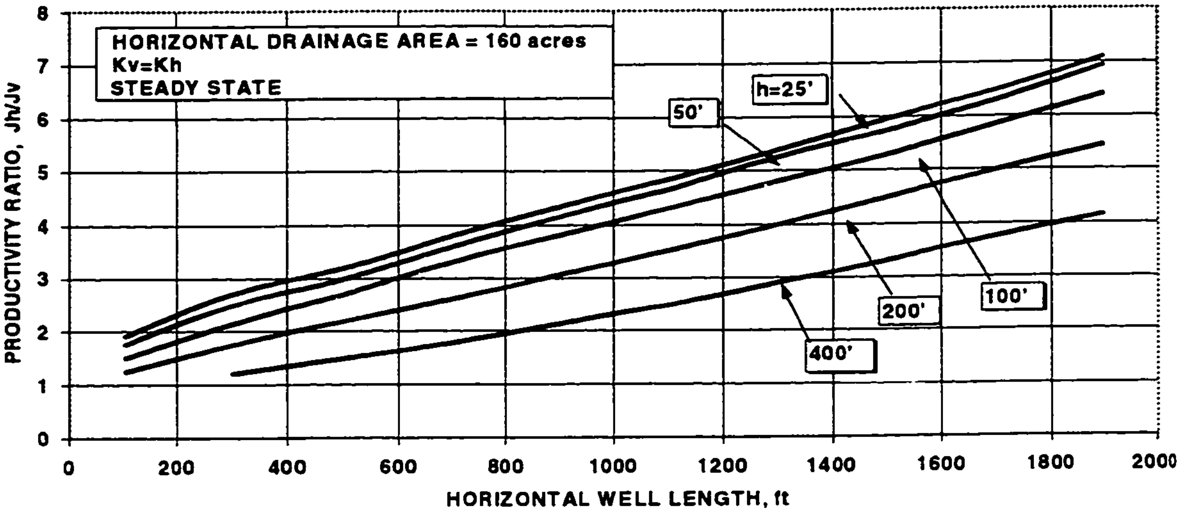


Fig. 1 Effect of horizontal section length on productivity for different pay thickness.

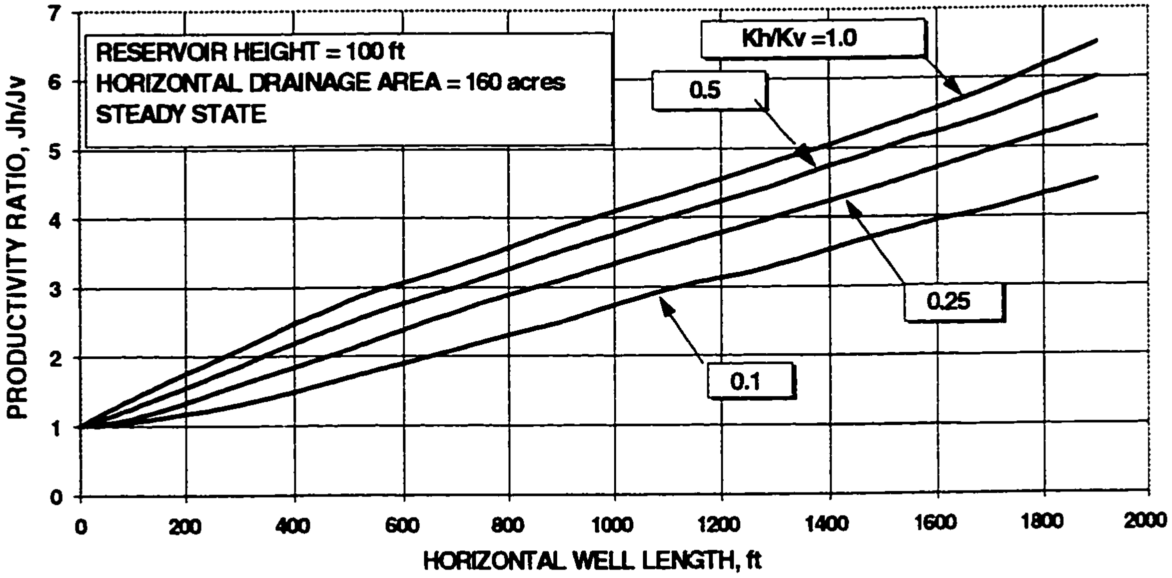


Fig. 2 Effect of horizontal section length on productivity for different pay anisotropy.

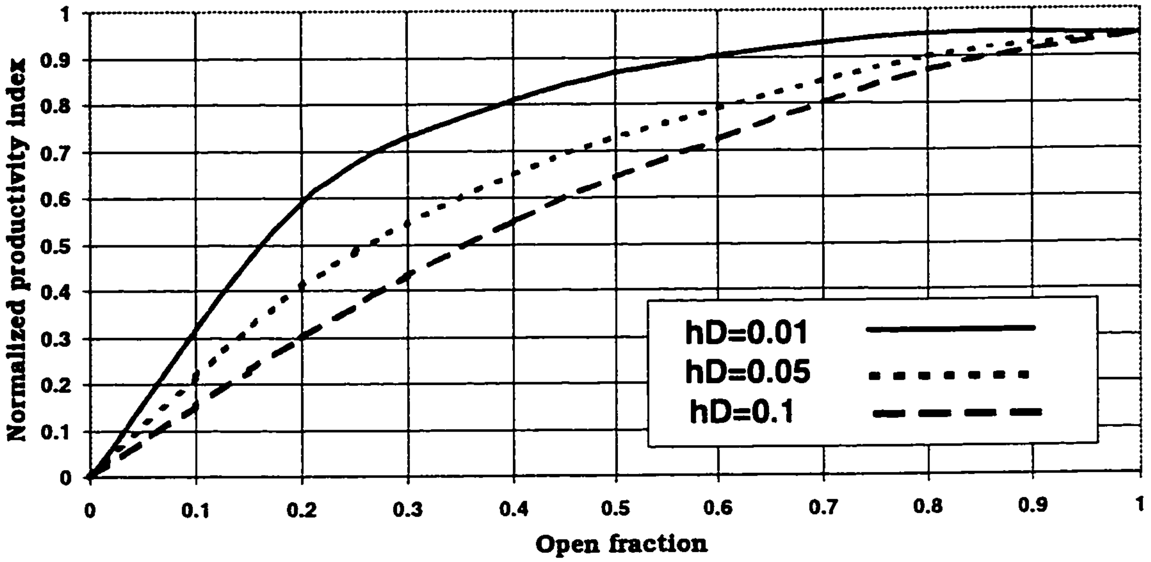


Fig. 3 Effect of formation damage on productivity

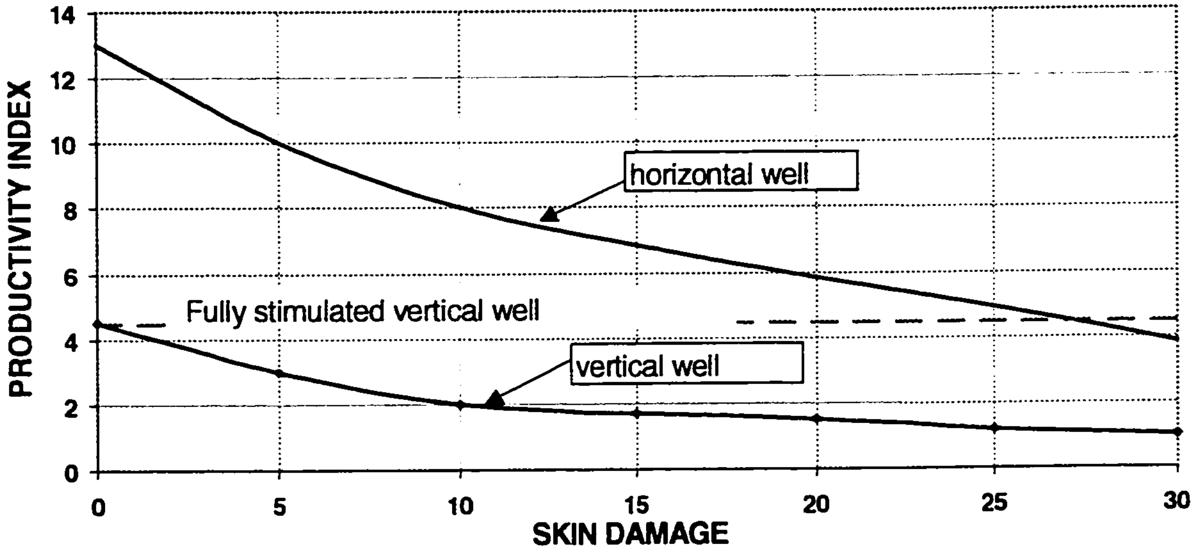


Fig. 4 Effect of partial perforation on productivity for different pay thickness

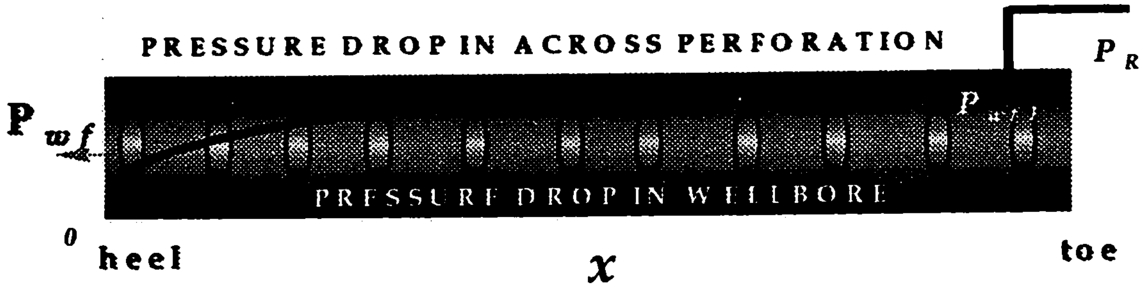


Fig. 5 Effect of frictional pressure losses on wellbore pressure

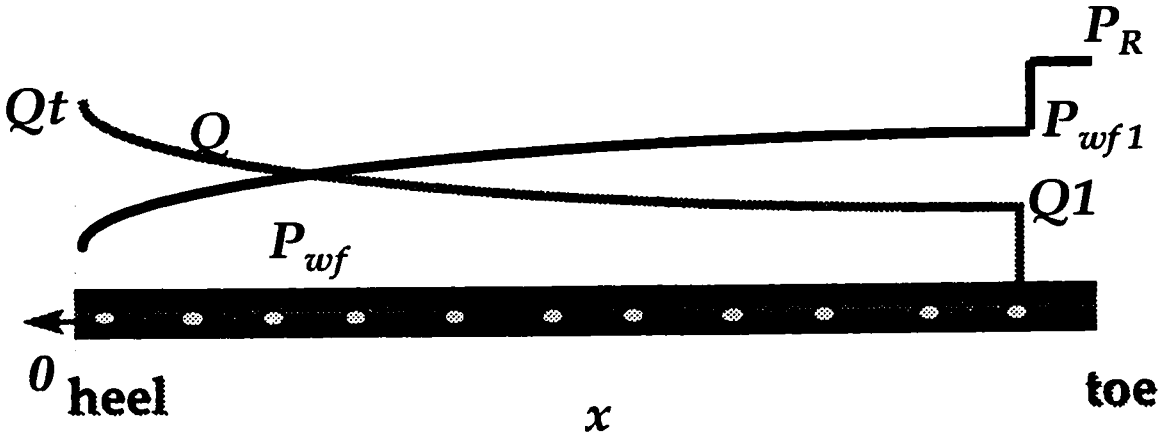


Fig. 6 Effect of frictional pressure losses on wellbore pressure and fluid influx

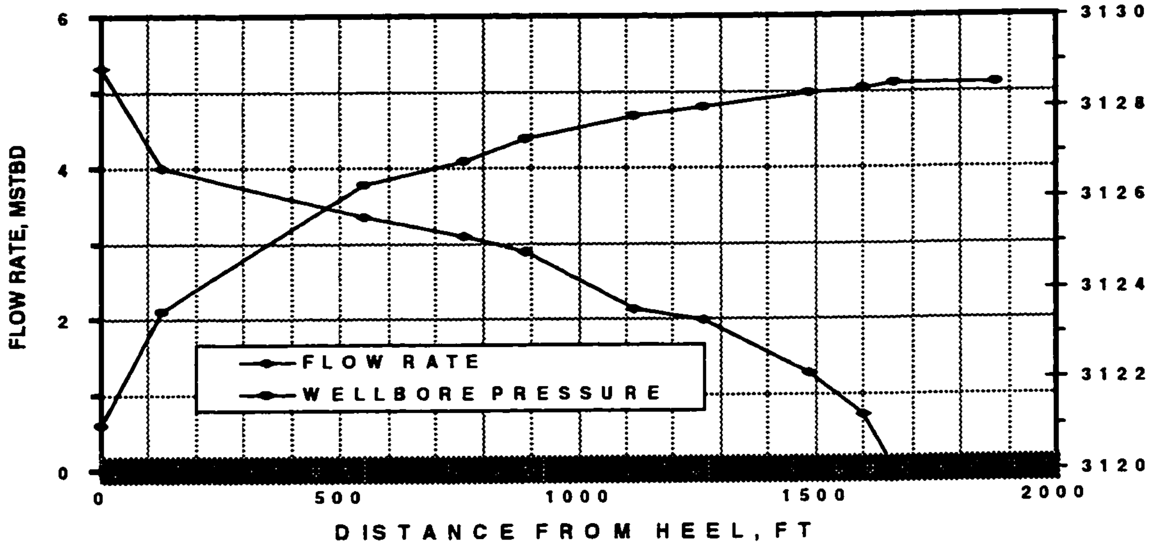


Fig. 7 Field example on the effect of frictional losses on flow and pressure profile

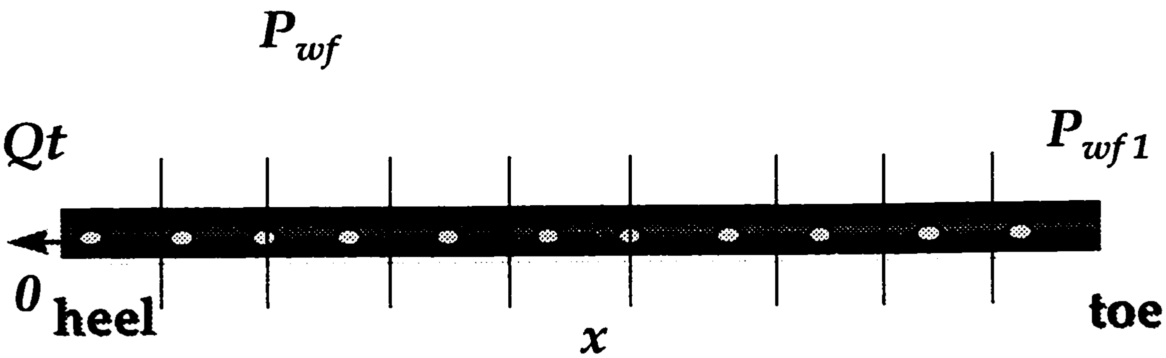


Fig. 8 Flow modeling of in a horizontal section

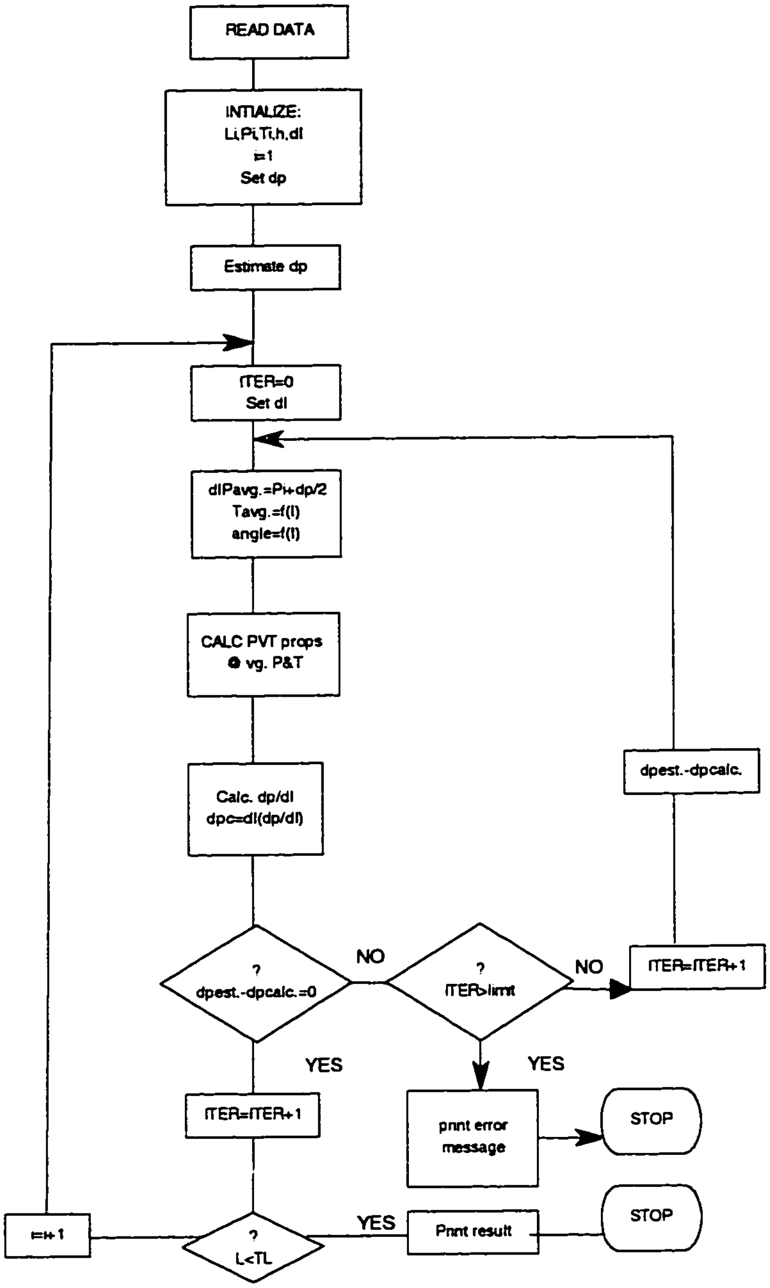


Fig. 9 Flow chart for pressure traverse calculations.

Table 1
Reservoir Characteristics
For the Four Different Fields

Case	1	2	3	4
k , darcy	3	7	4	6
L_{HW}	1795	1050	1785	2200
% Perforated	66	80	35	40
API Gravity	32	30	32	28
FVF	1.2	1.2	1.24	1.15
GOR	600	750	650	300
Rate	5371	11800	11200	19900
T, Degree F	165	165	165	160
P_{toe}, Psi	3128	3089	3083	2646
Dw, inch	7	4-1/2	7	7

Table 2
System output for the non-linear regression analysis
Well performance prediction; model 1

No. of data points	Constant	J_{hp}/J_{ho}	RMSE
1838	0.9236222302	0.1988473001	0.00478212

Table 3
System output for the non-linear regression analysis
Well performance prediction; model 2

No. of data points	Constant	L_w/L_x	RMSE
1772	0.7552904915	-0.2096495033	0.00420039

Table 4

System output for the linear regression analysis
Optimum well length correlation

No. of data points	Constant	k_h	D	U_o	RMSE
174	20649.2	-0.2385988	0.734163232	0.241627047	0.0121354

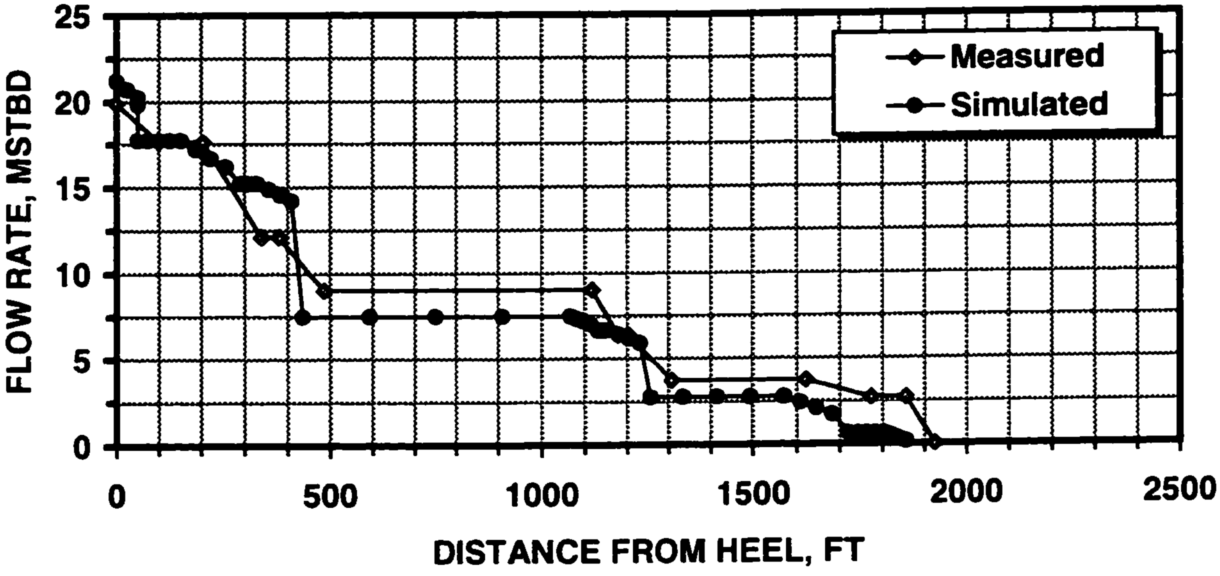


Fig. 10 Flow profile simulation, case 1

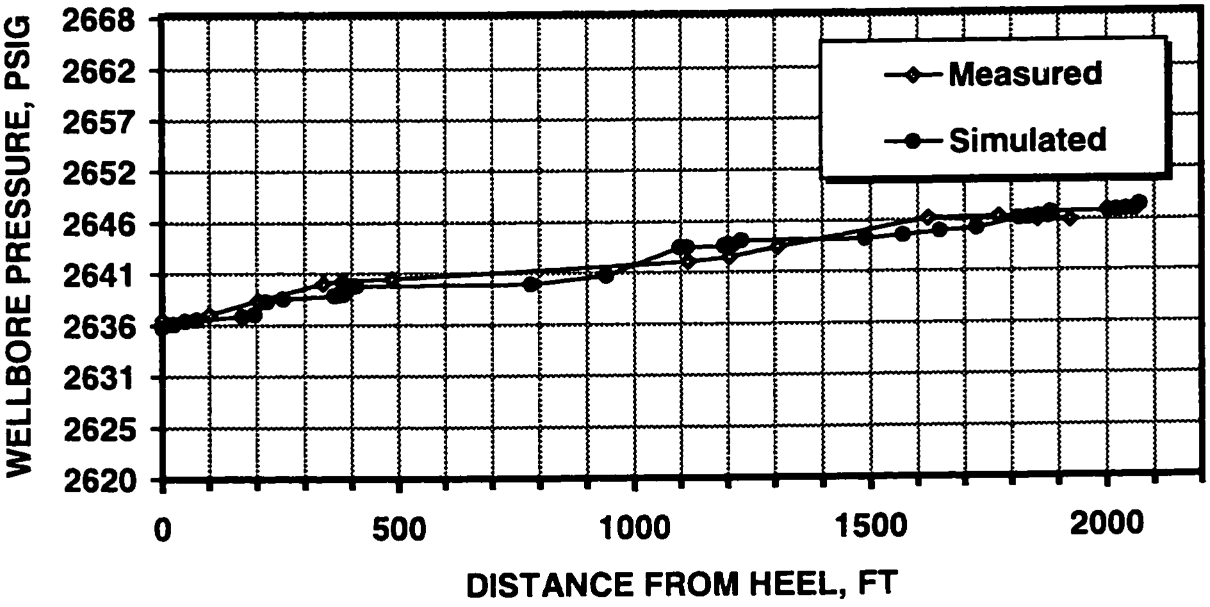


Fig. 11 Wellbore pressure profile simulation, case 1

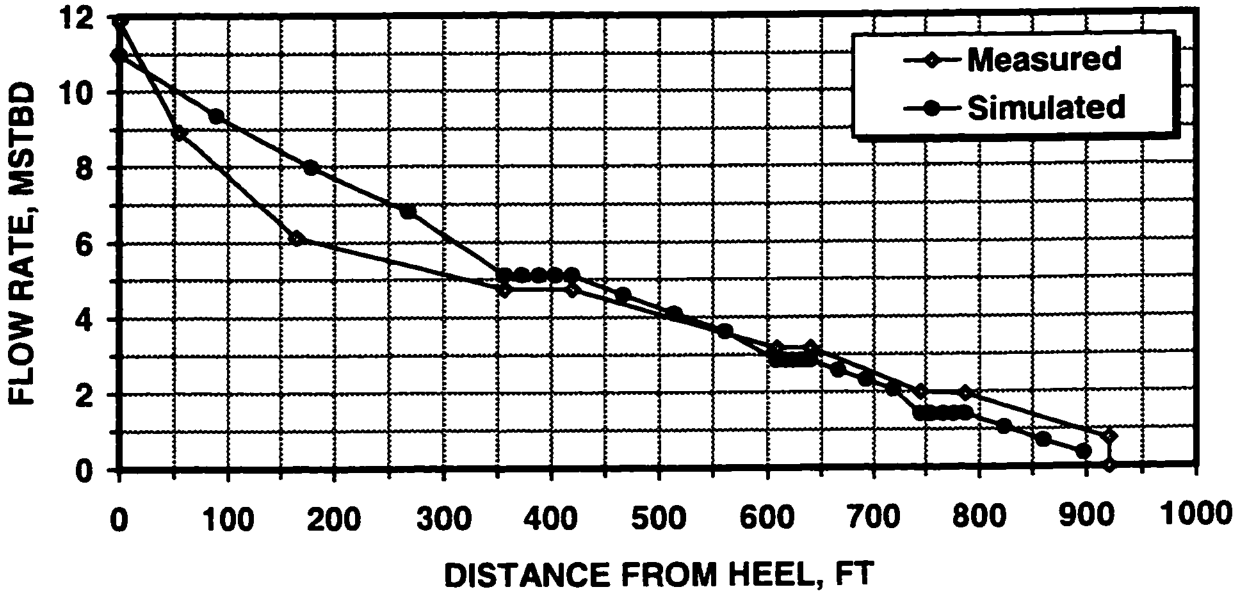


Fig. 12 Flow profile simulation, case 2

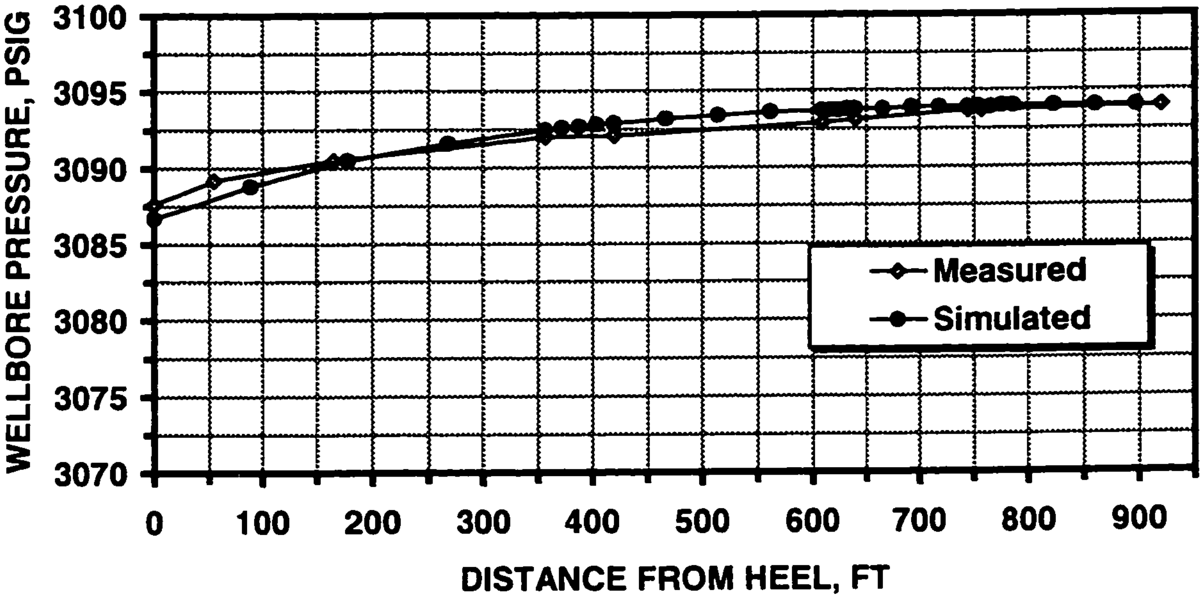


Fig. 13 Wellbore pressure profile simulation, case 2

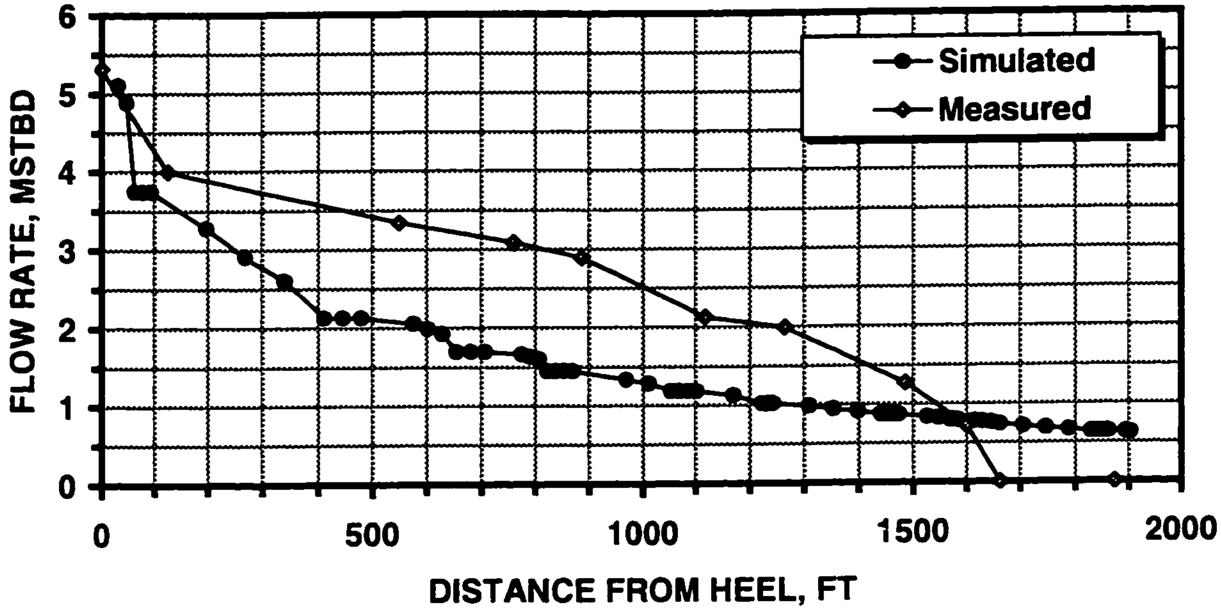


Fig. 14 Flow profile simulation, case 3

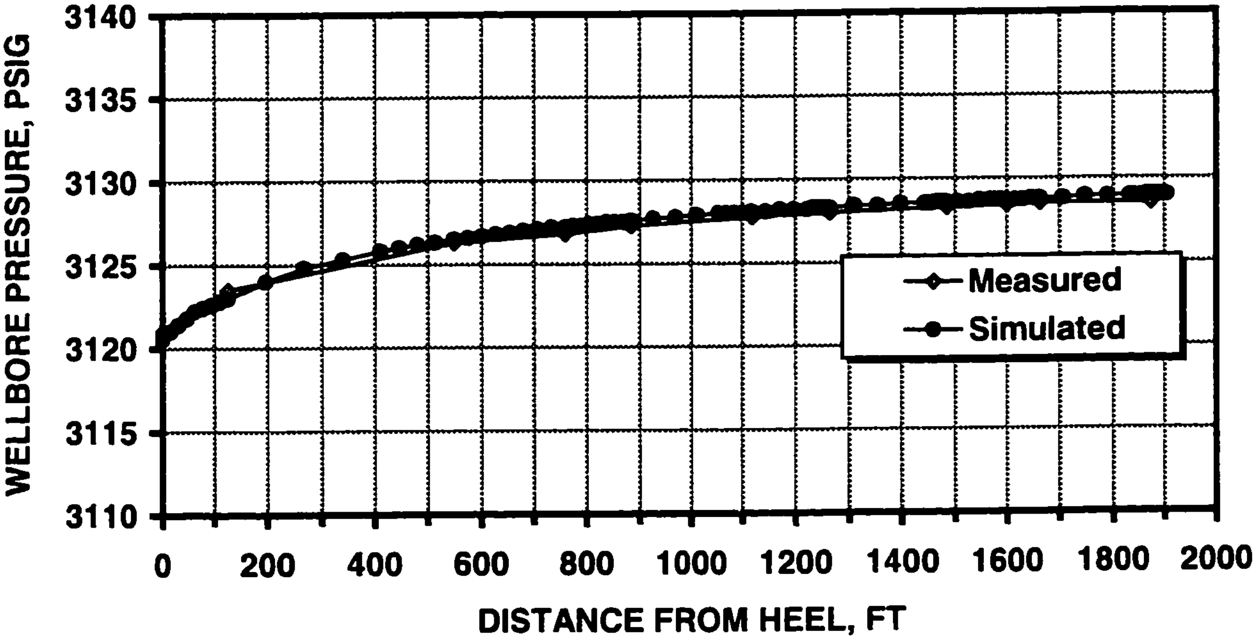


Fig. 15 Wellbore pressure profile simulation, case 3

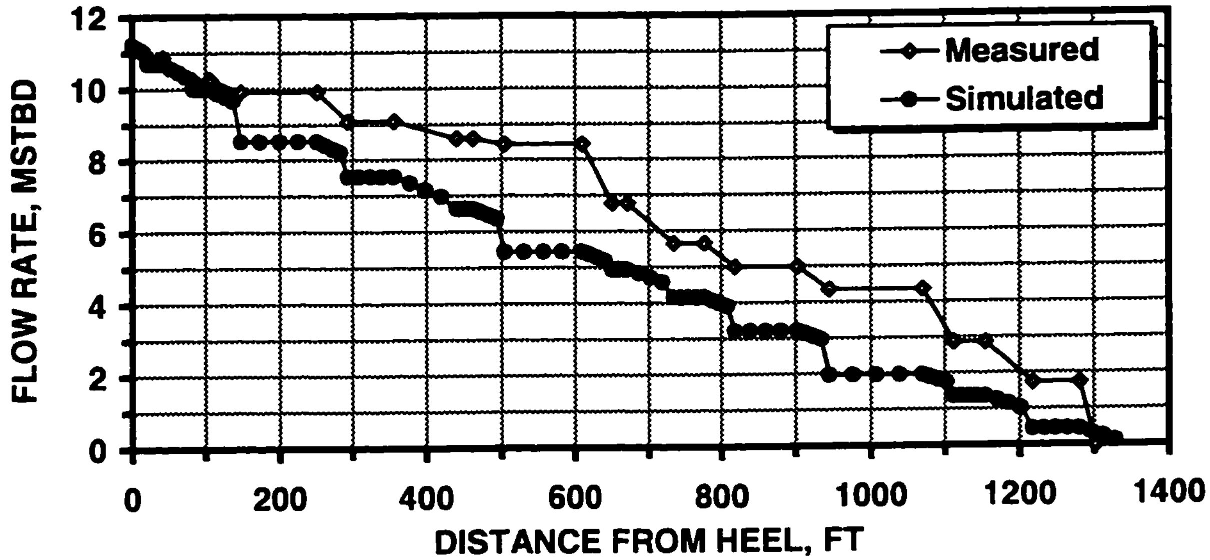


Fig. 16 Flow profile simulation, case 4

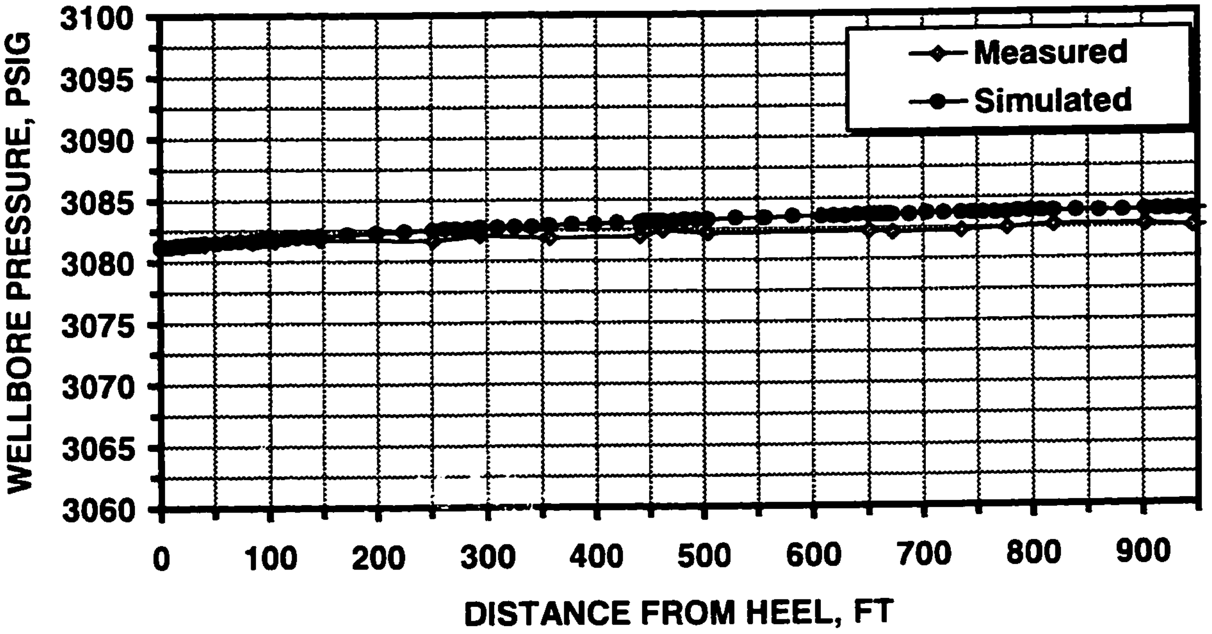


Fig. 17 Wellbore pressure profile simulation, case 4

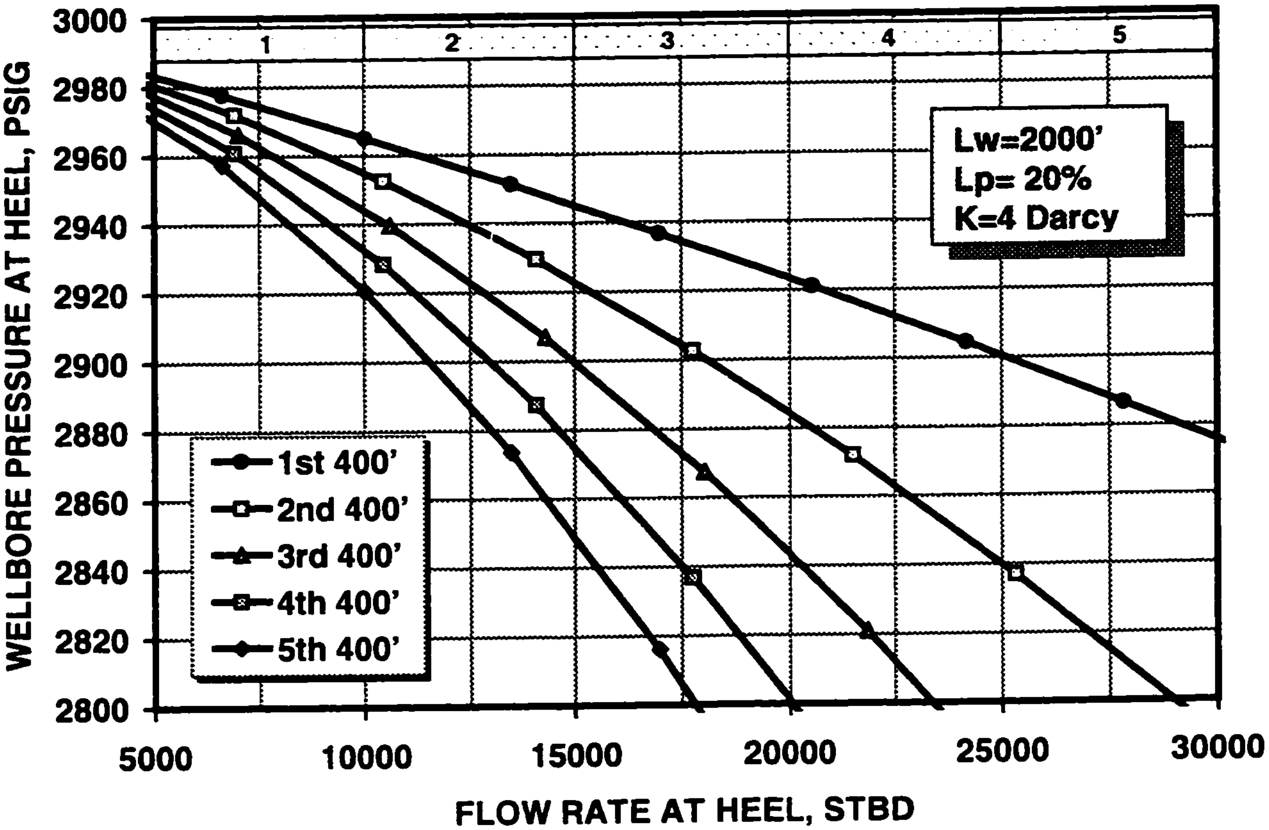


Fig. 18 Effect of perforation position on productivity

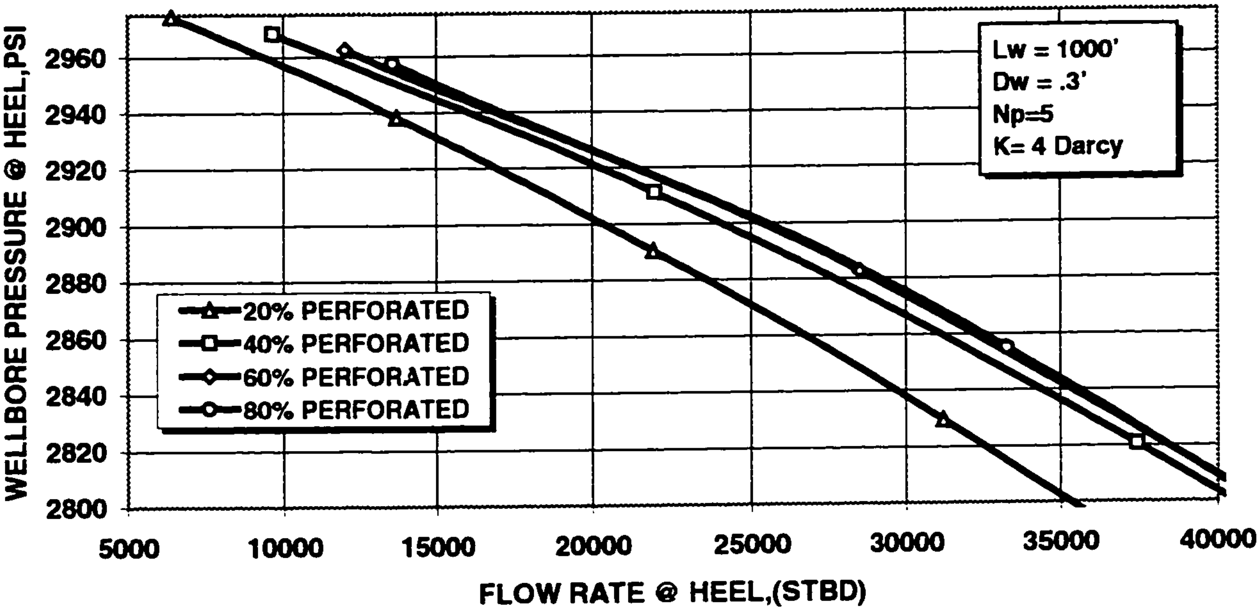


Fig.19 Effect of perforated Length Fraction on Production Rate, Lw=1000', Dw=.3'

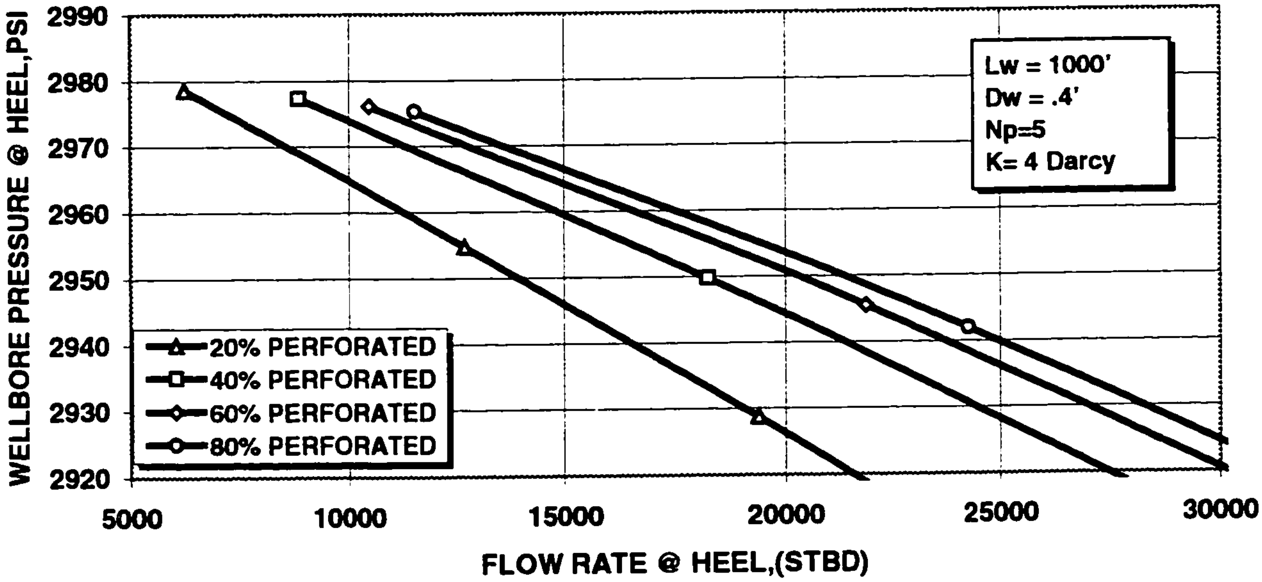


Fig.20 Effect of perforated Length Fraction on Production Rate, Lw=1000', Dw=.4'

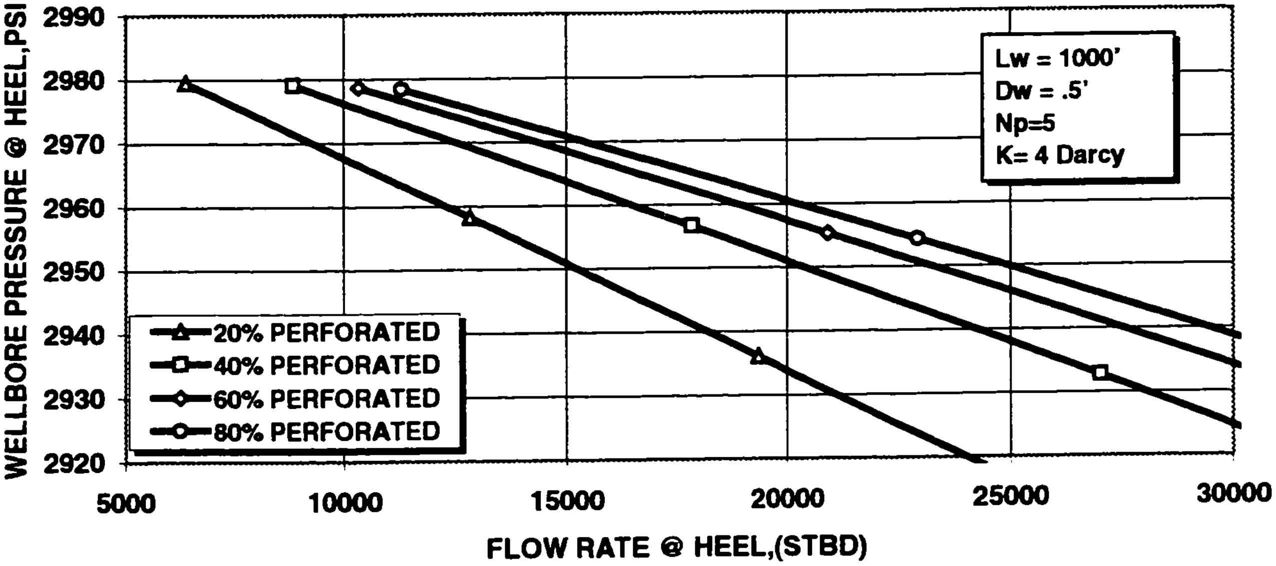


Fig.21 Effect of perforated Length Fraction on Production Rate, Lw=1000', Dw=.5'

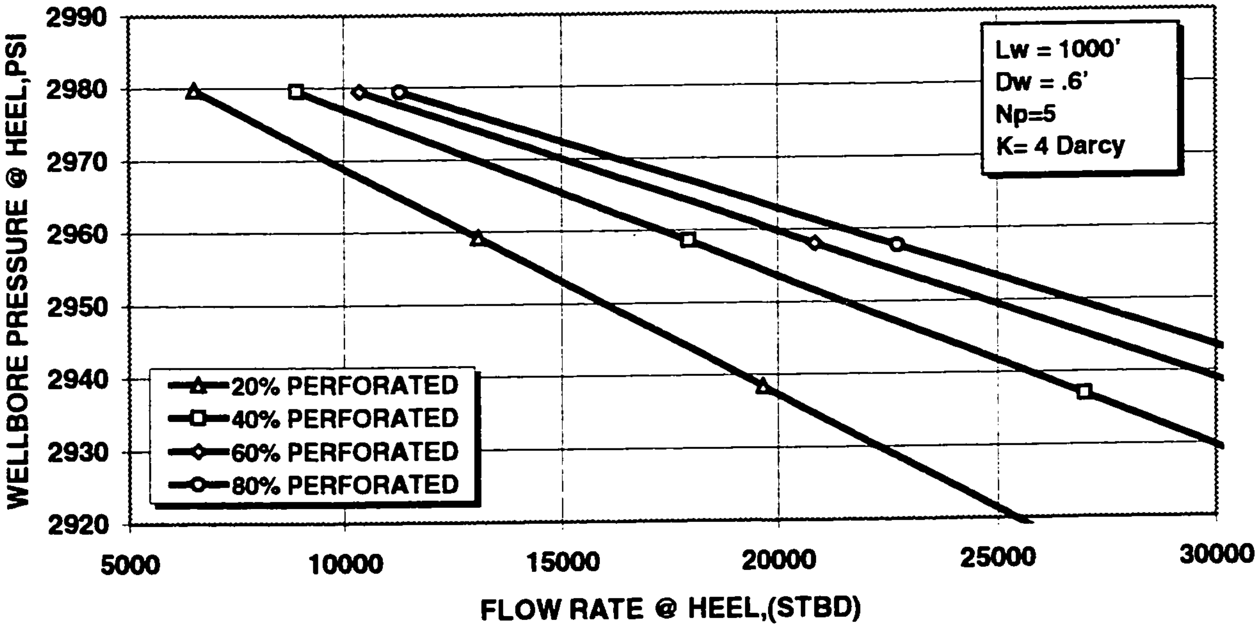


Fig.22 Effect of perforated Length Fraction on Production Rate, Lw=1000', Dw=.6'

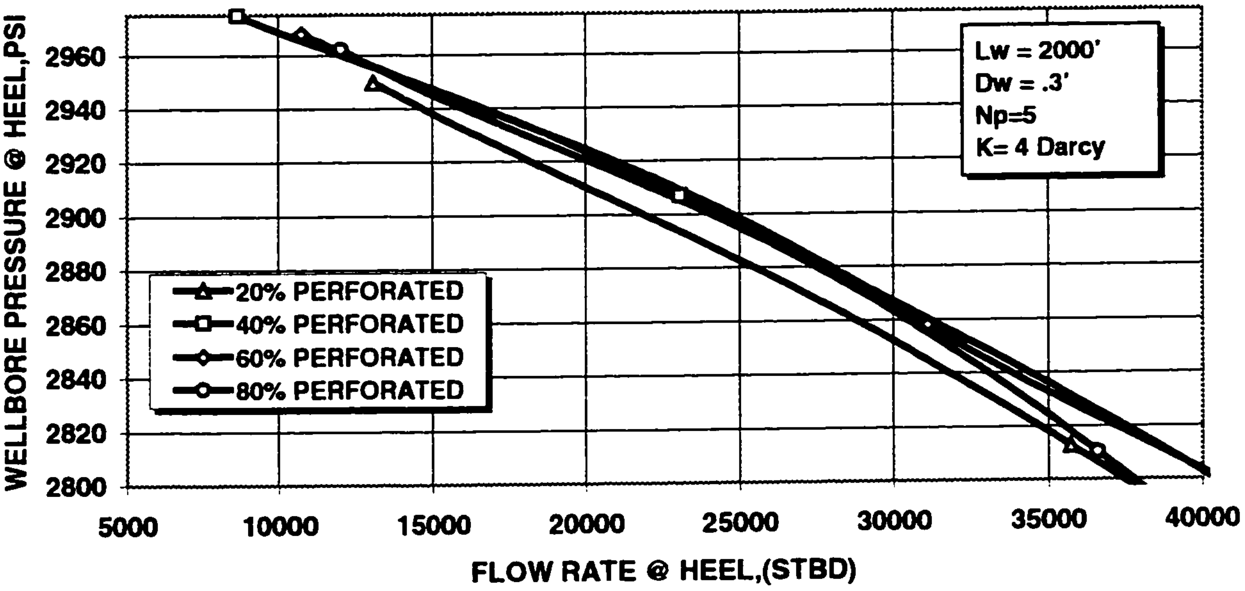


Fig.23 Effect of perforated Length Fraction on Production Rate, Lw=2000', Dw=.3'

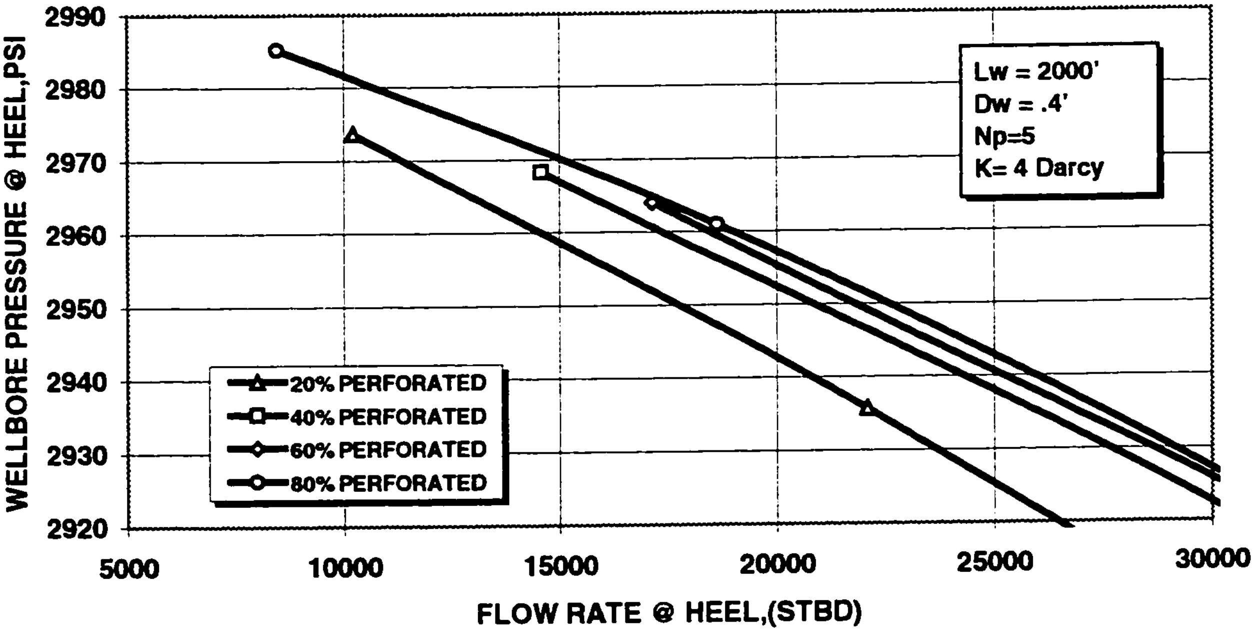


Fig.24 Effect of perforated Length Fraction on Production Rat, Lw=2000', Dw=.4'

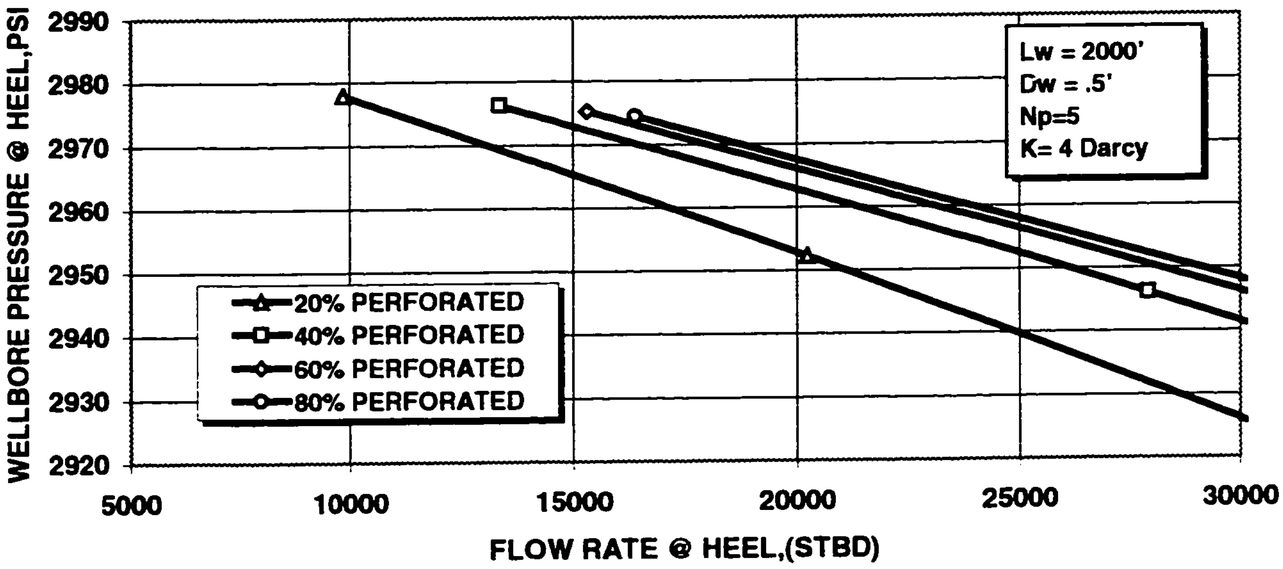


Fig.25 Effect of perforated Length Fraction on Production Rate, Lw=2000', Dw=.5'

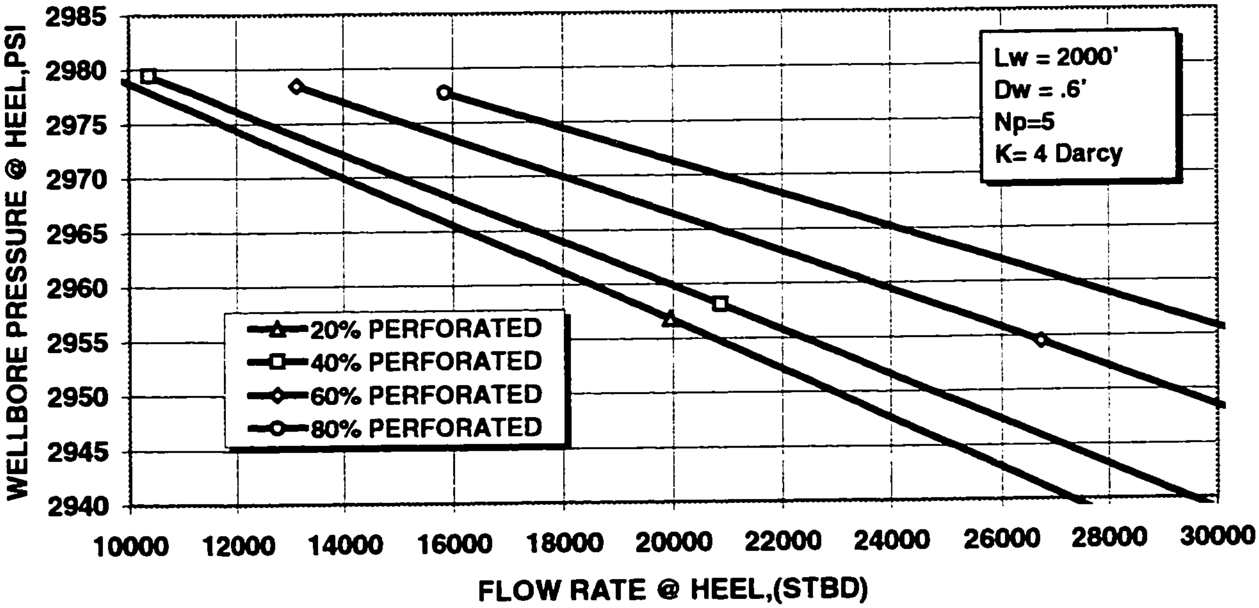


Fig.26 Effect of perforated Length Fraction on Production Rate, Lw=2000', Dw=.6'

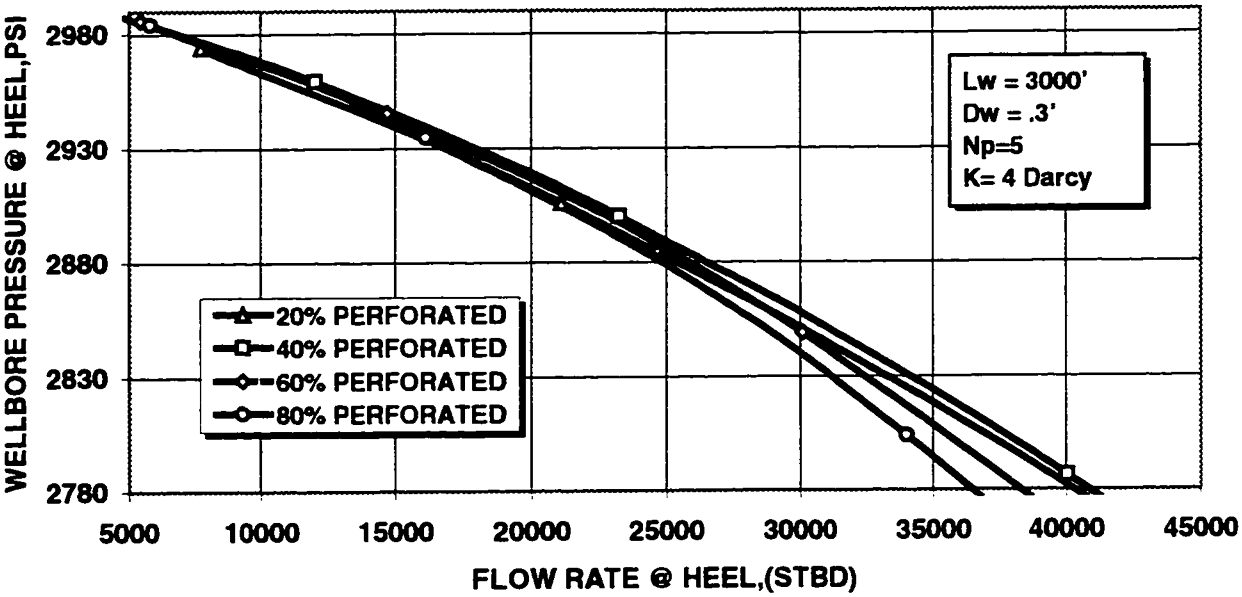


Fig.27 Effect of perforated Length Fraction on Production Rate, Lw=3000', Dw=.3'

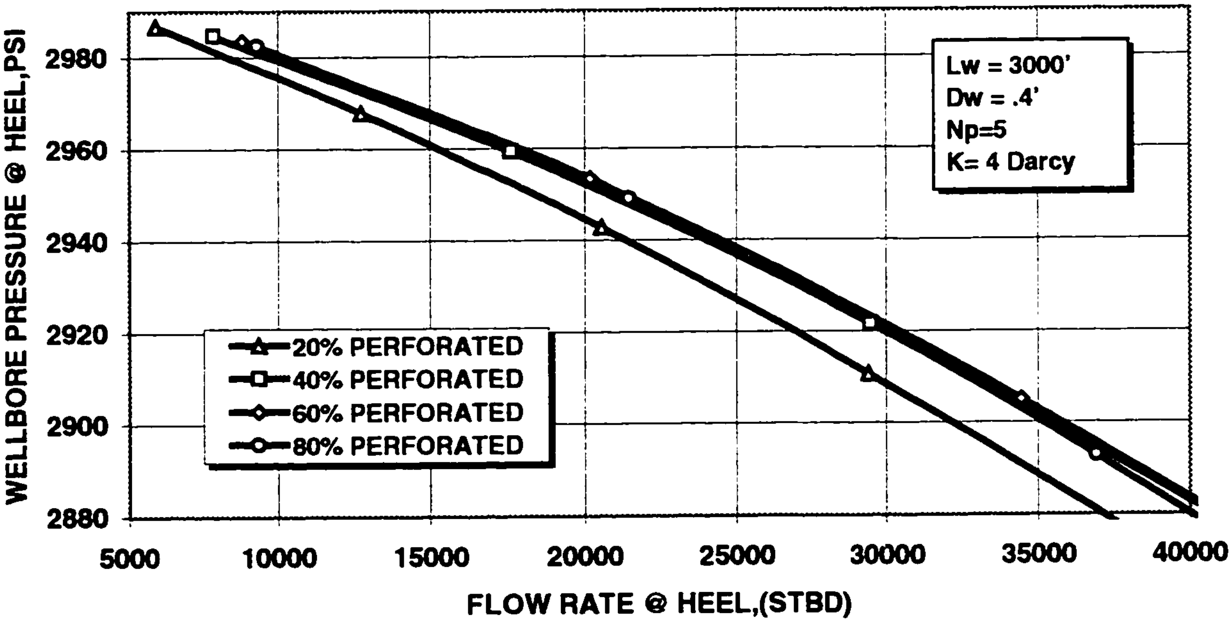


Fig.28 Effect of perforated Length Fraction on Production Rate, Lw=3000', Dw=.4'

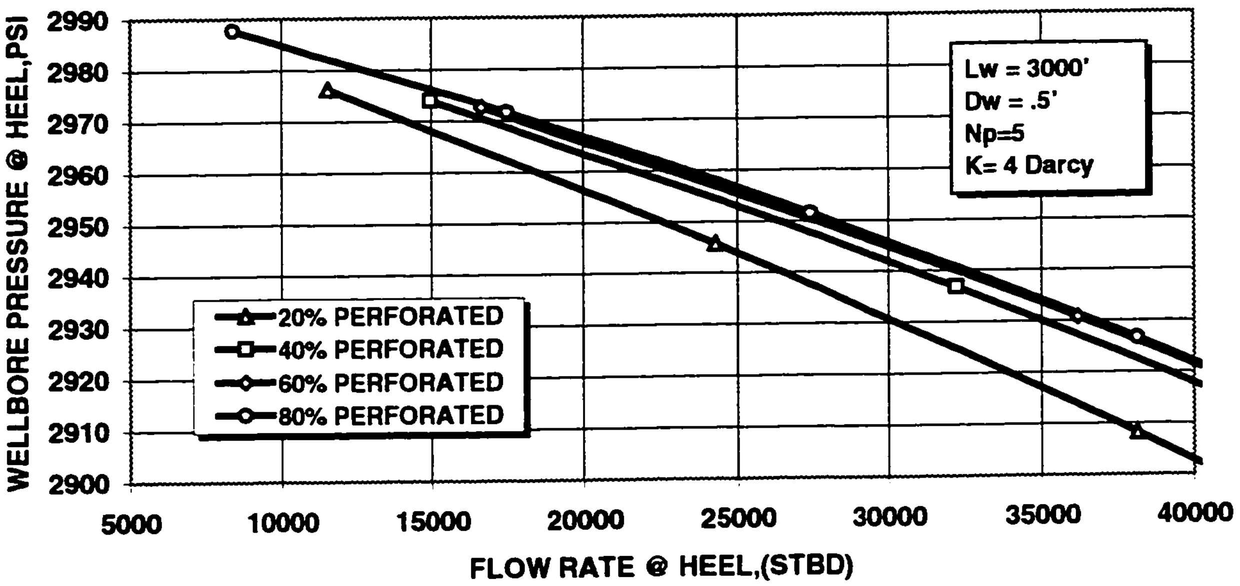


Fig.29 Effect of perforated Length Fraction on Production Rate, Lw=3000', Dw=.5'

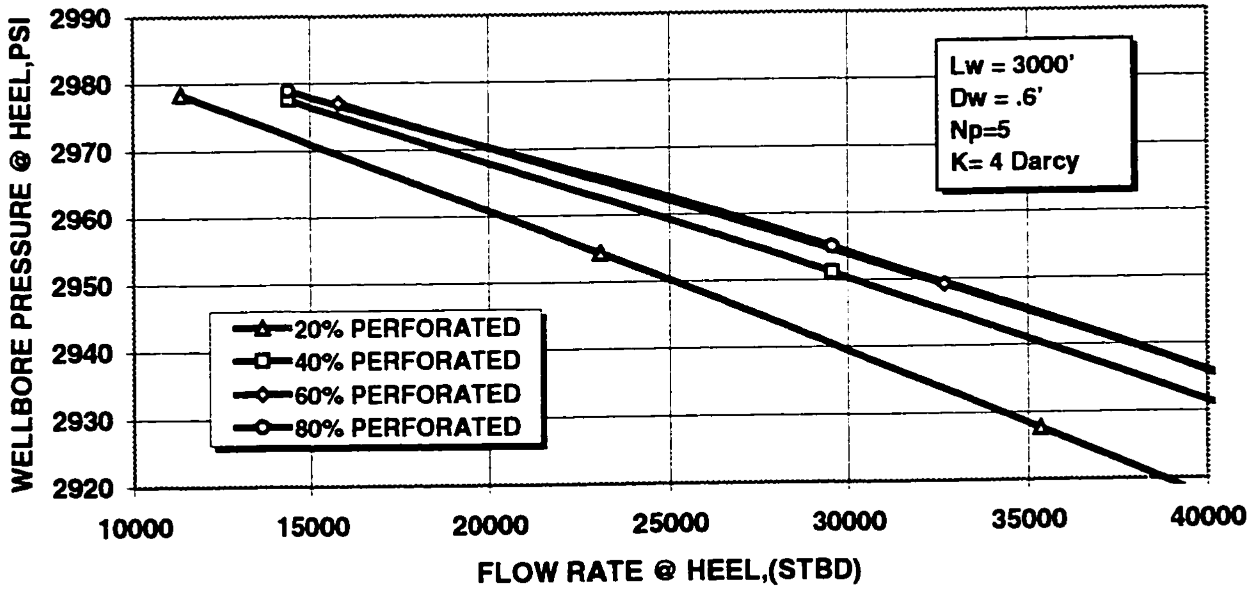


Fig.30 Effect of perforated Length Fraction on Production Rate, Lw=3000', Dw=.6'

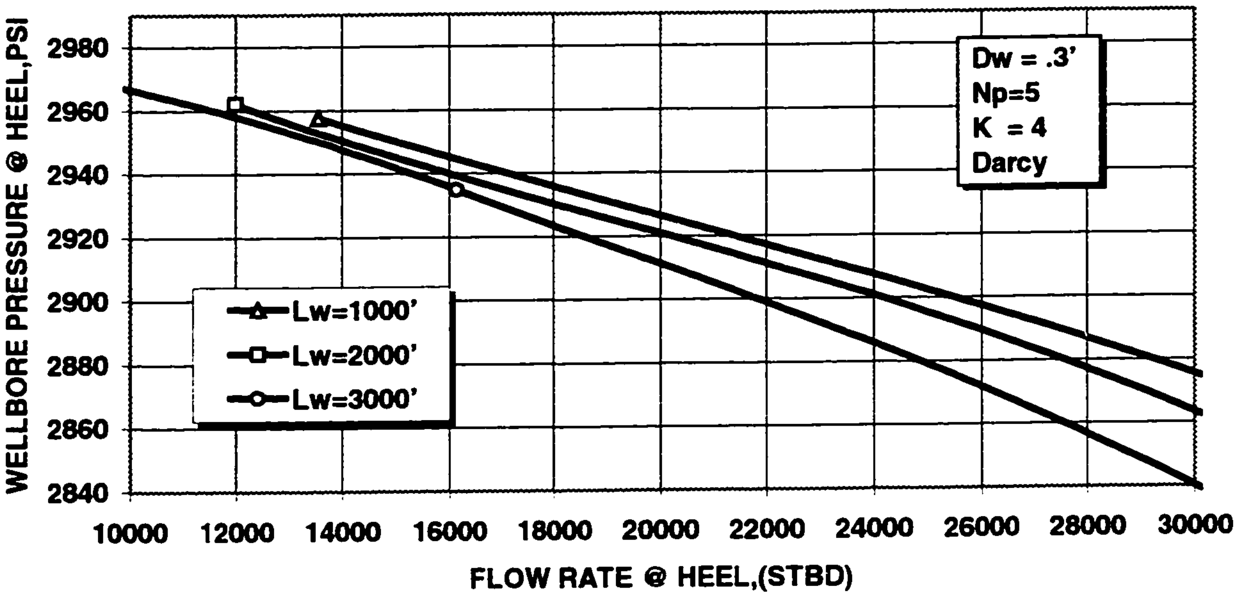


Fig. 31 Effect of horizontal section Length on Production Rate, Dw=.3'

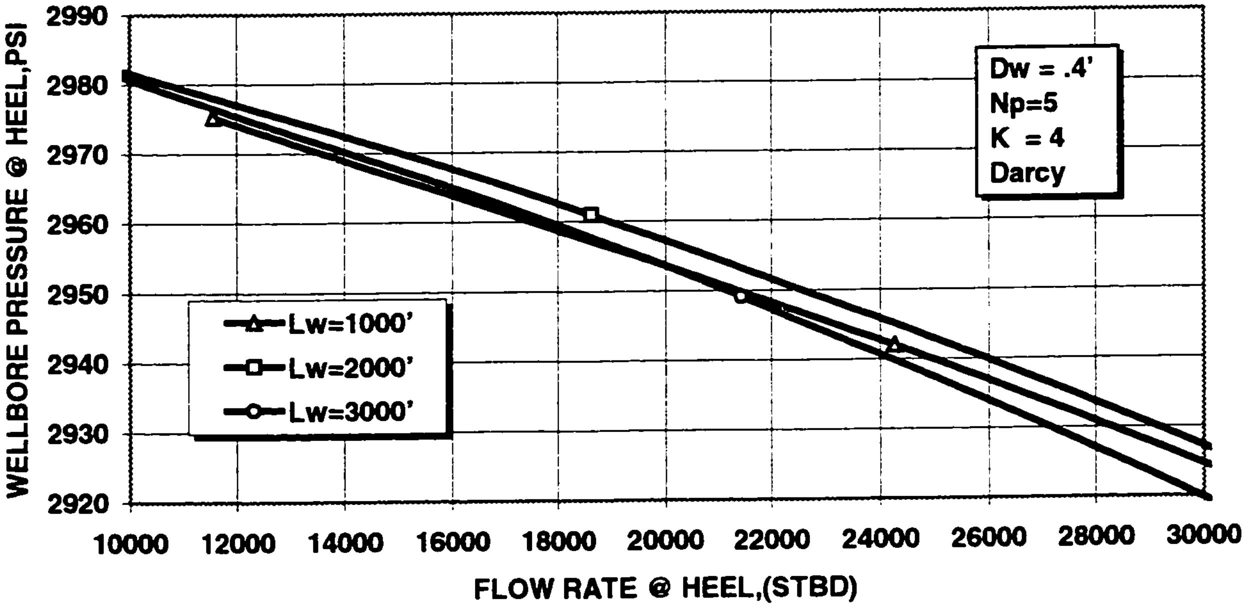


Fig. 32 Effect of horizontal section Length on Production Rate, Dw=.4'

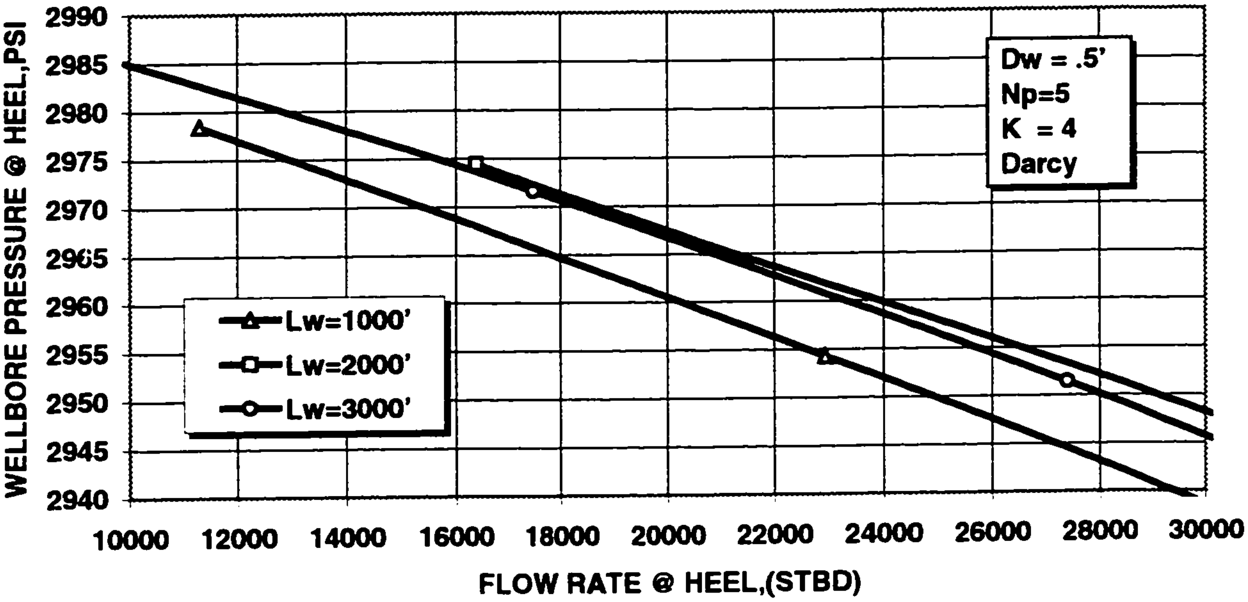


Fig. 33 Effect of horizontal section Length on Production Rate, Dw=.5'

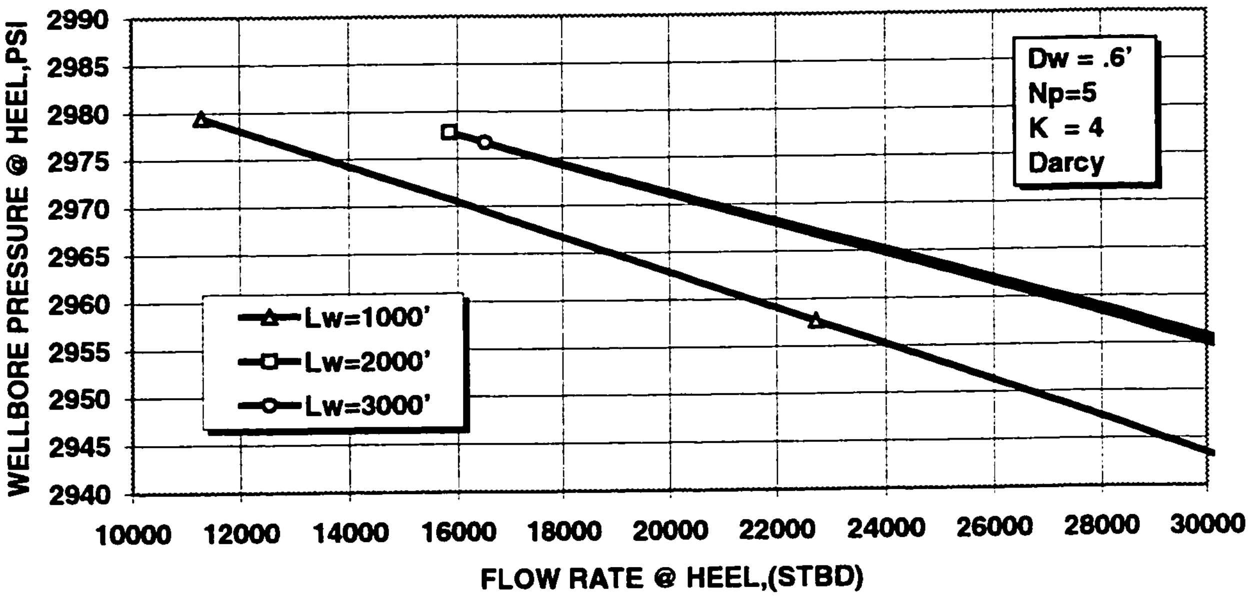


Fig. 34 Effect of horizontal section Length on Production Rate, Dw=.6'

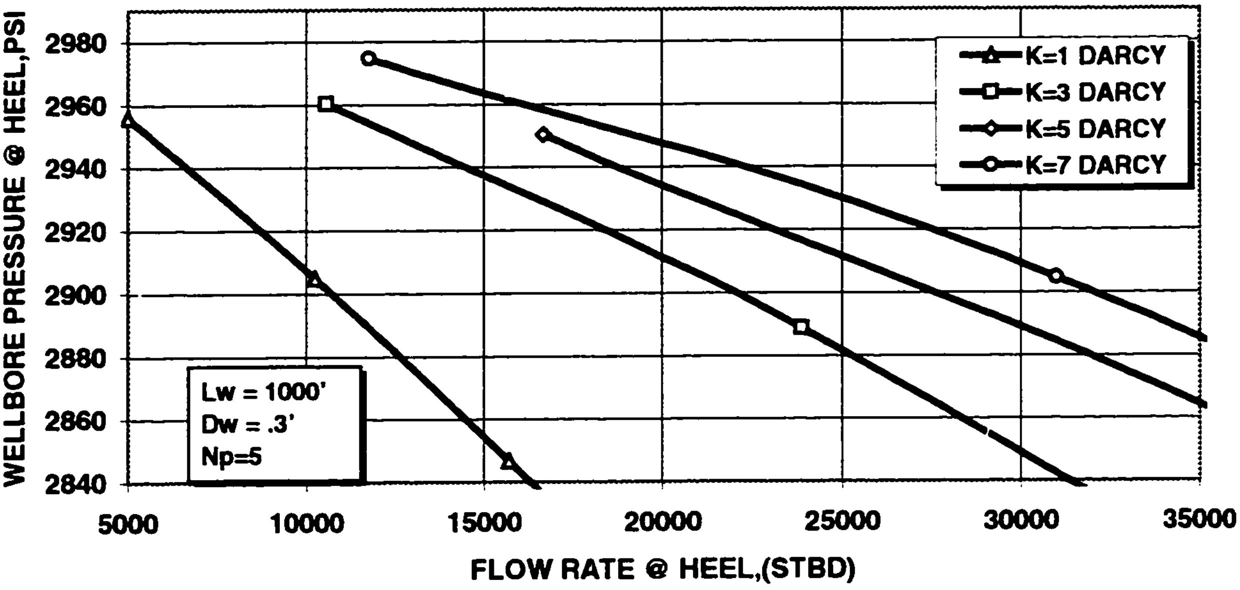


Fig. 35 Effect of permeability on Production Rate, Lw=1000', Dw=.3'

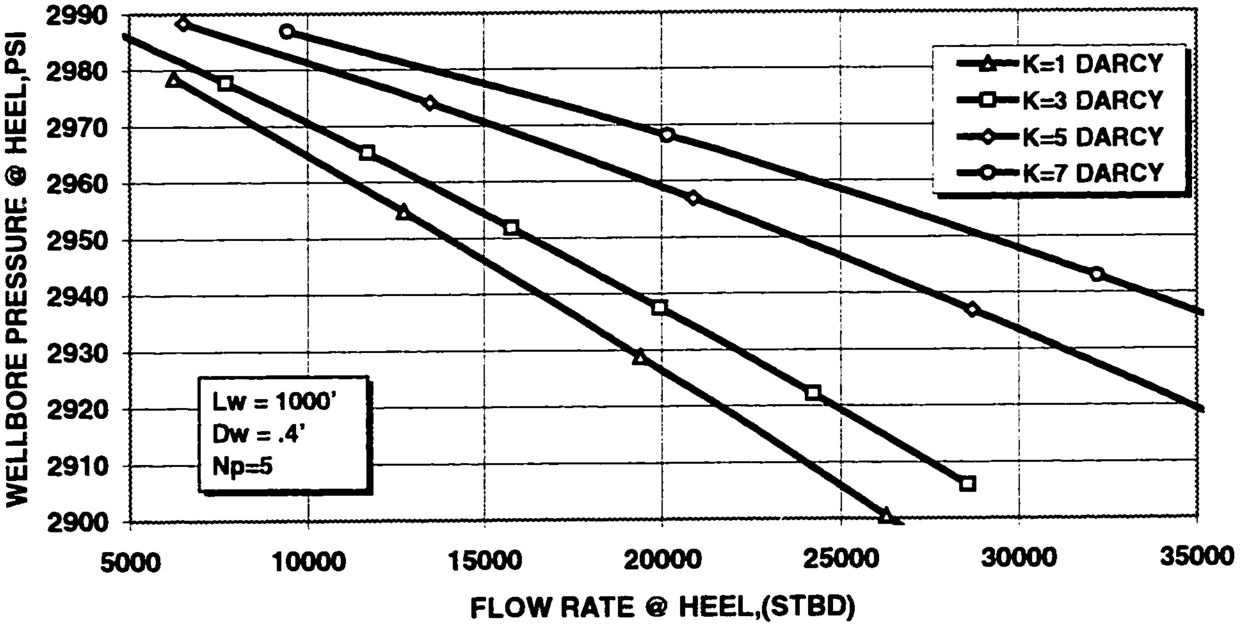


Fig. 36 Effect of permeability on Production Rate, Lw=1000', Dw=.4'

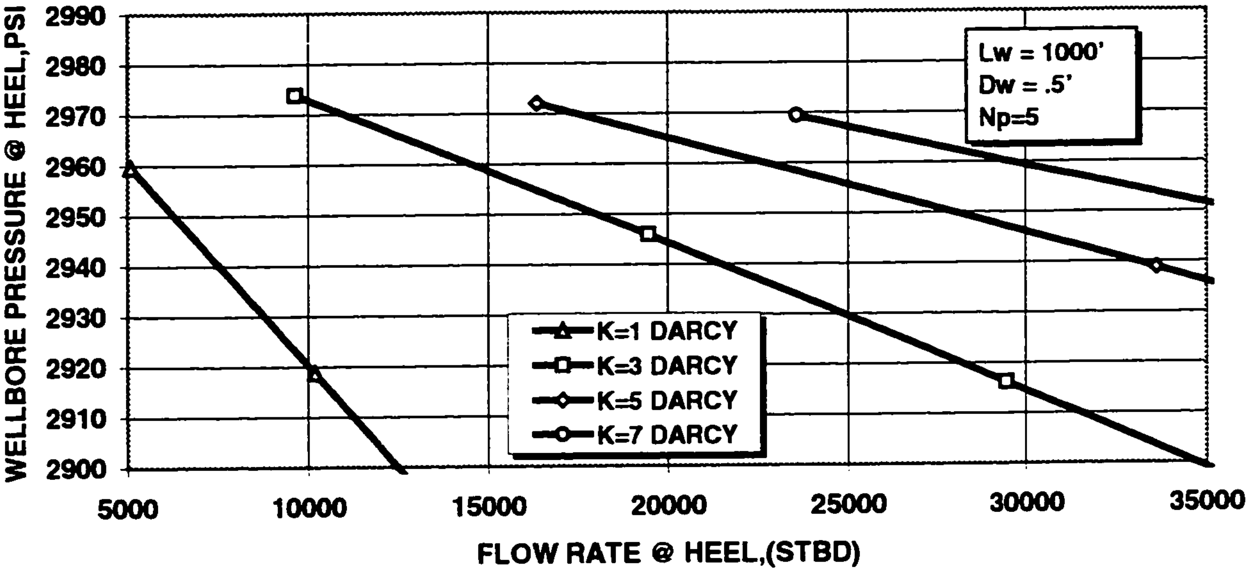


Fig. 37 Effect of permeability on Production Rate, Lw=1000', Dw=.5'

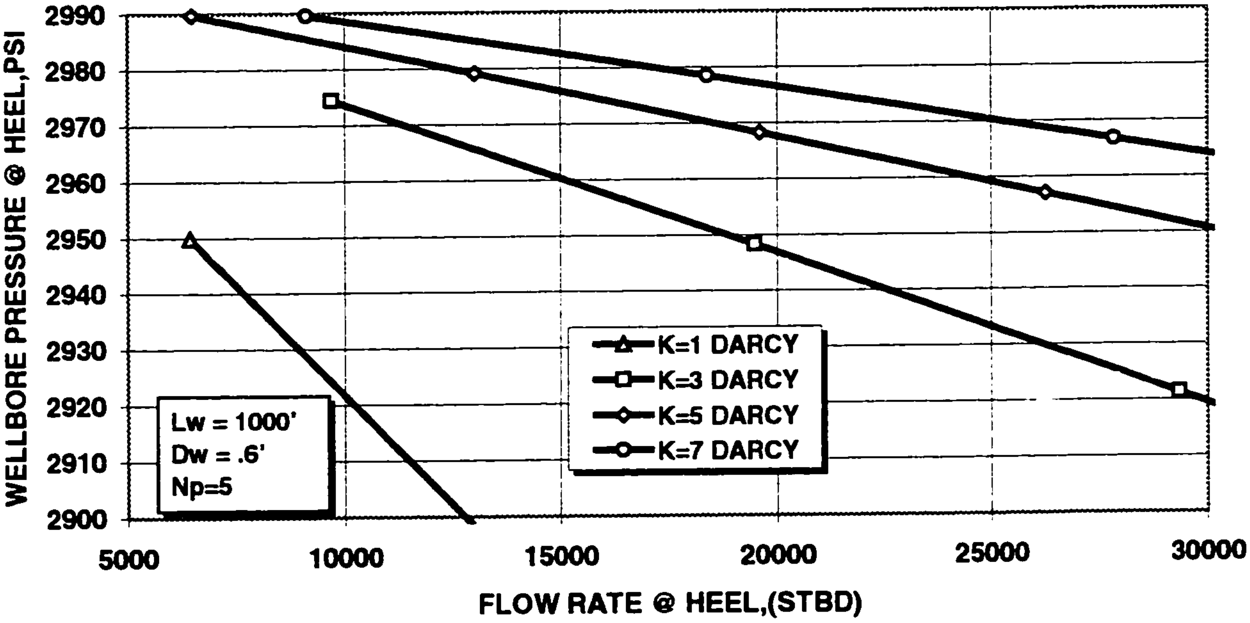


Fig. 38 Effect of permeability on Production Rate, Lw=1000', Dw=.6'

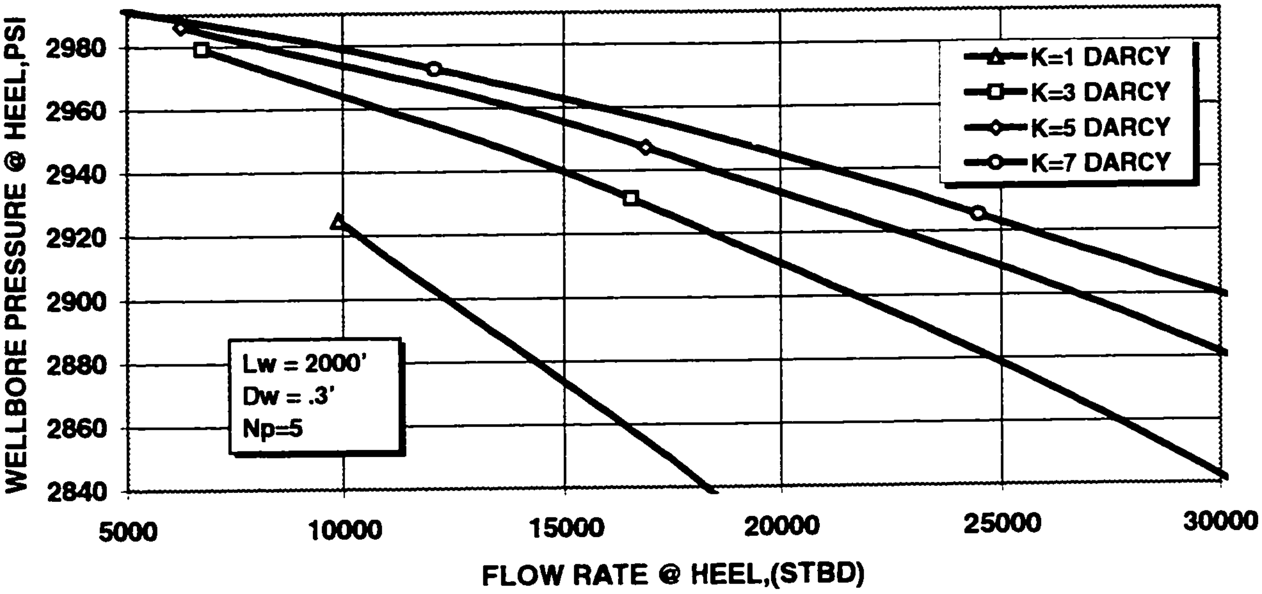


Fig. 39 Effect of permeability on Production Rate, Lw=2000', Dw=.3'

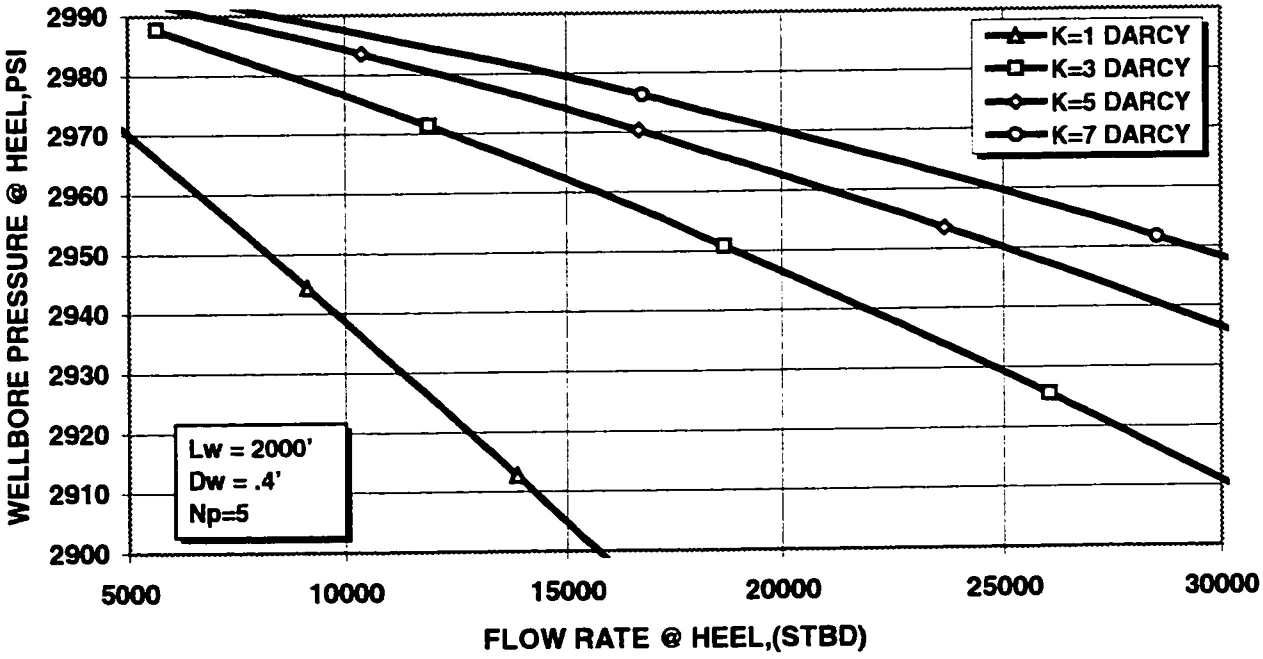


Fig. 40 Effect of permeability on Production Rate, Lw=2000', Dw=.4'

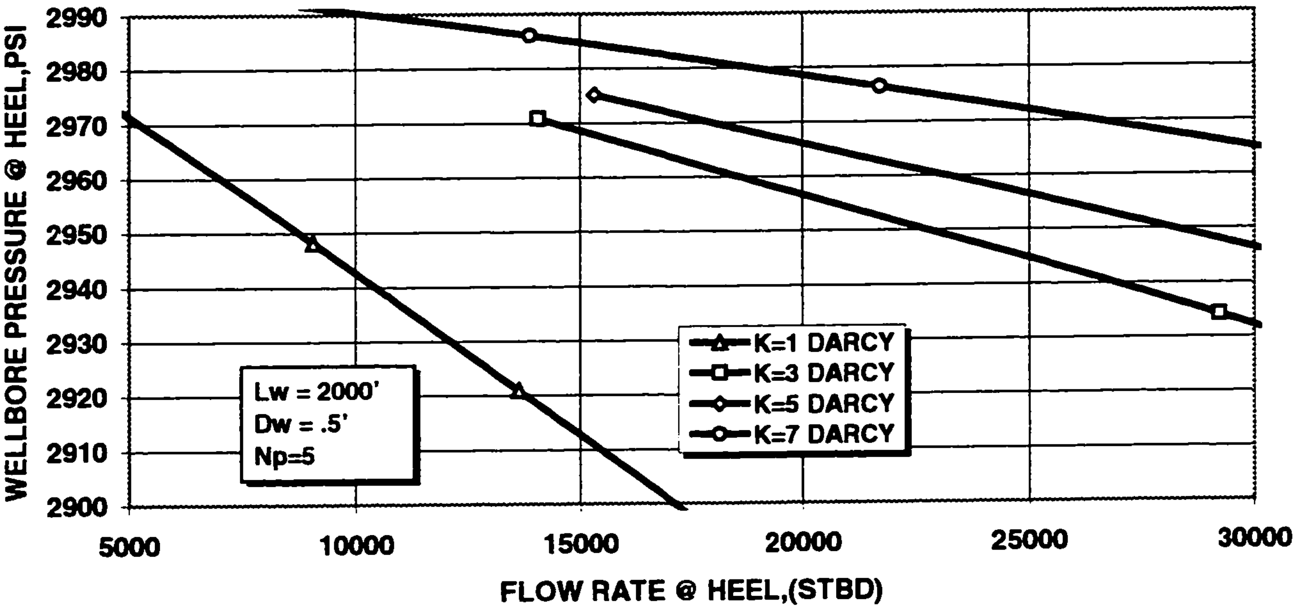


Fig. 41 Effect of permeability on Production Rate, Lw=2000', Dw=.5'

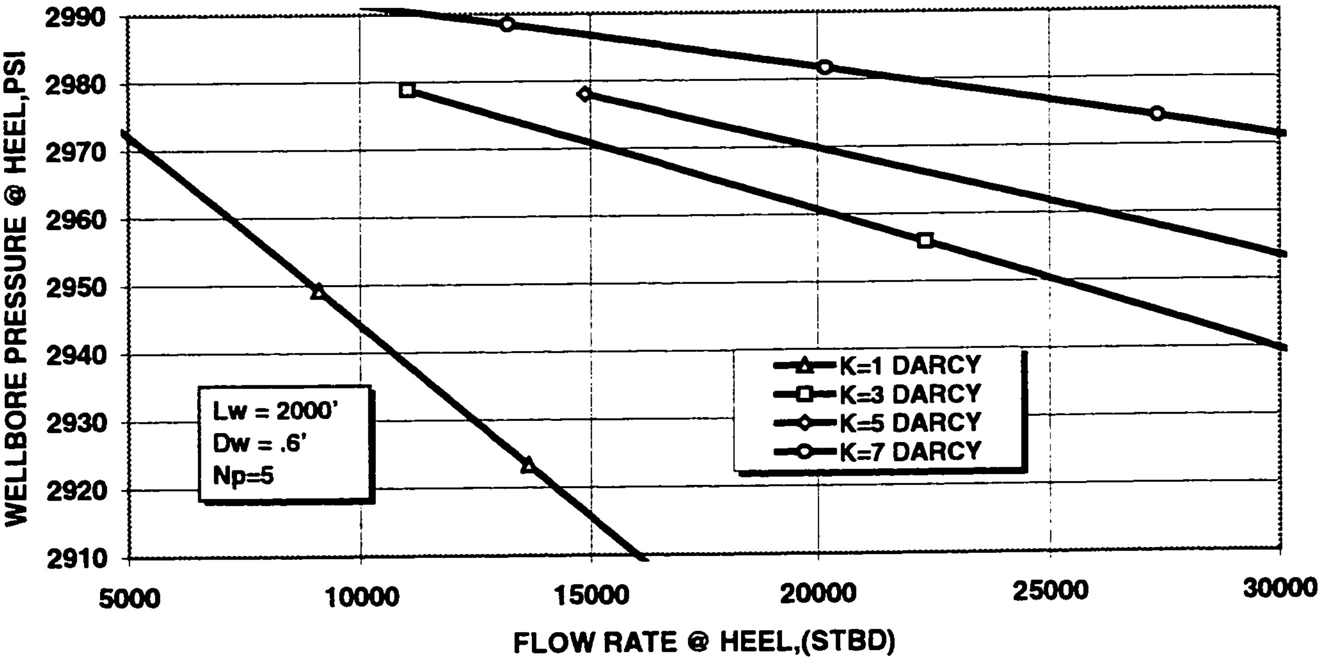


Fig. 42 Effect of permeability on Production Rate, Lw=2000', Dw=.6'

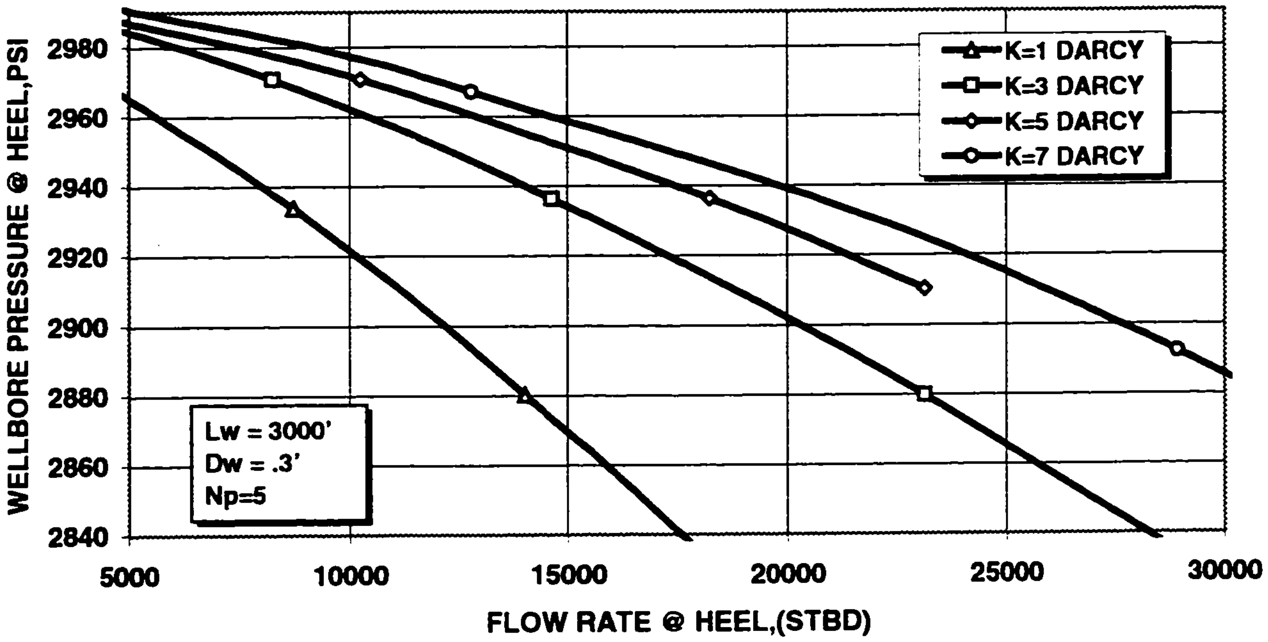


Fig. 43 Effect of permeability on Production Rate, Lw=3000', Dw=.3'

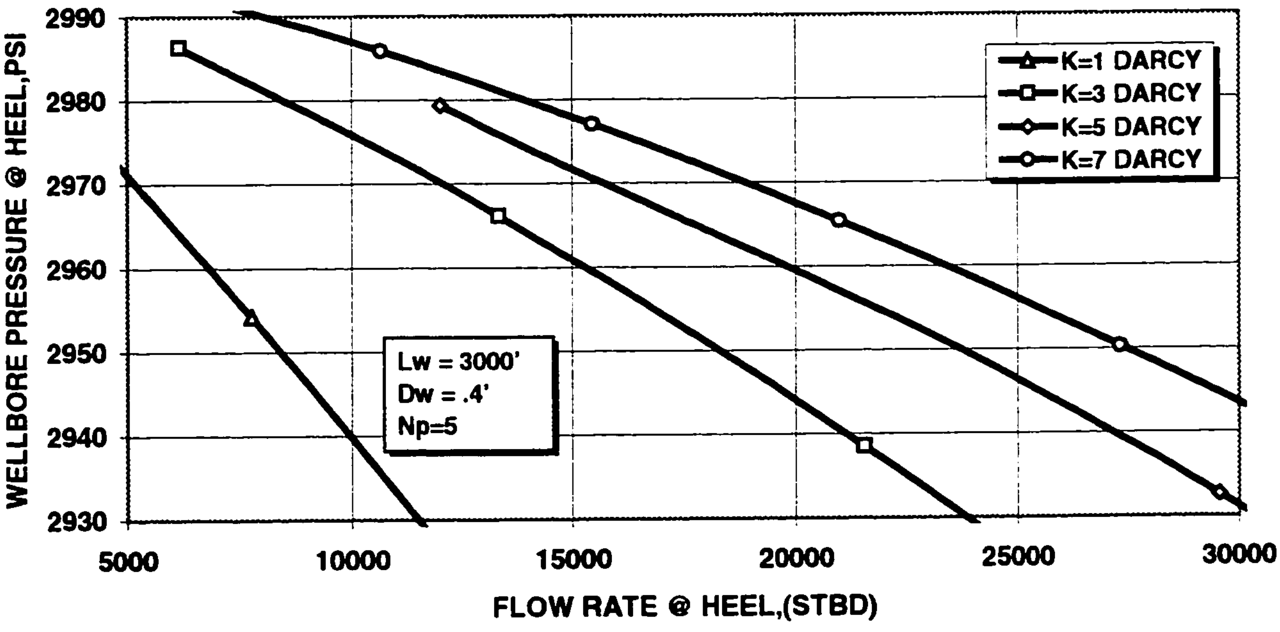


Fig. 44 Effect of permeability on Production Rate, Lw=3000', Dw=.4'

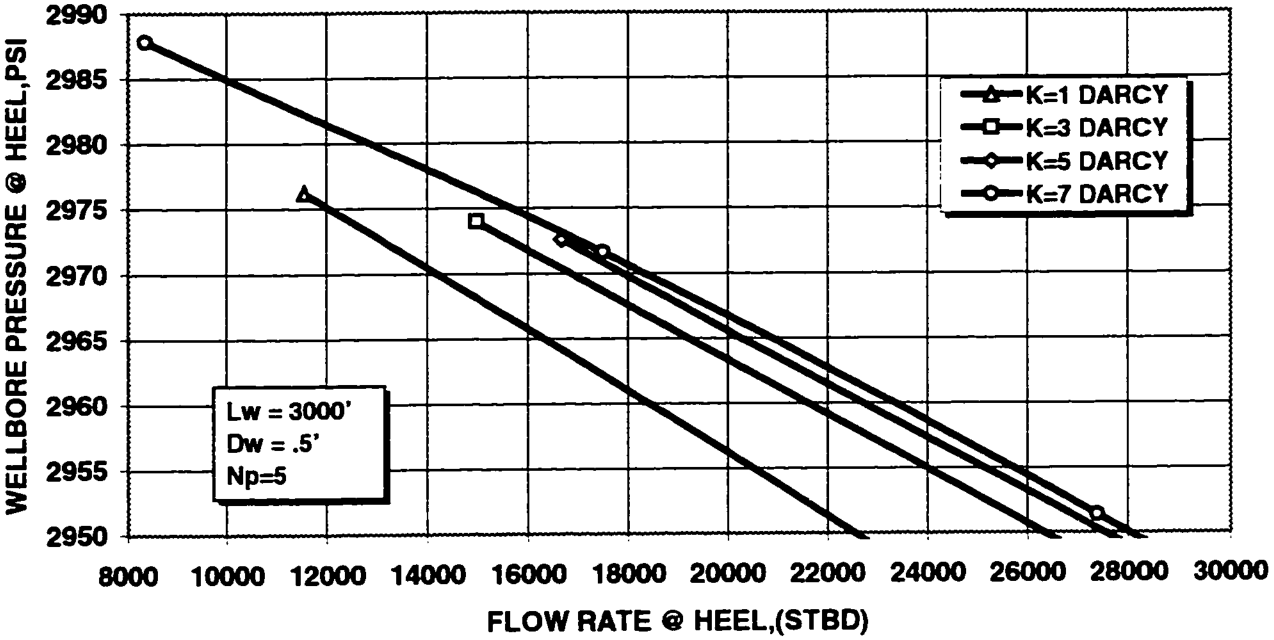


Fig. 45 Effect of permeability on Production Rate, Lw=3000', Dw=.5'

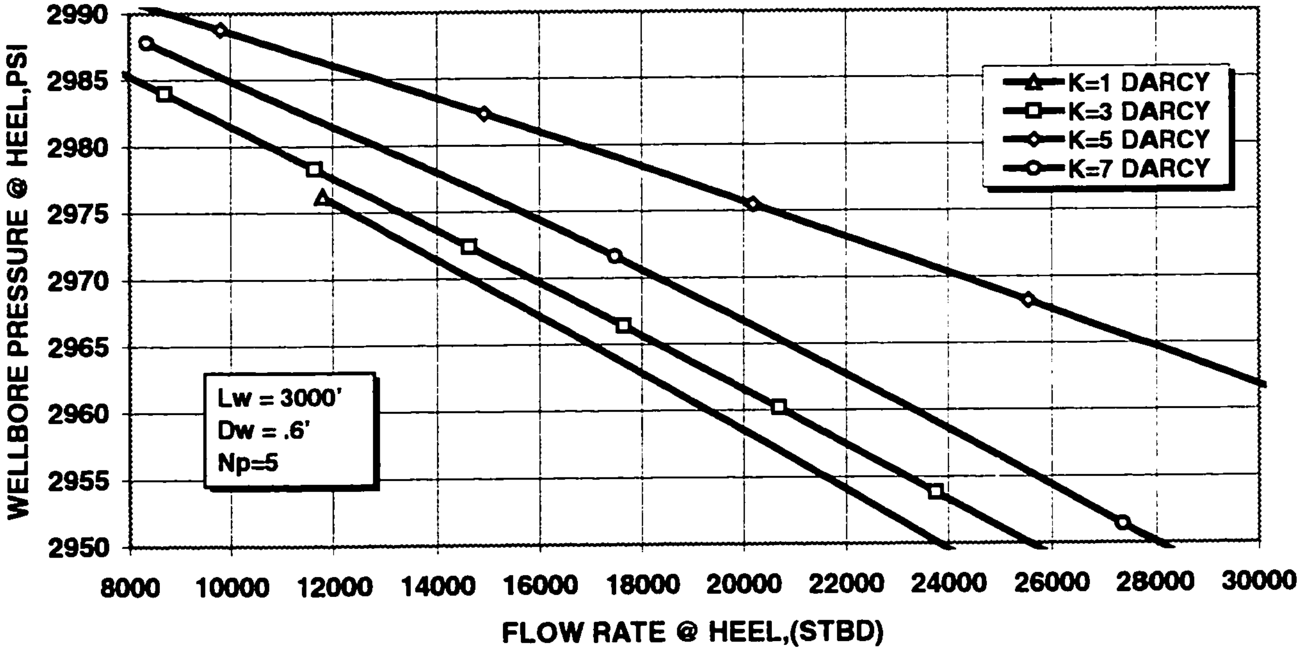


Fig. 46 Effect of permeability on Production Rate, Lw=3000', Dw=.6'

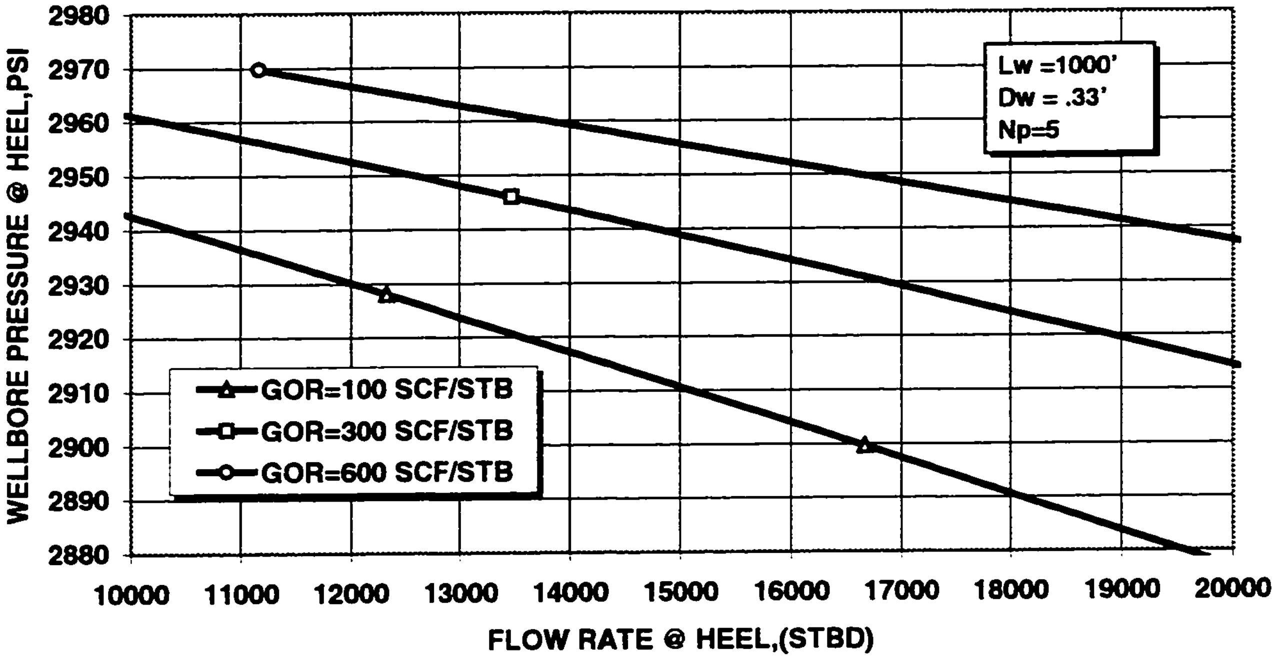


Fig. 47 Effect of solution GOR on Production Rate, Lw=1000', Dw=.33'

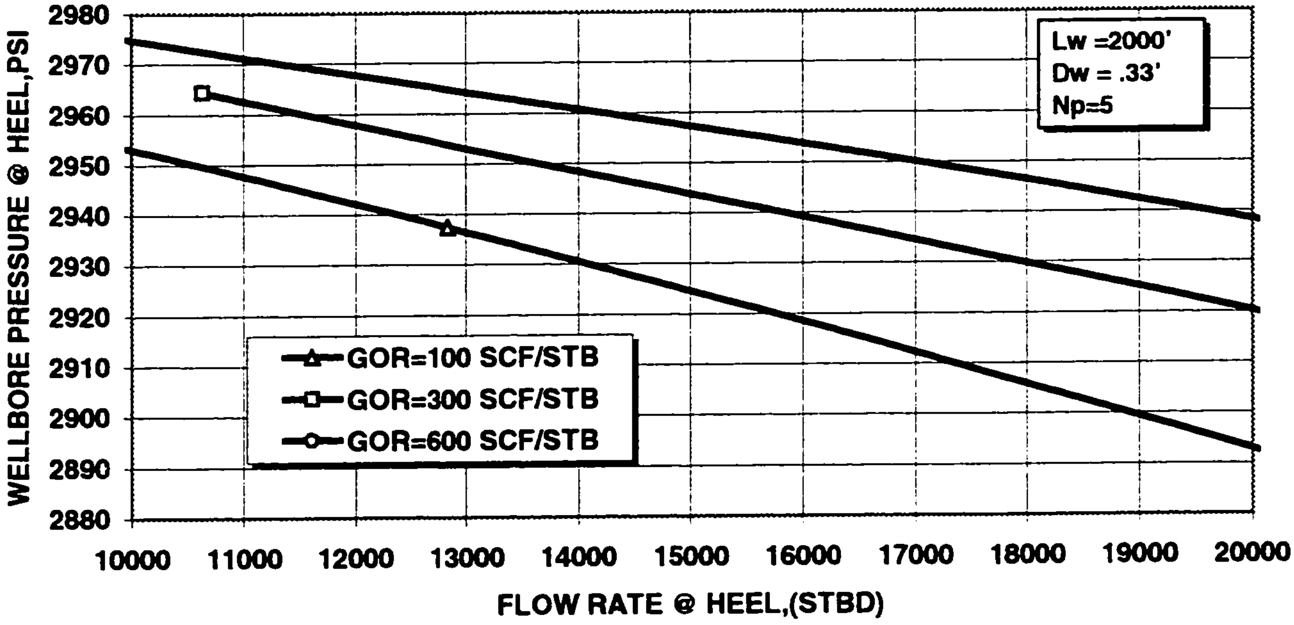


Fig. 48 Effect of solution GOR on Production Rate, Lw=2000', Dw=.33'

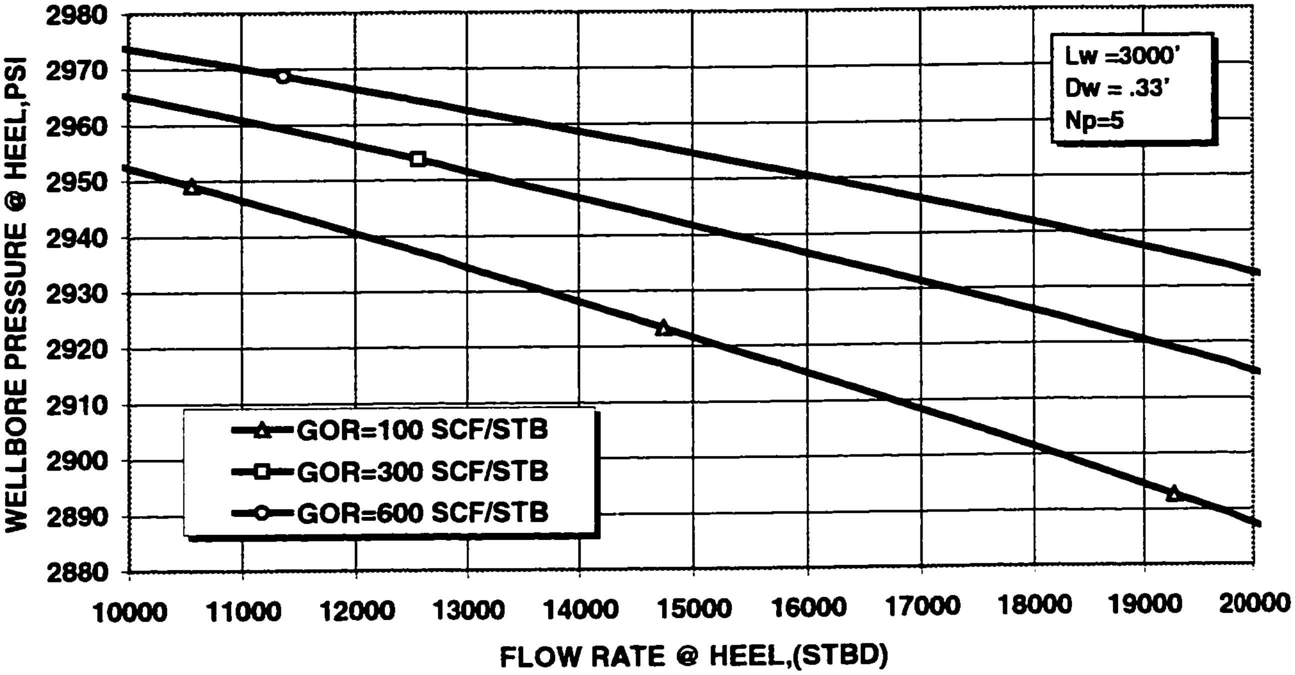


Fig. 49 Effect of solution GOR on Production Rat, Lw=3000', Dw=.33'

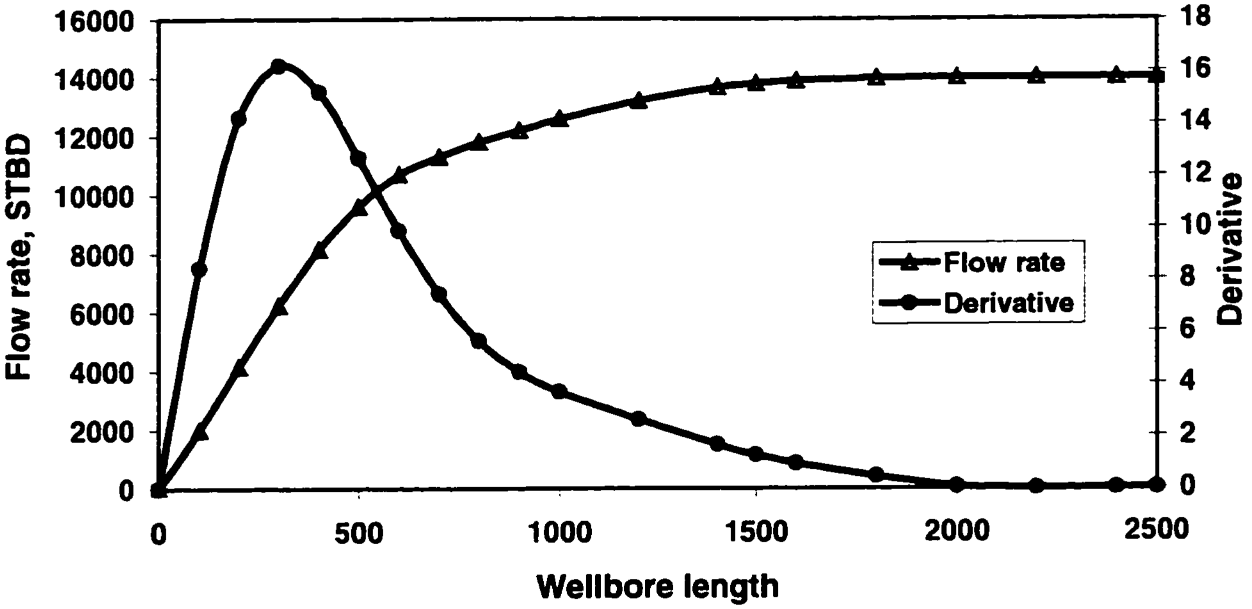


Fig. 50 Optimum horizontal section length determination

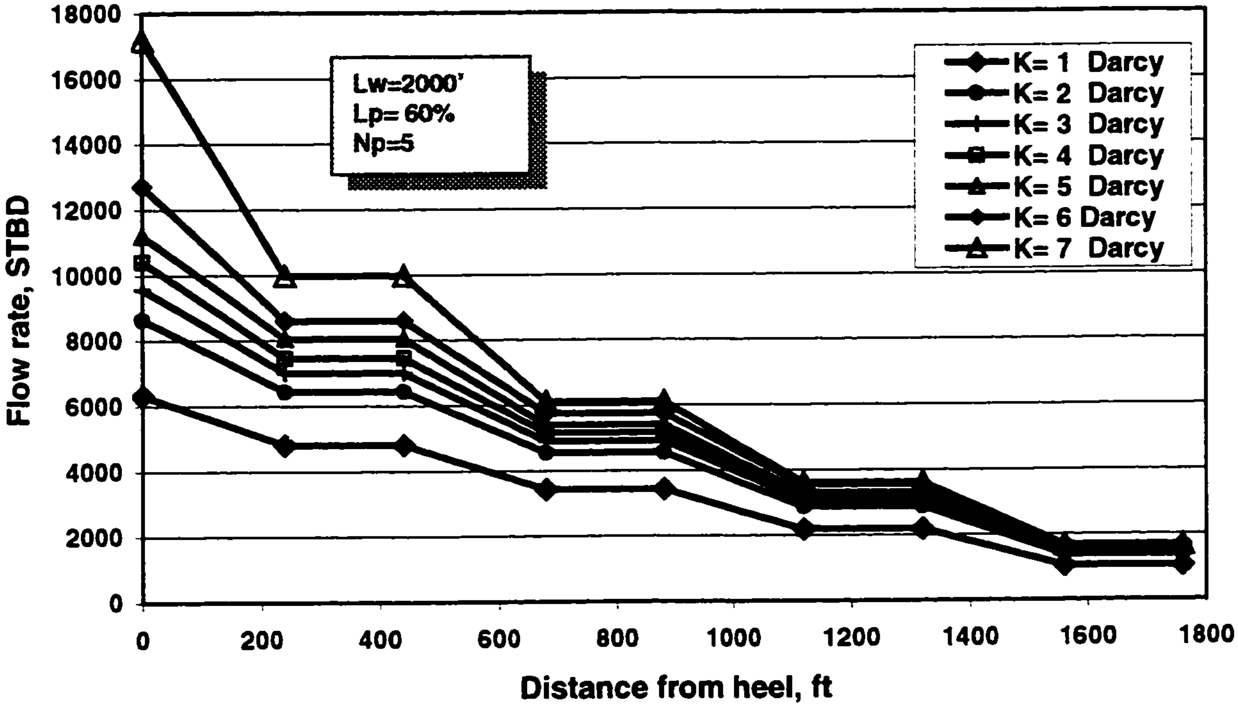


Fig. 51 Effect of permeability on horizontal well production rate

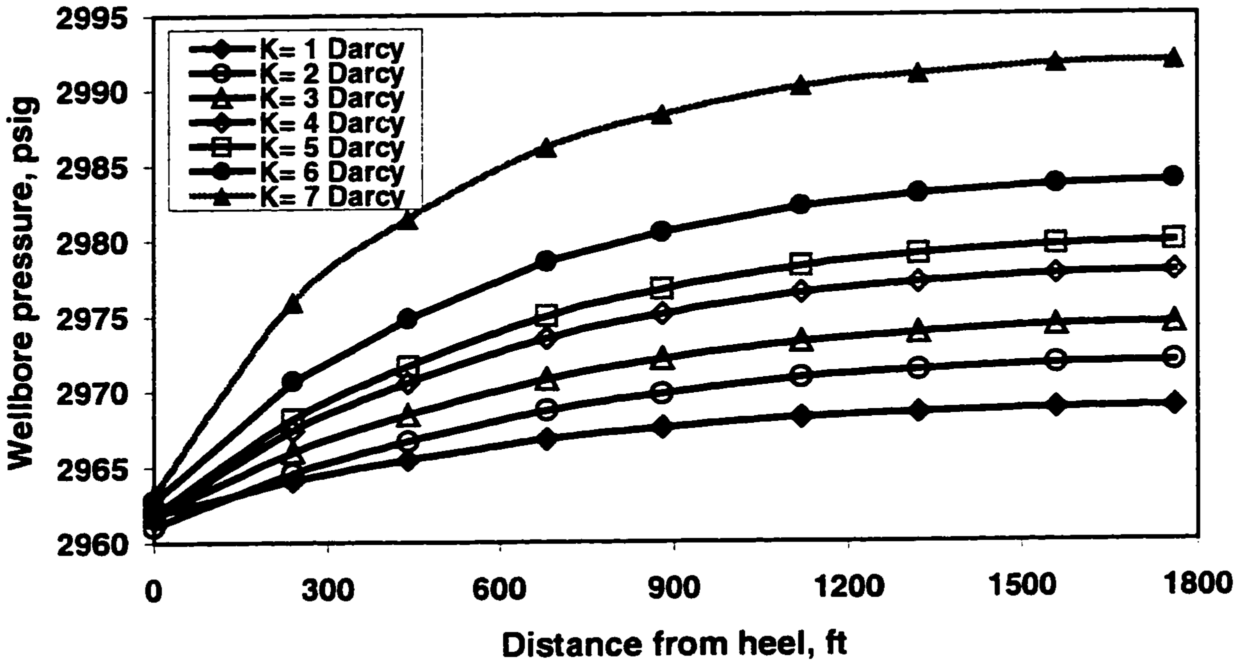


Fig. 52 Effect of permeability on wellbore pressure profile

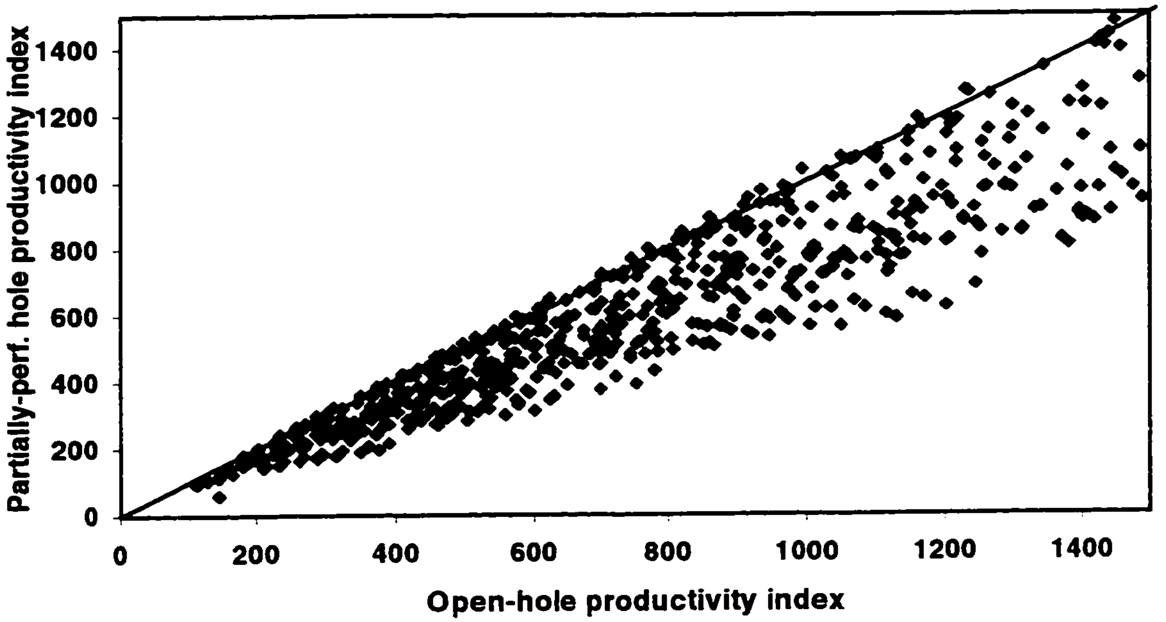


Fig. 53 Comparison of of perforated and openhole productivity

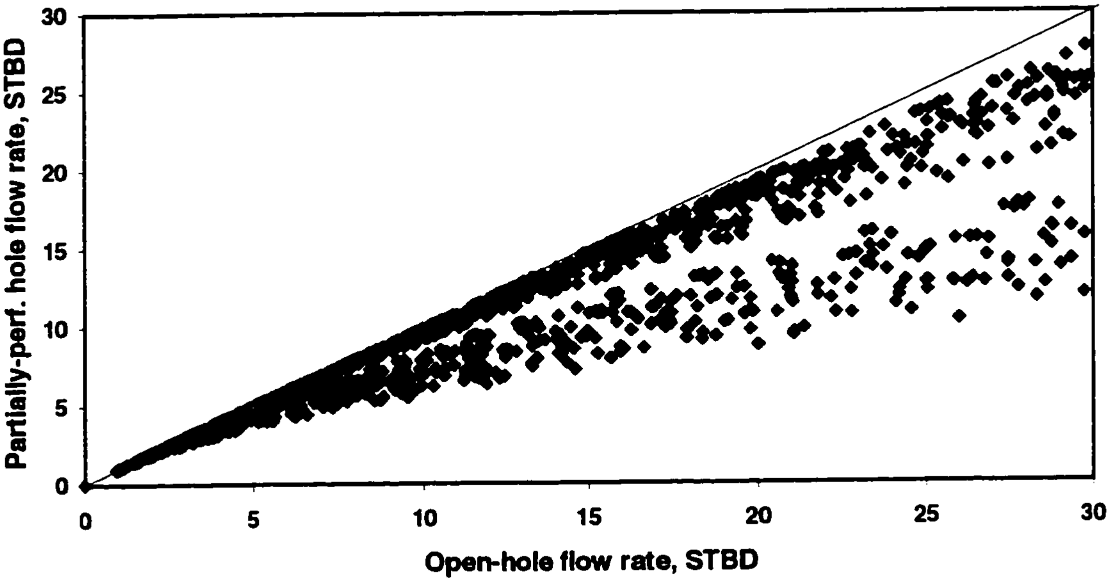


Fig. 54 A comparison of perforated and open-hole production rate

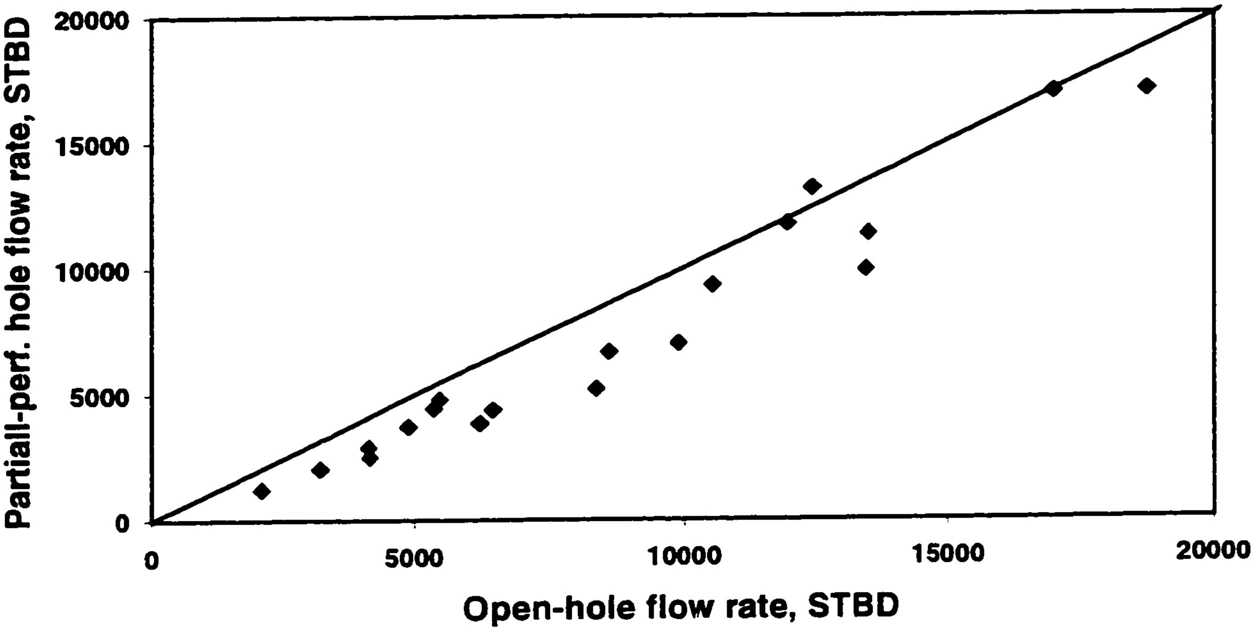


Fig. 55 Comparison of correlated and calculated flow rates.

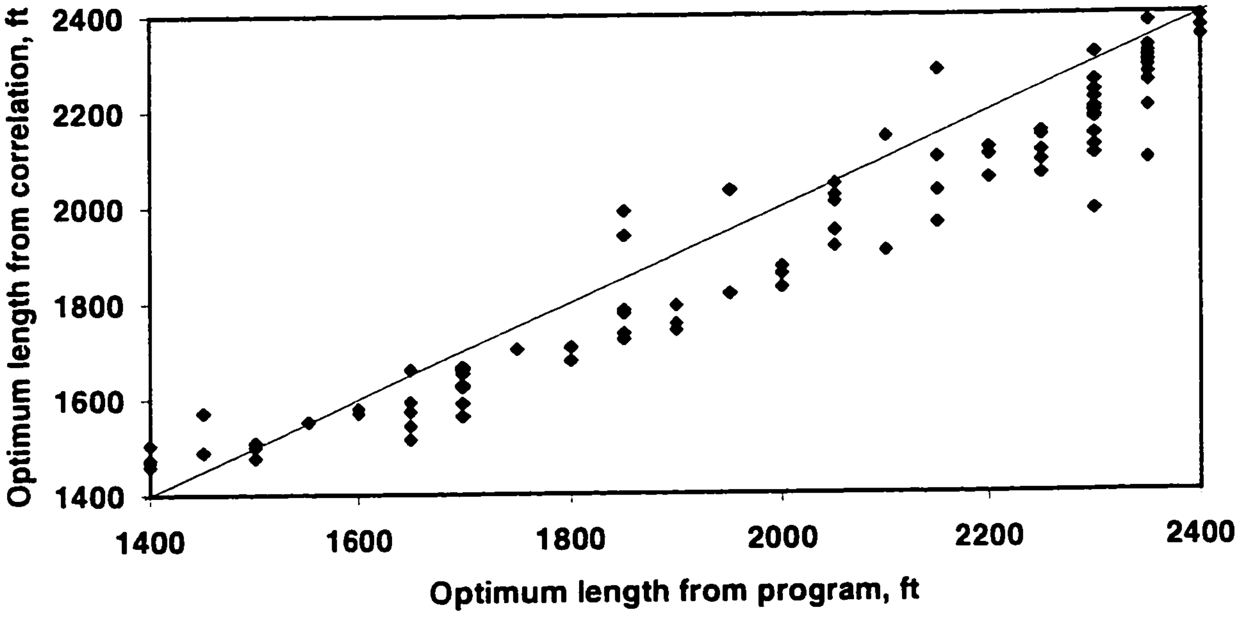
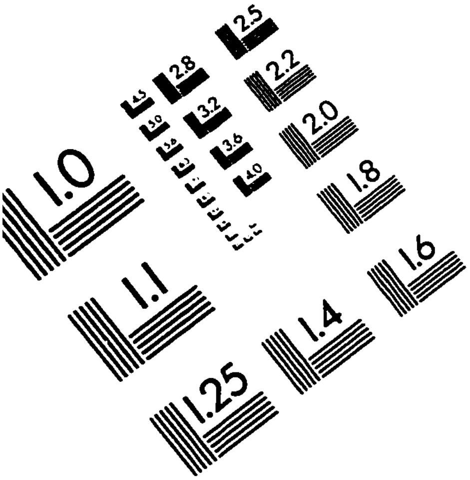
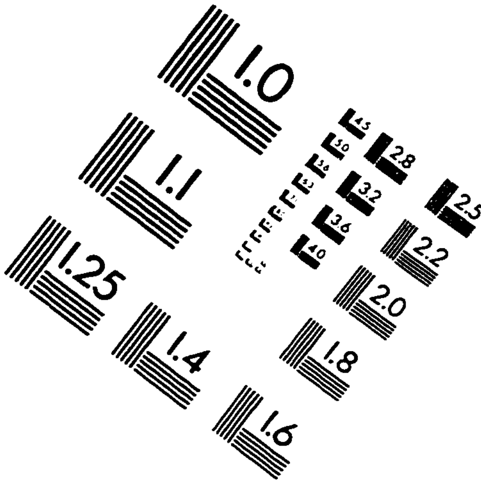
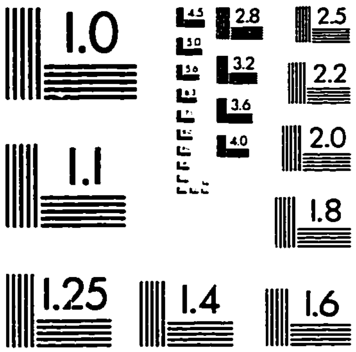


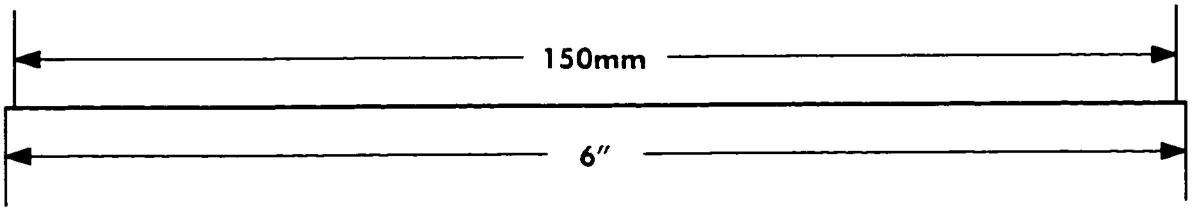
Fig. 56 Comparison of correlated and calculated optimum horizontal section length

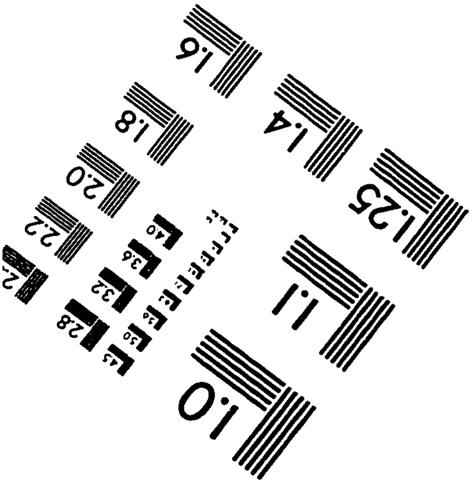
IMAGE EVALUATION TEST TARGET (QA-3)

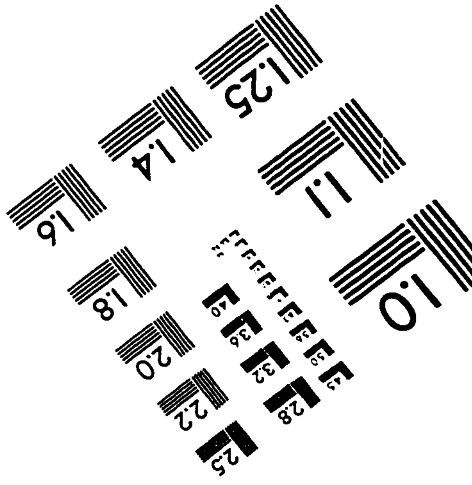












APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989