A Parametric Study of Water-Coning in Horizontal Wells

by

Ali Abbas Hakim

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

November, 1994

A Parametric Study of Water-Coning in Horizontal Wells

BY

ALI ABBAS HAKIM

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

November 1994

UMI Number: 1361063

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA

COLLEGE OF GRADUATE STUDIES

This thesis, written by **Mr. Ali Abbas Hakim** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, 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

M.A. Marhoun

Dr. Muhammad A. Al-Marhoun
Member

H.Y. Al-Yousef

Dr. Hasan Y. Al-Yousef
Member

Dr. Khalid A. Al-Fossail
Department Chairman

Jan. 15, 1995

Dr. Ala H. Al-Rabeh
Dean, College of Graduate Studies

DEDICATED TO MY PARENTS AND SISTER

ACKNOWLEDGEMENTS

I wish to express my deep gratitude and thanks to Dr. Habib Menouar, Chairman of the thesis committee, for providing assistance throughout the thesis work. I treasure his incessant patience and guidance.

I also wish to convey my admiration to Dr. Muhammad Al Marhoun and Dr. Hasan Al Yousuf, members of my thesis committee, for reading the final draft of the thesis most thoroughly and suggesting numerous improvements in substance and style.

My earnest acknowledgements to Dr. Abdul Aziz Al Kaabi for allowing me to use the computer facilities in his section in the Research Institute. Without his support this work would not have been possible. I shall not forget to praise Dr. Joseph Olarewaju in the section for all the invaluable time he spent on my problems at the workstation. My profound thanks to all the faculty and staff of the department for their cooperation and moral support throughout my stay. Finally, I wish to thank the Department of Petroleum Engineering for providing me with scholarship support to pursue graduate studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT (ARABIC)

خلاصة الرسالة

إسم الطالب : علـــي عبــاس حكيـــم

عنوان الدراسة : دراسة العوامل المؤثرة على تدفق الماء بشكل مخرطي في الأبار الأفقية

التخصص : هندسة البترول

تاريخ الدرجة : نوفمبر ١٩٩٤ م

تنتمي هذه الدراسة إلى إندفاع الماء بشكل مخروطي في الآبار الأفقية . وتم إقتراح ملاحظة (متابعة) الحد الفاصل بين الماء والزيت كأساس لتقدير معدل الأنتاج الحرج . ومن أجل هذا الغرض تمت محاكاة أحد الخزانات عددياً لمراقبة حركة الحد الفاصل بين الماء والزيت عند تغيير بعض العوامل المؤثرة عليه . وبأستخدام هذه الطريقة تمت دراسة تأثير بعض العوامل مثل نسبة التباين (المتغير) في الخواص ، طول البئر ، مكان البئر بالأضافة إلى نسبة حركة السوائل وكذلك العلامات بين تلك العوامل ومعدل التدفق الحرج . وقد أظهرت نتائج هذه الدراسة توافق مع الأبحاث الموجودة بالمراجع العلمية .

ABSTRACT

Name of Student : Ali Abbas Hakim

Title of the Study : A PARAMETRIC STUDY OF WATER CRESTING IN HORIZONTAL WELLS

Major Field : PETROLEUM ENGINEERING

Date of Degree : November 1994

The present work is related to water cresting in horizontal wells. A critical rate estimation method based on the observation of the water/oil interface is suggested. For this purpose, a prototype reservoir is simulated numerically to monitor the water/oil interface movement when some relevant parameters are changed. Applying this method, the effect of anisotropy ratio, well length, well position and mobility ratio has been studied and relations between the critical rate and these parameters are presented. The results compare favorably with the work available in the literature.

CHAPTER 1

INTRODUCTION

In the last few years many horizontal wells have been drilled around the world. The primary purpose of drilling a horizontal well is to enhance reservoir contact by virtue of its length and in this manner improve the productivity of the well.

A vertical well is defined as a well drilled perpendicular to the reservoir bedding plane. Therefore, a horizontal well is one that is drilled parallel to the bedding plane. The most commonly cited advantages of horizontal wells include reduction in coning (gas or water) and viscous fingering, improved sweep efficiency, increased productivity or injectivity and increased drainage area. Some disadvantages associated with horizontal wells are high cost, difficulty in logging, stimulation and selective perforation, limited recompletion alternatives for high gas or water rates and limitation of vertical sweep efficiency due to permeability barriers.

Oil production through a horizontal well causes the water-oil interface to deform into a crest. As production rate is increased, the height of the water crest also increases until the rate reaches a critical rate, at which the crest becomes unstable and water flows into the well. This is called 2-phase interface coning.

Water coning is a serious problem in many oil field operations, significantly reducing oil production. Producing oil at a water cut higher than necessary is always a difficult task for practicing engineers. The existence of a critical rate above which excessive water production occurs has been studied earlier by many researchers. It is important to minimize or at least delay coning. Coning is induced by a certain type of pressure distribution in the reservoir. For example, a vertical well producing at a substantial rate, exhibits a large pressure drawdown in the vicinity of the well-bore which results in coning. In horizontal wells, coning is mitigated by virtue of reduction in pressure drawdown. This may result in low production rate per unit length. However the low oil production rate per unit length is more than compensated by the long length of the horizontal well. The maximum production rate for a displacement with stable water cone is termed critical rate. Critical rate is therefore the rate above which water cone becomes unstable and water breakthrough occurs impromptu.

CHAPTER 2

OBJECTIVES OF THE STUDY

Since the pioneering studies carried out by Muskat [1] and Dietz [2], numerous papers have been published on critical rate studies. Some of these were based on laboratory experiments, while others were derived analytically. Both approaches have limitations in the sense that they neglect the following reservoir and fluid flow aspects:

1. permeability variations and layering
2. relative permeability and capillary pressure effects
3. properties of the aquifer and gas cap
4. interference from neighbouring wells and boundaries
5. after-breakthrough production.

To account for the above effects and then calculate the after breakthrough performance, it is more convenient to use a numerical simulator. Present day reservoir simulation is becoming a valuable tool that if properly used, allows the petroleum engineer to gain greater insight into the mechanism of oil displacement by water.

In the present work a method of estimation of the critical rate based on the observation of the water/oil interface is presented. Since the water/oil interface is obtained from the saturation distribution, this work is carried out using numerical simulation. A commercial simulator, ECLIPSE, is used for this purpose. The sensitivity of the critical rate to the length of horizontal wells, the anisotropy ratio, the reservoir geometry, and the mobility ratio will be studied.

CHAPTER 3

LITERATURE SURVEY

A literature survey of published material related to water coning in vertical and horizontal wells is presented in this chapter with emphasis on research studies related to the critical rate.

3.1 EFFECT OF LENGTH

The effect of horizontal well length on water coning behavior has been studied by numerous authors in the last 5-6 years. The research work carried out to date has been either based on theoretical formulations or numerical simulation by carrying out a parametric study.

3.1.1 Simulation Study by Kossack and Kleppe

Kossack and Kleppe [3] made a simulation study of oil production from Troll Field in the North Sea. They compared the performance of horizontal wells with that of vertical wells. The most significant result observed was that a 1500ft. horizontal well would produce the same amount of oil as two vertical wells in a typical sector pattern and a 2000ft. horizontal well would perform even better than three vertical wells. A circular drainage area of radius 5000ft. was divided in sectors of 30°, 45°, 60° and 90°. Results of a sensitivity study of the length of horizontal well are shown in Figure 3.1. The *time to shut in* is the time the well produces before shut-in is necessary due to high water-cut.

3.1.2 Work of Butler

In his historical paper, Butler [4], presented a simplified and simple relation between horizontal and vertical critical rates:

$$\frac{q_{hc}}{q_{vc}} = \frac{4L}{S} \tag{3.1}$$

It shows that the ratio of horizontal well critical rate to vertical well critical rate is equal to four times the ratio of length, L, of the horizontal well and the spacing, S, between parallel horizontal wells. It is clear that a length equal to one quarter of the spacing between parallel horizontal wells has the same critical rate as a vertical well. It also shows that critical rates in horizontal wells are proportional to the length of the horizontal wells.

3.1.3 Seventh SPE Comparative Solution Project

In this remarkable project in which fourteen organisations took part with their own simulators, the effect of varying the rates and lengths of the horizontal wells upon recovery of oil from reservoirs where coning is important was studied [5]. They all consistently predicted a decrease in coning behavior with an increase in well length. It would be worth while to mention that the group also included the effect of well-bore hydraulics in their study. They found that its' effect is more pronounced in high permeability reservoirs than in low permeability reservoirs. An important parameter considered in well-bore hydraulics was the pressure drop along the length of the horizontal wells.

3.1.4 Study of Horizontal wells in Helder Field

Zagalai and Murphy [6] carried out simulation of horizontal wells in the Helder Field which is underlain by a water aquifer and has a very high and unfavorable mobility ratio. The effect of well length on performance was investigated by the use of a drainage area of 60 acres (2600*1000 sq.ft.). Figure 3.2 shows cumulative oil production and water-cut versus cumulative gross production for well lengths of 500ft., 1000ft., 1500ft., 2000ft. and for a vertical well.

It can be observed that a 500ft. horizontal well recovers 18% more oil than a vertical well. Increasing well length to 1500ft. increases incremental recovery over vertical well to 33%. However beyond 1500ft. increase in length produces diminishing benefits. This is due to the fact that as length increases the length of the non-penetrated section of the reservoir decreases and the relative oil flux from the edges towards the ends of the horizontal well decreases. It was found that optimum length for horizontal well is 60% of the length of the drainage area.

3.1.5 Parametric Study by Wang

Ben Wang [7] carried out a parametric study of the gas and water coning in vertical and horizontal wells. Figures 3.3, 3.4 and 3.5 illustrate the effect of well length on coning. Figure 3.5 is the GOR curve for a 50ft. gas cap (no aquifer) reservoir with a horizontal well whose length varies from 200ft. to 4000ft. The well is located 35ft. below the GOC. The vertical well is perforated 32.5ft. to 37.5ft. below the GOC. It is evident from these figures that the longer the well the lower the GOR. The breakthrough time increases from 5 days to 229 days as well length increases from 200ft. to 4000ft. The plot of recovery factor versus well length shows that at 6000 days recovery increases rapidly from 4.1% to 14.1%. The increase is linear for horizontal wells. However, it was shown that short horizontal wells (around 200ft.) are not successful in effectively reducing coning. The water coning effect is shown in Figure 3.4 for a 300ft. bottom water drive reservoir (no gas cap). Again it is observed that longer horizontal wells give delayed breakthrough and lower water cut. The economic recovery also increases linearly with the well-length. For simultaneous gas-water coning a gas cap of 50ft. and bottom aquifer of 300ft. were taken. The same linear trend is observed in economic recovery as shown in Figure 3.5.

3.1.6 Parametric Study by Yang and Wattenbarger

Yang and Wattenbarger [8] gave a correlation to predict critical rate, breakthrough time and WOR after breakthrough for both vertical and horizontal wells. It was found that the height between the WOC and horizontal well, h_{wb}, at which water breakthrough occurs decreases with increase in well length. Therefore, longer horizontal wells give higher WOC displacement prior to water breakthrough.

3.1.7 Study of thin oil zones by Haug

Haug et al. [9] studied the effect of locating the horizontal in water zone for producing from thin oil zones underlain by an aquifer and overlain by a gas cap. They developed a correlation for gas break through time (GBT). It was found that GBT is directly proportional to $L^{2.5}$ where L is horizontal well length.

3.1.8 Work of Suprunowicz and Butler

Suprunowicz and Butler [10] studied productivity and pattern dimensions for optimum draining of a reservoir. They came up with very simple relationships. A dimensionless pressure drawdown was defined for drainage areas less than $35L^2$ as follows:

$$P^* = \ln \frac{1 + \frac{A}{L^2}}{12} \tag{3.2}$$

For larger drainage areas:

$$P^* = \frac{1}{4\pi} \ln \frac{16A}{\pi L^2} - 1.5 \tag{3.3}$$

Using the above equation flow rate can be found from:

$$q = \frac{kh}{\mu} \frac{\left(\bar{P} - P_w\right)}{P^*} \tag{3.4}$$

It was shown that productivity of a 500ft. well draining a 16 hectare area is 27 times that of a vertical well. However, the derivation was based on a simplified 2D diffusivity equation solution. The solution is good for small reservoir thickness. However for thick formations it was proposed that a pressure drop term should be added to compensate for the vertical convergence of flow into the horizontal well. The result was the following equation:

$$q = \frac{kh}{\mu} \frac{\left(\bar{P} - P_W\right)}{P^* + P_S^*} \tag{3.5}$$

$$\text{and } P_S^* = \frac{1}{2\pi} \frac{h}{L} \ln \frac{h}{2\pi r_W} \tag{3.6}$$

3.1.9 Work of Gilman

In part I of their article [11], the authors compared the horizontal productivity for a given set of reservoir parameters. Figure 3.6 shows the productivity of a horizontal well as a function of well length. It can be seen that productivity is linear with length. In part II, Gilman et al. [12] studied the effect of horizontal well length. Figure 3.7 shows a plot of cumulative oil recovery at economic limit versus well length for gas and water coning. It can be observed that recovery is linear with length.

3.1.10 Study of horizontal well arranged in a staggered pattern

Suprunowicz and Butler [10] studied the productivity and optimum pattern shape for horizontal wells arranged in staggered rectangular arrays. They modified the dimensionless pressure drawdown, P*:

$$P^* = \overline{P}_N P_{max} \frac{1}{4} \frac{L^2}{A} \tag{3.7}$$

$$where \quad \overline{P}_N = \frac{1}{N} \int P_N dA \tag{3.8}$$

P_N is a modified pressure which is the value of actual pressure divided by the largest pressure in the area which is farthest from the well. For 3D:

$$P_N^* = \frac{1}{2\pi} \frac{h^*}{L} \ln \frac{h}{2\pi r_w^*} \tag{3.9}$$

$$q = \frac{k_h}{\mu} \frac{\left(\bar{P} - P_w\right)}{P^* + P_S^*} \tag{3.10}$$

$$h^* = h\sqrt{\frac{k_h}{k_v}} \tag{3.11}$$

$$r_w^* = r_w \frac{2}{1 + \frac{k_h}{k_v}} \tag{3.12}$$

3.1.11 Coning Study for Ratawi Oil Field [13]

In this study the effect of length was evaluated for well lengths of 1000ft., 2000ft. and 3000ft. It was found that the longer the length the more the cumulative oil production and the lower the water-cut. See Figures 3.8 and 3.9. Drop in water cut was attributed to smaller pressure drawdown which tends to suppress water coning in horizontal wells. Thus 3000ft. well gives maximum oil production for minimum water-cut.

3.2 EFFECT OF RATE

3.2.1 Study by Karcher

Karcher [14] studied post breakthrough performance of horizontal wells and carried out a numerical simulation study using a 3-phase 3D simulator. He also studied the effect of rate. It was found that for favorable mobility ratio critical rate did not exhibit any major sensitivity. However for unfavorable mobility ratio recovery dropped from 11.6% to 6.5% as rate increased from 22 to 42 times the critical rate. Consequently supercritical production rates bring the same gains after breakthrough but these gains do not increase afterwards except for unfavorable mobility ratio.

3.2.2 Work of Kossack and Kleppe

Kossack and Kleppe [3] compared oil production in the Troll-Field in North Sea using both horizontal wells and vertical wells. They found that the performance of a horizontal well is greatly dependent upon production rates.

In order to extend the life of the well a production schedule of gradually lowering production rates was suggested. For the purpose of this study as the GOR increased above the solution GOR, production rates were lowered. It was observed that the GOR reverted back to a lower solution GOR. After a period of time, breakthrough would again occur and the rate would be further reduced. Table 3.1 [3] shows the schedules. The time given is the breakthrough time and the rate given is the corresponding rate. Figure 3.10 and Figure 3.11 respectively show gas-oil ratio performance of schedules C and D for the 1500ft. section. By gradually lowering the production rates, final shut-in times were extended to 3649 and 3723 days respectively.

Table 3.1: Production Schedule

SCHEDULE	TIME (DAYS)	RATE (STBPD)
A Vertical	0-2700	1000
B Horizontal	0-6720	1000
C Horizontal	0-100	8000
	100 - 240	4000
	240-1730	2000
	1730-3649.4	1000
D Horizontal	0-370	4000
	370-1800	2000
	1800-3722.5	1000

It was observed that schedule of high initial rates followed by gradually reducing rates as the GOR increases recovers significant amount of oil. For schedules C and D the recovery is found to be nearly the same as observed in case B. However, it is observed that for the horizontal wells the time taken is slightly more than half the time it takes for case B.

3.2.3 Work of Zagalai and Murphy [6]

They carried out a reservoir simulation study of horizontal wells in the Helder-Field located in the Dutch Continental Shelf. They studied the effect of gross rate to water cut sensitivity. Figure 3.12 shows that a horizontal well is affected more adversely by high rates especially at early times and at rates below 3000 STBPD. Above 6000 STBPD there is less sensitivity to gross rates. The plot of water cut versus time, Figure 3.13, shows that rate has a strong influence on water cut performance.

3.2.4 Parametric Study by Wang

Wang [7] studied the effect of gross production rate on performance of a horizontal well. He studied the effect of gross production rate for a horizontal well, q_t, on GOR, WOR and recovery. He found that for a gas cap, decreasing q_t from 4000 rbpd to 500 rbpd delayed GBT from 10 days to 1200 days while the ultimate recovery increased from 15% to 30% of OOIP. As for the GOR sensitivity to q_t, it was observed that GOR drops instantaneously as rate changes and moves along with the curve of new rate, q. He also studied the rate effect on water coning and considered three cases:

1. low viscosity oil (0.95 cp) and 300 ft. aquifer (see Figure 3.14)
2. low viscosity oil and infinite water influx (see Figure 3.15)
3. viscous oil (20 cp) and 300 ft. aquifer (see Figure 3.16).

He found for the first case that the lower the q_t, the lower the water cut and the higher the ultimate recovery. However increasing the rates did not result in a considerable change in behavior. Similar trend was observed for case two. But for case three, it was found that q_t at breakthrough, water cut after breakthrough and ultimate recovery did not change greatly. This led to the conclusion that q_t is an important parameter in water coning for low viscosity oil with limited aquifer but not in other cases.

3.2.5 Simulation Study by Yang and Wattenbarger

Yang and Wattenbarger [8] carried out an extensive sensitivity analysis for horizontal wells. They found that increasing gross production rates resulted in early breakthrough of water. They gave a correlation for predicting WOR after breakthrough:

$$\log(WOR + 0.25) = m(h_{bp} - h_{wb}) + \log 0.25 \tag{3.13}$$

Since the equation is valid only for $h_{bp} \leq h_{wb}$ while the slope, m, for the above equation is always negative and increases with increase in q_t, it can be concluded that for higher q_t, WOR increases. However the correlation is limited because it assumes that rate changes which causes hysteresis in WOR do not influence the performance. In addition, the correlation is only valid for cases of mobility ratio (water-oil) less than 5.

3.2.6 Work of Gilman

Gilman [11] compared the recovery from horizontal wells versus vertical wells for water coning situation. Breakthrough occured within days after production began. Cumulative oil production at 50% water cut for vertical wells was found to be 7,000 STB and about 210,000 STB for horizontal wells. Oil rate declined rapidly for both but less rapidly for horizontal wells. After a period of 5 years horizontal wells had produced 229,000 STB while vertical wells produced only 70,000 STB.

3.3 EFFECT OF WELL SPACING

The decreased resistance to flow around an extended horizontal well as compared to that around a vertical well implies that fewer horizontal wells are required to achieve the same reservoir drainage. The improved contact with reservoir achieved by means of the horizontal wells has a dual nature:

1. The near well-bore flow resistance is reduced due to the extended length and resulting lower velocity.
2. For long wells, length carries the well through larger reservoir area. Extending length of the well reduces the distance that the reservoir fluids must travel in order to reach the well.

3.3.1 Work of Kossack and Kleppe

Kossack and Kleppe [3] studied the well spacing parameter. They considered a circular drainage area of radius 5,000ft. and subdivided it into a number of equal sectors. Each sector was drained by one, two or three vertical wells or by one horizontal well. This comparison between production from sectors of different sizes gave the effect of interference between the groupings of the wells. For example a 30° sector has 72 groupings of wells in a 360° pattern while a 90° sector has 4 groupings of wells. Runs were made on ECLIPSE simulator by employing sectors of 30°, 45° and 90°. It was found that cumulative oil recovery is highest for smallest angle. Between 30°-45° there was a significant drop in recovery, while between 45°-60° this drop was smaller. Reduction in the recovery between 60°-90° is again found to be significant. See Figure 3.17.

3.3.2 Work of Ozkan and Ragahvan

Ozkan and Ragahvan [15] determined the maximum drainage radius for the case of vertical wells needed to avoid water coning. They gave the following relationship:

$$r = 2.3h_o\sqrt{\frac{k_h}{k_v}} \tag{3.14}$$

To drain a larger area, horizontal well lengths must be more than twice this value so that the drainage area is approximately L^2. This indicates the need of vertical wells with closer spacing or horizontal wells in a thin oil column in a reservoir which has an aquifer or gas cap.

3.3.3 Work of Yang and Wattenbarger

Yang and Wattenbarger [8] carried out an extensive sensitivity analysis for horizontal wells. They found that for both vertical and horizontal wells increasing the drainage radius (in vertical wells) or drainage width (in horizontal wells) resulted in delayed breakthrough.

3.3.4 Work of Wang

Ben Wang [7] carried out a parametric study of gas and water coning in vertical and horizontal wells. He studied four different well spacings: 1,000,000 sq. ft., 4,000,000 sq. ft., 9,000,000 sq. ft. and 16,000,000 sq.ft. for gas coning in both horizontal wells and vertical wells (equivalent radius of 564.2ft., 1128.4ft., 2258ft. and 3385.1ft. respectively). The length of the horizontal well was the same as the linear dimension of the square block in which it was centrally located. For the same gross production rate of 1000 rbpd the GOR was plotted versus economic recovery and it was found that :

1. Breakthrough times for vertical wells were all within days and GOR increased much faster with economic recovery increments for larger well spacing runs.
2. For horizontal wells breakthrough time was 15, 40, 230 and 560 days respectively for 1000ft., 2000ft., 4000ft. and 6000ft. respectively.But overall GOR versus economic recovery curves were close for various well spacings.

Therefore gas coning is important in vertical well spacings than horizontal wells. Due to large pressure drop in radial direction the gas will flow towards the radial direction for large well spacings. But since flow lines are linear in a horizontal well the pressure drop is greatly reduced. As a result the gas cap can still effectively push down the oil column. For water coning it was found that large spacing resulted in delayed breakthrough, higher water-cut after breakthrough and lower economic recovery for both vertical and horizontal wells.

Therefore horizontal well spacing is important in water coning but not important in case of gas caps.

3.3.5 Work of Lacy et al.

Lacy et al. [16] studied well spacing and found that higher well spacing is desirable in horizontal wells for two reasons:

1. Incremental reserves should be proportional to incremental costs.
2. Early production data demonstrates that the horizontal wells can drain a large area in a small time even in tight reservoirs.

It was found that in a naturally fractured reservoir, spacing along the fracture trend should be greater than that perpendicular to it. However, they did not study the effect of spacing on water or gas coning.

3.3.6 Work of Butler and Suprunowicz

Butler and Suprunowicz [17] studied the production of oil from reservoirs underlain by an active aquifer assuming water and oil of equal density and viscosity. They used the formula describing the velocity potential distribution and streamlines in a steady state, 2-D potential field as a basis for their work. Recovery ratio at breakthrough time is:

$$R = \frac{a_l}{\pi h} \ln\left(\cosh \frac{h}{a_l} \right) \tag{3.15}$$

Therefore the closer the well spacing the more complete and rapid is the recovery of oil [18]. In another publication [18] the authors developed quantitative means of defining the shape of optimum pattern i.e. the ratio of length to breadth of a rectangular pattern. A 2D pseudo-steady state was assumed and relations for optimum pattern shape were found for a horizontal well in rectangular patterns:

$$a_l = \sqrt{L^2 + A} \tag{3.16}$$

$$b = \frac{A}{a_l} \tag{3.17}$$

$$A = a_l * b \tag{3.18}$$

The aspect ratio is defined as:

$$\alpha = \frac{b}{a_l} = \frac{A}{L^2} \Big/ \left(\frac{A}{L^2} + 1 \right) \tag{3.19}$$

It was found that the minimum drawdown can be found using a simple correlation:

$$P^* = \frac{k_h}{q\mu}\left(\bar{P} - P_w\right) = \ln\frac{1+\frac{A}{L^2}}{12}$$

(3.20)

These results are derived for a thin reservoir and may be extended to a thicker reservoir i.e. in 3D by adding a term to the pressure drop required to achieve vertical convergence of flow to the central well:

$$P^* + P_S^* = \frac{k_h}{q\mu}\left(\bar{P} - P_w\right)$$

(3.21)

$$P_S^* = \frac{1}{2\pi}\frac{h}{L}\ln\frac{h}{2\pi r_w}$$

(3.22)

For different k_h and k_v :

$$P_S^* = \frac{1}{2\pi}\frac{h}{L}\ln\frac{h^*}{2\pi r_w^*}$$

(3.23)

$$h^* = h\sqrt{\frac{k_h}{k_v}}$$

(3.24)

$$r_w^* = r_w \frac{2}{1+\frac{k_h}{k_v}}$$

(3.25)

By applying the equations to a 500m long horizontal well draining 16 hectares, 27 times higher productivity was achieved for a = 640m and b = 250m as optimum pattern shape parameters. If for the same system a 15m thickness and $k_h/k_v = 10$ is assumed, then for r_w=0.1m productivity 17 times rather than 27 times high is obtained. The optimum aspect ratio for horizontal wells in staggered rectangular arrays was found [18]:

$$\alpha_{opt} = \frac{A/L^2}{1.15A/L^2 + 1}$$

(3.26)

3.4 EFFECT OF ANISOTROPY RATIO

3.4.1 Work of Chaperon

Chaperon [19] found that the critical rate is directly proportional to $\sqrt{k_v k_h}$. Thus q_c increases with increase in $\sqrt{k_v/k_h}$. Chaperon also found that the ratio q_{ch}/q_{cv} increases with an increase in k_v/k_h. This is due to the fact that as k_v increases q_{cv} decreases. But for horizontal wells an increase in k_v results in an increase in q_{ch}.

3.4.2 Work of Butler

Butler reported [4] that the length of horizontal well equivalent to a vertical well can be found using the following equation: (See Figure 3.18)

$$L = \frac{4}{3} h \sqrt{\frac{k_h}{k_v}} \tag{3.27}$$

The higher the k_v/k_h, the lower the equivalent horizontal well length.

3.4.3 Work of Haug

Haug [9] studied the effect of anisotropy ratio in thin oil zones and found that isotropic reservoirs give the highest value of the recovery, while recovery decreases with increase in the degree of isotropy. It was found that isotropy was less important than the absolute permeability.

3.4.4 Work of Ben Wang

Ben Wang [7] also studied the effect of anisotropy. Figures 3.19 through 3.22 show the results of his parametric study. The value of the ratio k_v/k_h was varied from 0.01 to 1.0. It is clear that the value of this ratio is important in water coning phenomena. The economic recovery decreases with increasing k_v/k_h ratio. This result is in consonance with observations made for vertical wells.

3.4.5 Work of Yang

Yang and Wattenbarger [8] studied the effect of the anisotropy ratio in their simulation study of water coning phenomenon. In consistence with the published literature they also found that high values of the vertical permeability k_V resulted in later breakthrough of water.

3.4.6 Work of Lacy et al.

Lacy et al. [16] studied the effect of low vertical permeability. It was observed that low k_V results in suppression of water coning but in turn also reduces well productivity. It was found that horizontal well in low k_V do not perform better than vertical well in water coning applications.

3.4.7 Work of Guo and Lee

Guo and Lee [3] developed critical rate correlations for horizontal wells. They found that the behavior of the critical rate is insensitive to the vertical permeability k_v. However they found that the critical rate is directly proportional to the horizontal permeability k_h.

3.4.8 Work of Gilman

Gilman [11] studied the effect of vertical permeability and found that for higher k_v cumulative oil recovery decreases due to coning. See Figure 2.23.

3.5 CRITICAL RATE CORRELATIONS

All the research work carried out to solve the gas and water coning tendencies in reservoirs lead to the conclusion that water and gas coning can be avoided by producing at low rates. Quantitative relationships have been developed that give precisely the rate, which if exceeded would result in gas or water coning. This rate is defined as the critical rate.

In this section we shall review all the work that has been carried out in evaluating the critical rate for a reservoir beset with gas and water coning problems.

Unlike horizontal wells, vertical wells have pressure drop concentrated around the well-bore. For a reservoir underlain by an aquifer the high pressure drop around a vertical well-bore would lift the water cone towards the well. For the same production rate, the smaller drawdown in the horizontal well would lift an equal volume of a water crest but having a much lower height, thereby delaying coning. Thus, the critical rate is expected to be higher for horizontal wells.

3.5.1 Critical Rate Correlation By Chaperon

Chaperon [19] made a 2D study of the coning phenomena for anisotropic formation for both steady state and un-steady state conditions

and found that critical rate is directly proportional to:

1. Transmissivity of the layer, $k_h h/\mu_o$.
2. Initial oil thickness.
3. Length of the horizontal well.
4. Anisotropy ratio, $\sqrt{k_v/k_h}$.

Critical rate decreases with increase in lateral dimensions of the reservoir drainage area. Thus close well spacing would result in higher critical rate. However the effect of small vertical permeability is to decrease the critical rate. This equation applies only where the length is more than one quarter of the drainage volume dimension along the well. The equation is derived for both steady state and pseudo-steady state cases. If aquifer maintains reservoir pressure the steady state equation applies while for no flow boundary pseudo-steady state equation applies. For steady state:

$$Q_{ch} = 4\beta \, L / X_A \quad for \quad \alpha = 13 \tag{3.28}$$

$$\beta = 3.486E-5(\Delta\rho h)\left(k_h h / \mu_o B_o\right) \tag{3.29}$$

$$\alpha = {X_A}/{h} \sqrt{k_v / k_h} \tag{3.30}$$

For pseudosteady state the above equation can be used after replacing X_A by $0.5X_e$ and r_e by $0.607r_e$.

The following important result follows from this:

$$q_{ch} / q_{cv} = 4L / X_A \quad \text{for } \alpha = 13 \tag{3.31}$$

Thus for large well spacings it is found that the improvement in critical rate is insignificant if a vertical well is replace with a horizontal well.

3.5.2 Critical Rate Correlation By Efros

Efros [20] developed the following equation using hodograph method :

$$q_o = \frac{4.888E - 4k_h \Delta\rho h^2 L}{\mu_o B_o \left(2X_e + \sqrt{\{2X_e\}^2 + h^2/3} \right)} \tag{3.32}$$

Joshi suspects that X_e in the denominator should be replaced by $2X_e$ [20].

3.5.3 Critical Rate Correlation By Giger

Giger [21] proposed the following equation which was derived using the hodograph method of calculation:

$$q_c = \frac{3k_h \Delta\rho g X_e}{\mu_o \left(\sqrt{1 + \frac{4}{3}\frac{h^2}{X_e^2}} - 1 \right)}$$

(3.33)

3.5.4 Critical Rate Correlation By Giger and Karcher [14]

They presented following equation:

$$q_c = 4.888E-4 \frac{k_h}{\mu_o B_o} \frac{\Delta\rho h^2}{2Y_e} \left(1 - \frac{1}{6}\left(\frac{h}{2Y_e} \right)^2 \right) L$$

(3.34)

3.5.5 Critical Rate Correlation Of Yang And Wattenbarger

Yang and Wattenbarger [8] gave a correlation in 1991 for the critical rate. Their work was based on the observation that GOR versus average height of oil column above the perforations yields a straight line after breakthrough on a semi-log scale. This observation was first made for the case of gas breakthrough [8]. For horizontal wells:

$$q_{CD} = 4.7921E-4 X_A^{0.32} \frac{1}{X_D^{0.65}} \frac{1}{1+M^{0.4}} \frac{h_{bp}^2}{\left(h-h_{ap}\right)^2 - h_{bp}^2}$$

(3.35)

$$q_c = \frac{\sqrt{k_v k_h}\, k_{ro}' L \Delta\rho g h}{\mu_o} q_{CD}$$

(3.36)

$$X_D = \frac{X_A}{h} \sqrt{k_v k_h}$$

(3.37)

It is observed that q_c decreases with height, h_{bp}, time or cumulative oil production. The work is based on closed outer boundaries which never reach steady state conditions. That is, critical rate is time dependent. This correlation gives good results for mobility ratios less than 5 or when viscous forces are not dominant.

3.5.6 Critical Rate Correlation By Guo And Lee

Guo and Lee [22] presented analytical solution for water coning in 1992.They used conformal mapping theory and numerical simulation for validation. It was based on the following assumptions:

1. homogeneous

2. isotropic
3. oil is incompressible
4. steady state flow conditions prevail
5. well-bore is horizontal and straight and
6. capillary pressure is negligible; abrupt 2-phase interface exists.

To determine the critical rate, following equation is used:

$$k' = \sqrt{k_V k_H} \tag{3.38}$$

$$d' = d\sqrt{k'/k_V} \tag{3.39}$$

Then using:

$$H_D = 0.033\left(1.18 - 0.00246d'\right)(2.286\Delta\gamma + 0.77)(100 - 67L_W)\left(\log k' + 8.14\right)\log X_e \tag{3.40}$$

q_D is found from Figure 24 [22] and using:

$$q_D = \mu_o q_c / 2\pi k' d' g\Delta\rho \tag{3.41}$$

q_c is found in rb/D.ft. This is finally converted to Q_c in STBPD using:

$$Q_c = q_c L / B_o \tag{3.42}$$

3.5.7 Critical Rate Correlation By Guo Molinard And Lee [23]

They presented another correlation in 1992 for critical rates in horizontal wells. They found that the critical rates are proportional to effective k, $\sqrt{k_v k_h}$, thickness of the oil column, $\Delta\rho$, and inversely proportional to μ. It also depends upon the relative location of the well-bore in the oil reservoir and is maximum when horizontal wellbore is placed at about 70% of the reservoir thickness from unwanted fluid. This work is based on asumptions of homogeneous reservoir, dimensional flow, well-bore can be treated as a line sink, steady state flow conditions prevail and capillary pressure is negligible:abrupt 2-phase interface exists.

The critical rate is estimated based upon the examination of the profile development of the stable water cone. The critical oil rate depends upon the well-bore location in the oil reservoir. To determine the critical rate, the paper refers to certain dimensionless curves plotted from the results of the analytical solution. Based upon the value of the well location a dimensionless graph gives the value of q_{CD} dimensio- nless (critical rate) which can be converted into real rates.

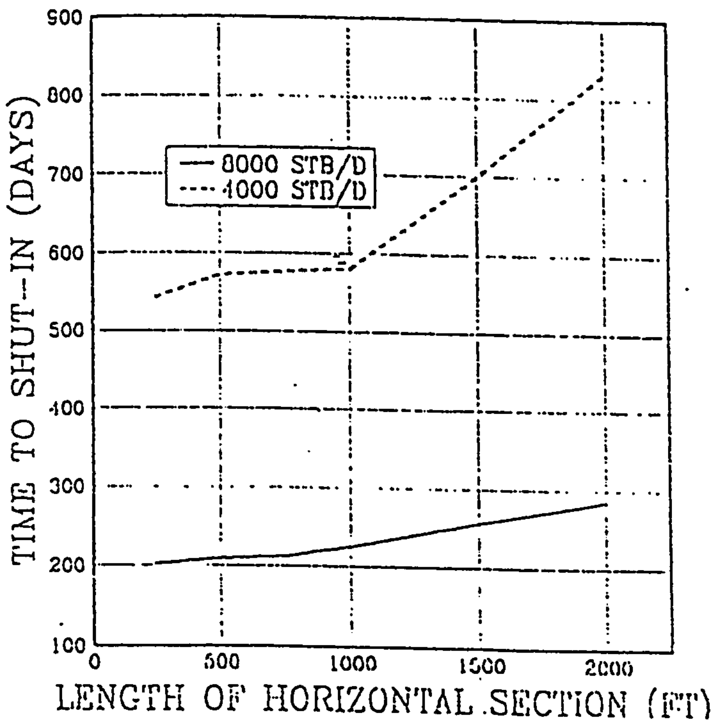


Figure 3.1: Effect of length of horizontal well on performance [3]

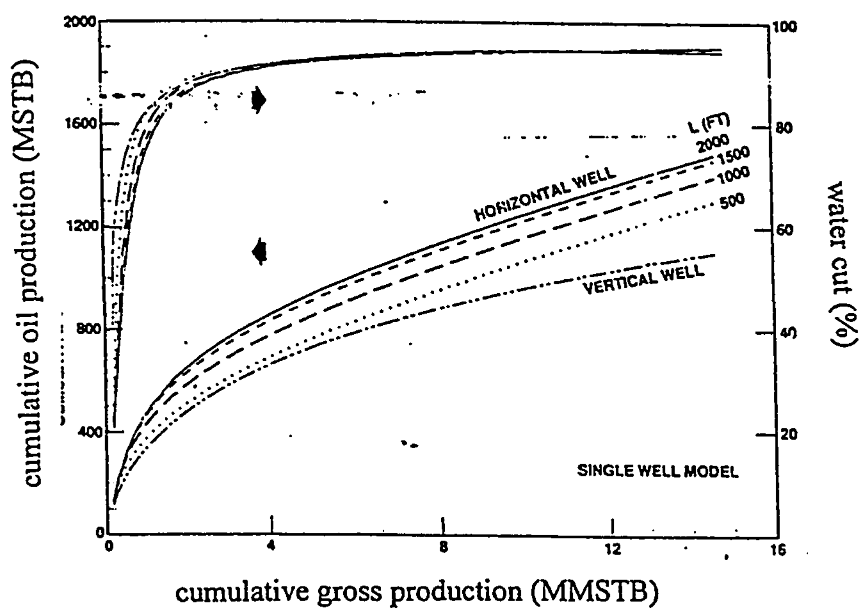
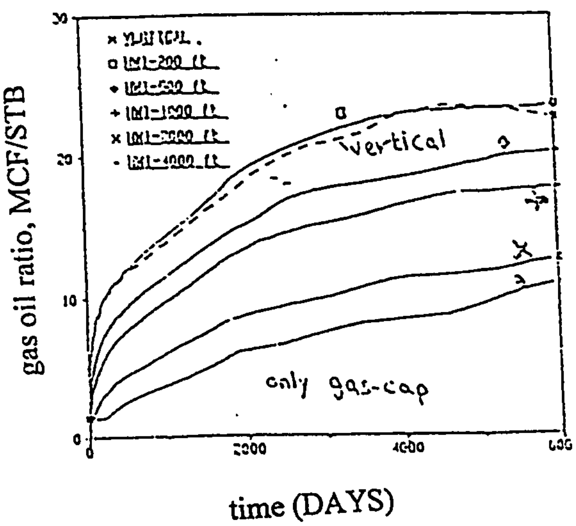


Figure 3.2: Horizontal well performance as a function of horizontal interval [6]



. Figure 3.3: Horizontal well length effect on gas coning [7]

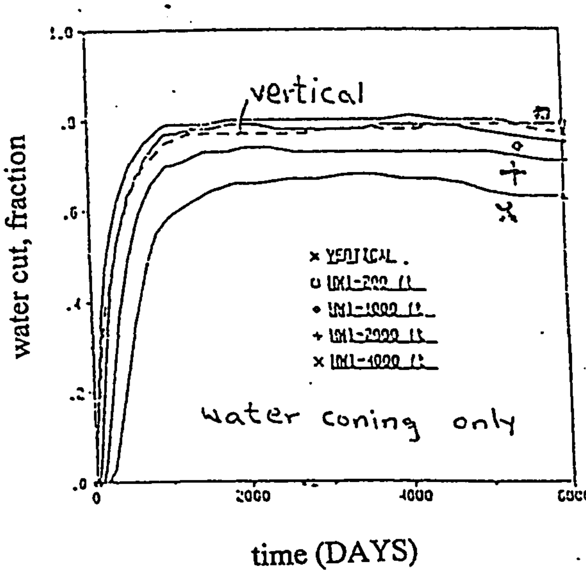


Figure 3.4: Horizontal well length effect on water coning. [7]

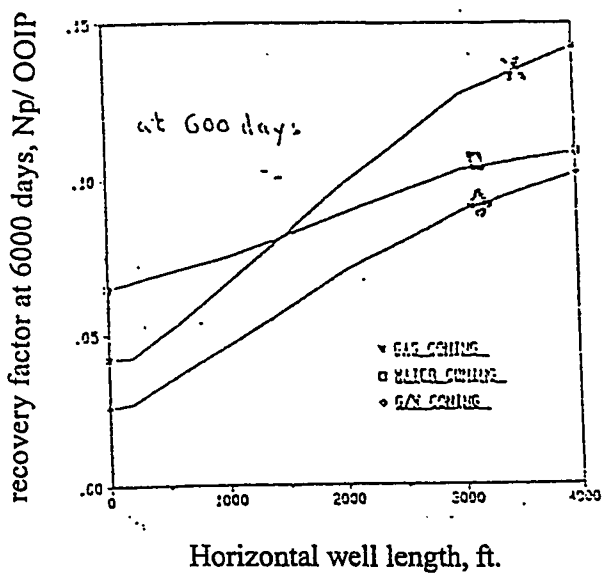


Figure 3.5: Horizontal well length effect on ER [7]

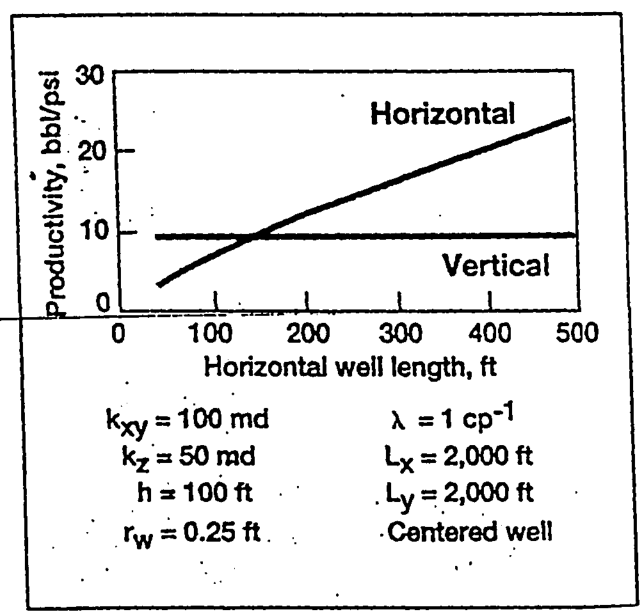


Figure 3.6: Horizontal well productivity as a function of well length [11]

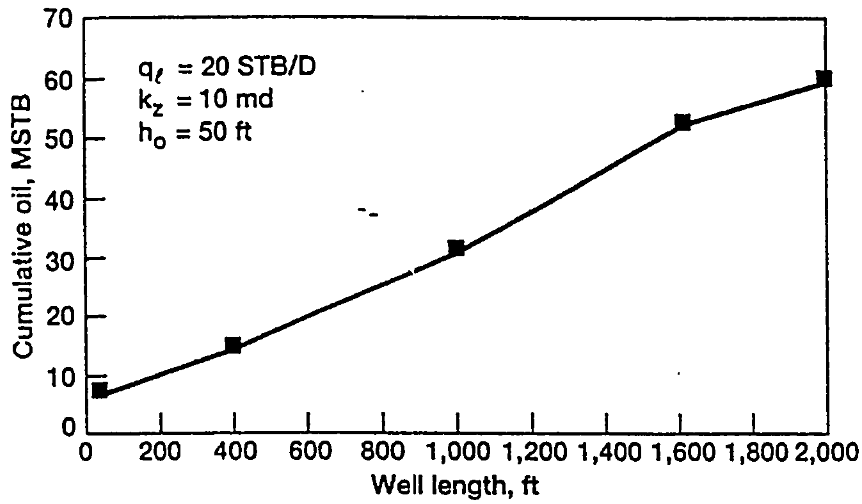


Figure 3.7: Cumulative Oil at 95% water-cut vs. Horizontal well length in a constant pressure, bottom water system [12]

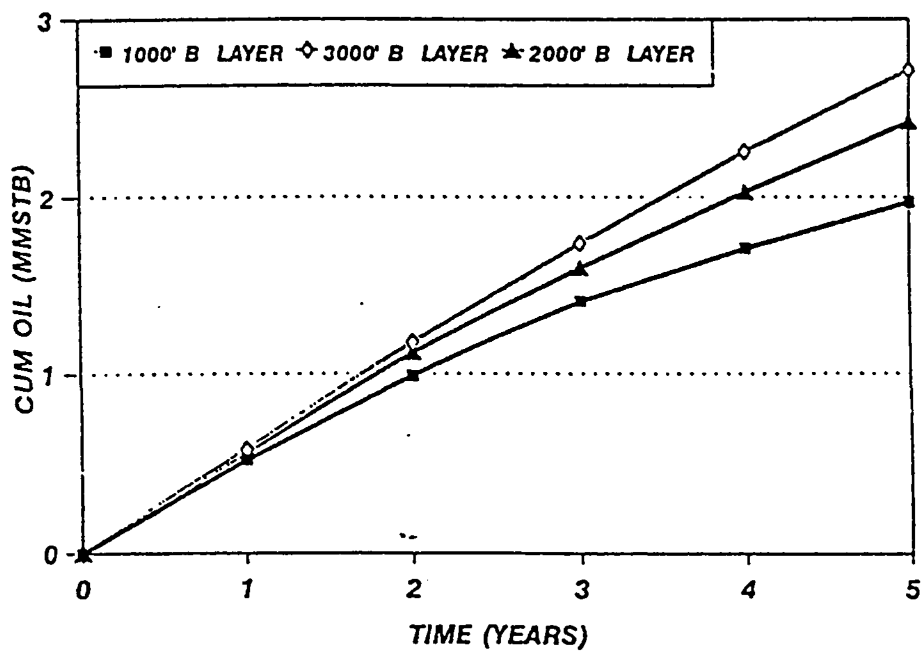


Figure 3.8: Ratawi OOlite reservoir well, Cumulative oil for different wells [13]

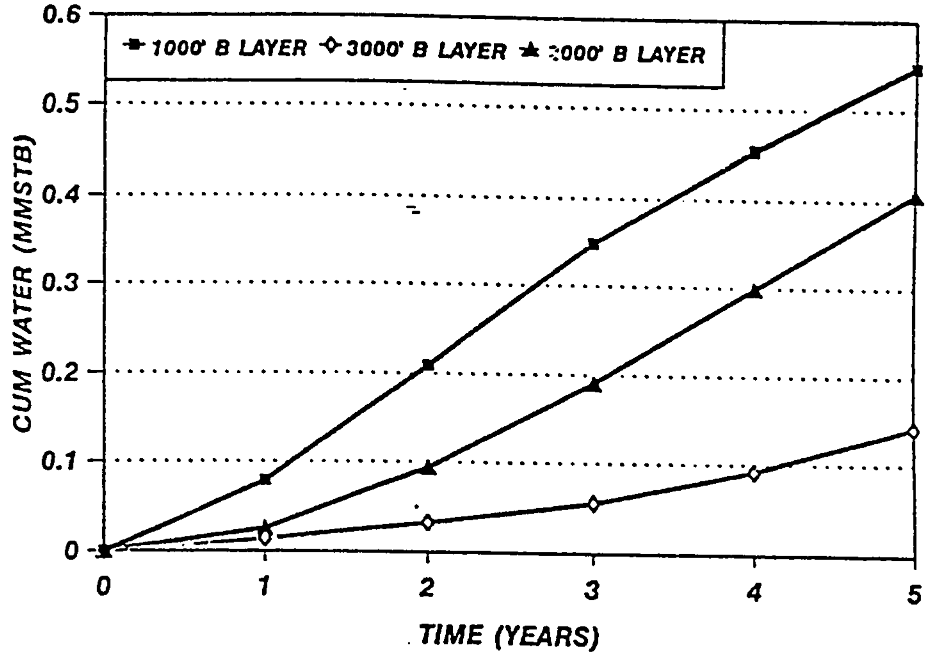


Figure 3.9: Ratawi OOlite reservoir well, Cumulative water for different wells [13]

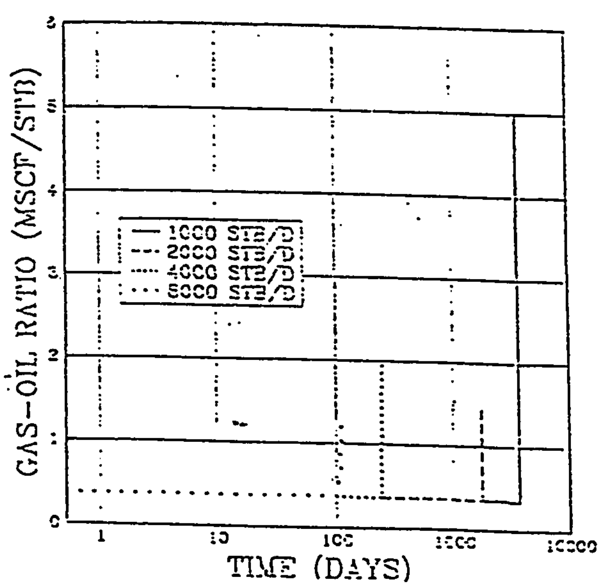


Figure 3.10: Gas-Oil performance for production schedule C, see Table 3.1 [3]

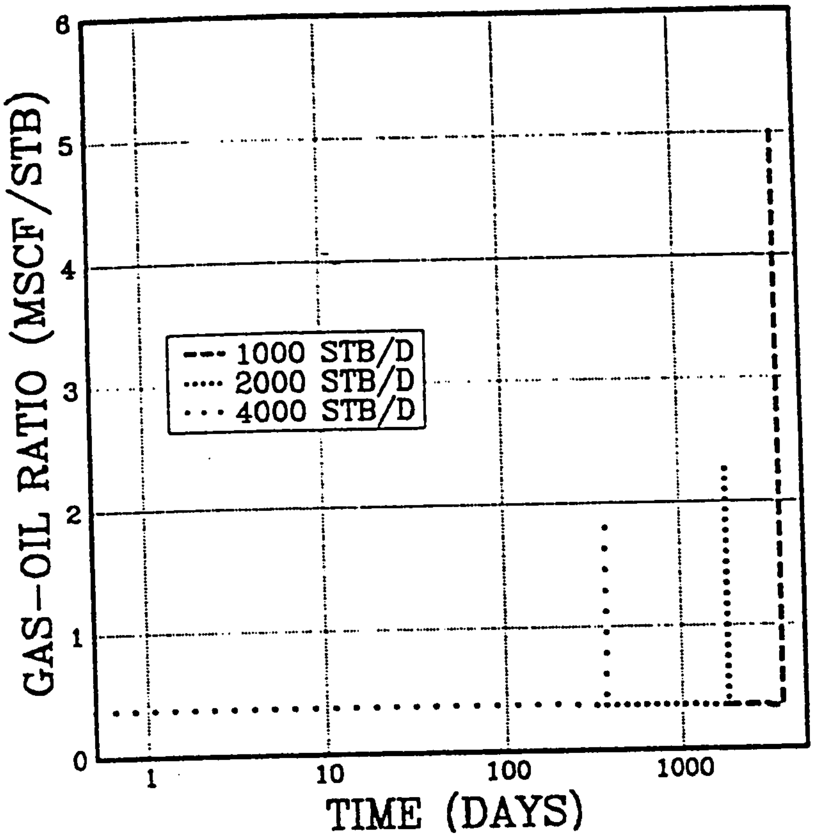


Figure 3.11: Gas-Oil performance for production schedule D, see Table 3.1 [3]

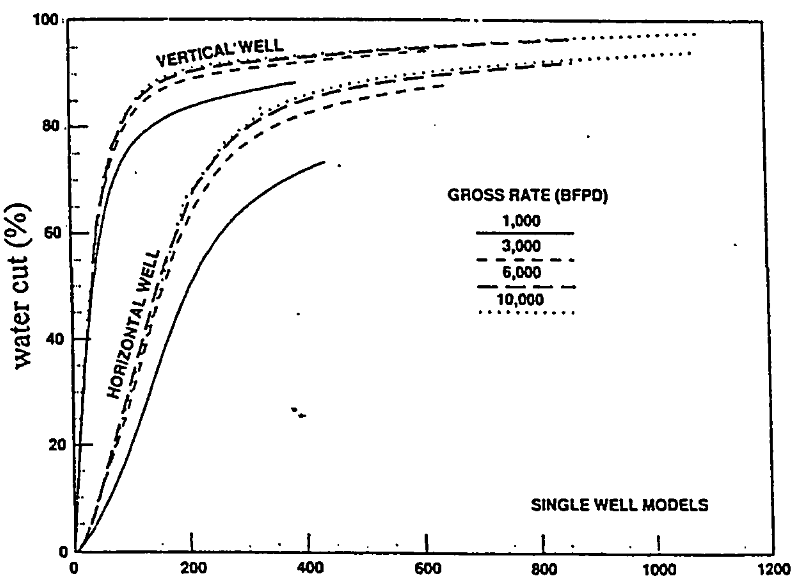


Figure 3.12: Horizontal well sensitivity to gross off-take rate [6]

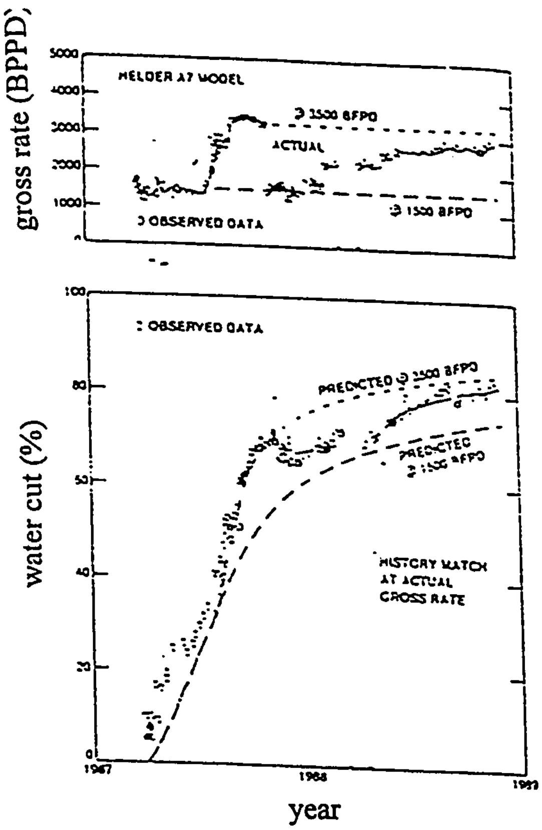


Figure 3.13: Well model sensitivity to gross off-take rate [6]

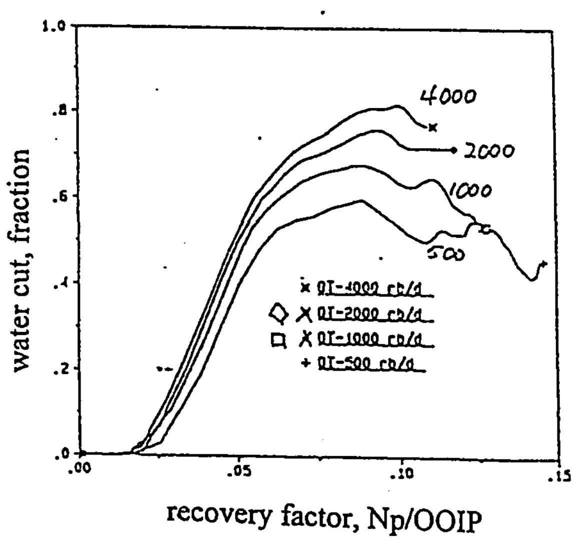


Figure 3.14: Rate effect on coning in horizontal wells, water coning in low viscosity oil, 300' aquifer [7]

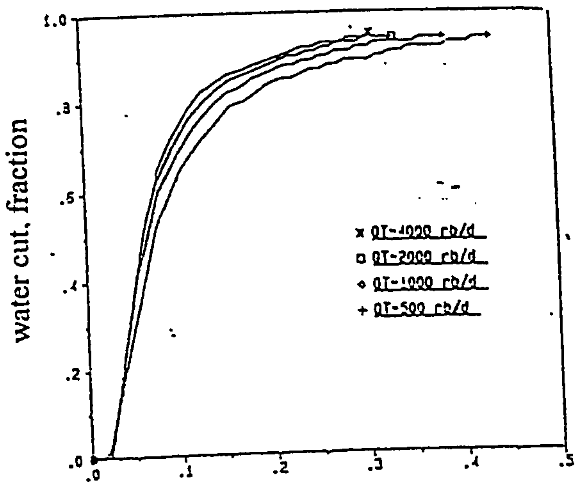


Figure 3.15: Rate effect on coning in horizontal wells, water coning in low viscosity oil, infinite aquifer [7]

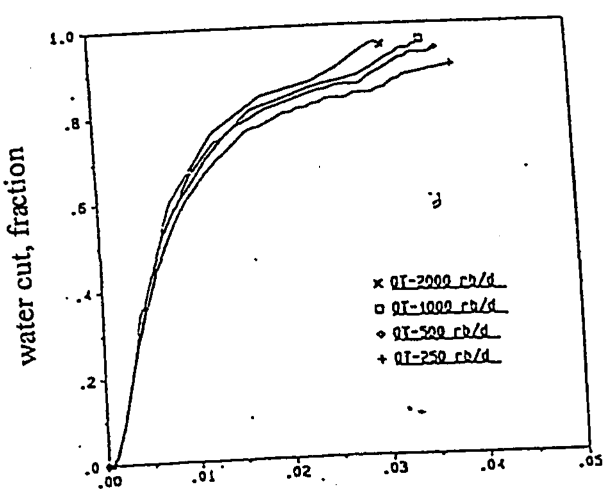


Figure 3.16: Rate effect on coning in horizontal wells, water coning in high viscosity oil, 300' aquifer [7]

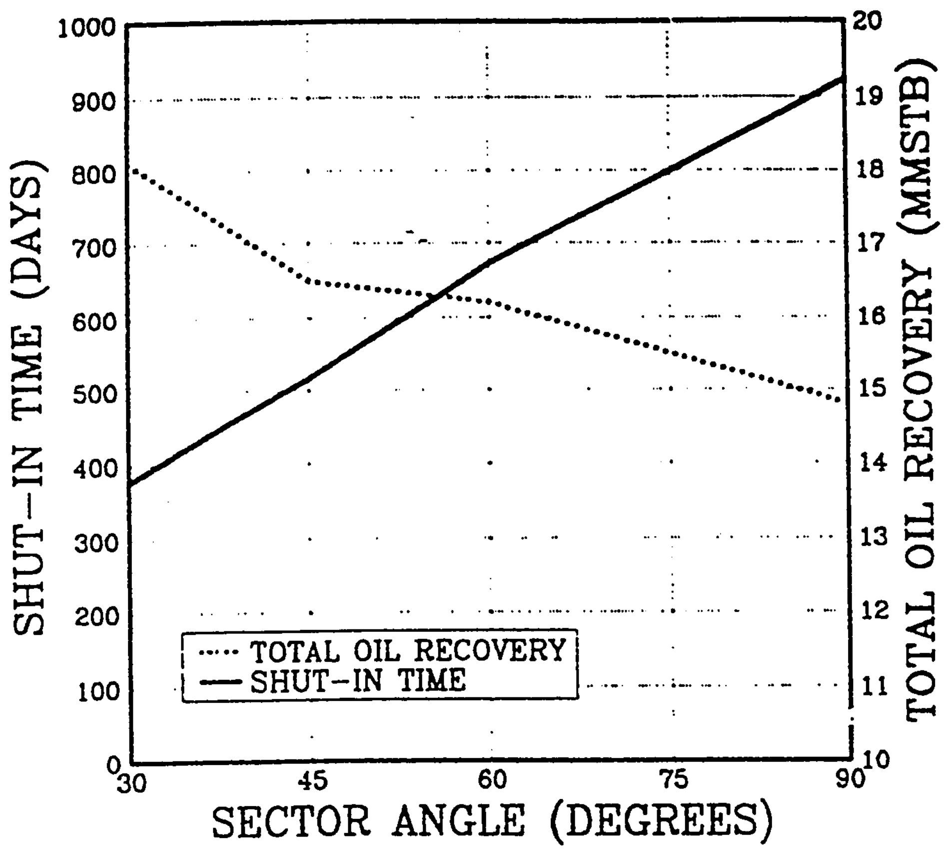
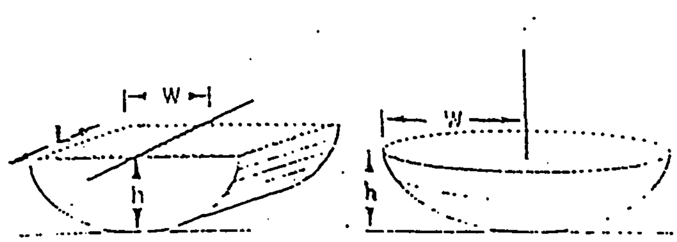


Figure 3.17: Effect of sector angle on performance [3]



$$W = h\sqrt[4]{k_h/k_v}$$

$$L = \frac{4}{3}h\sqrt[4]{k_h/k_v}$$

Figure 3.18: Horizontal well length from same cone volume [4]

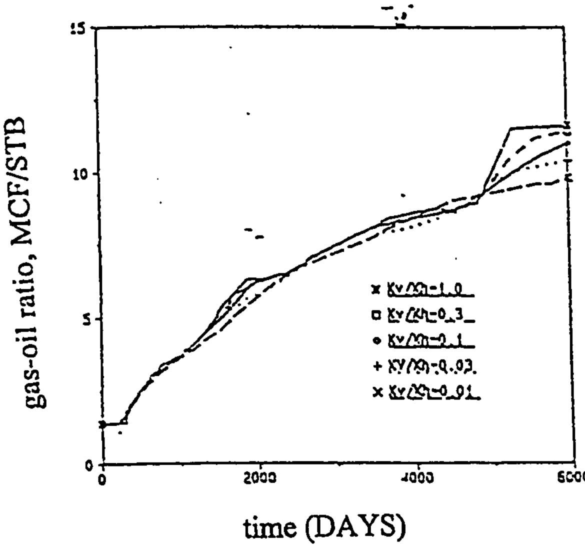


Figure 3.19: Effect of anisotropy on gas coning [7]

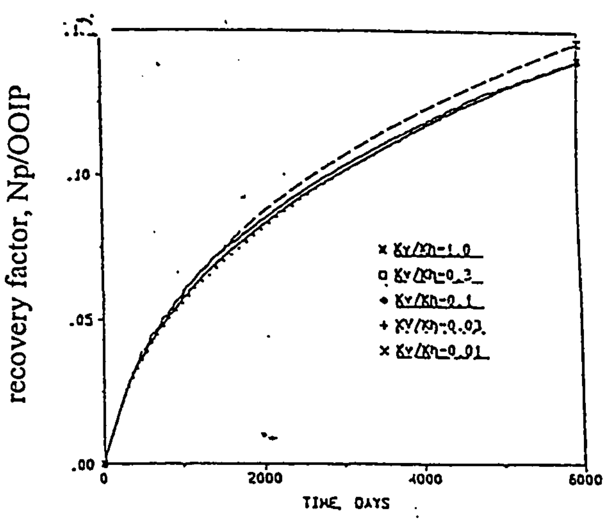


Figure 3.20: Effect of anisotropy on ER for gas coning [7]

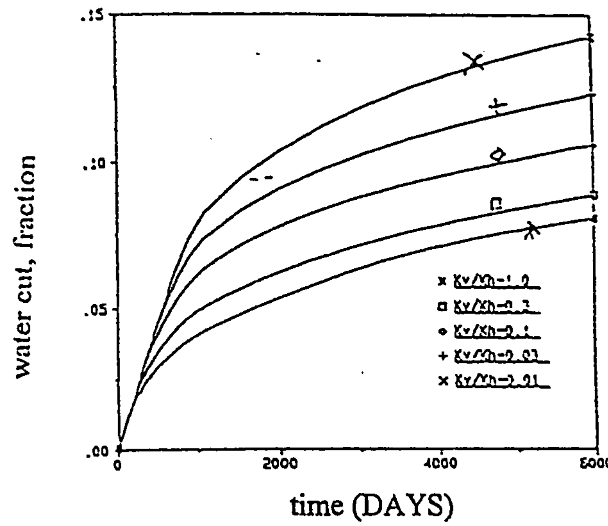


Figure 3.21: Effect of anisotropy on water coning [7]

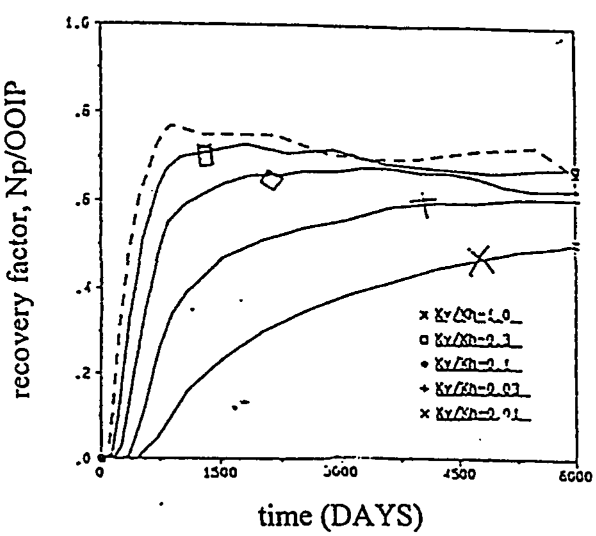


Figure 3.22: Effect of anisotropy on ER for water coning [7]

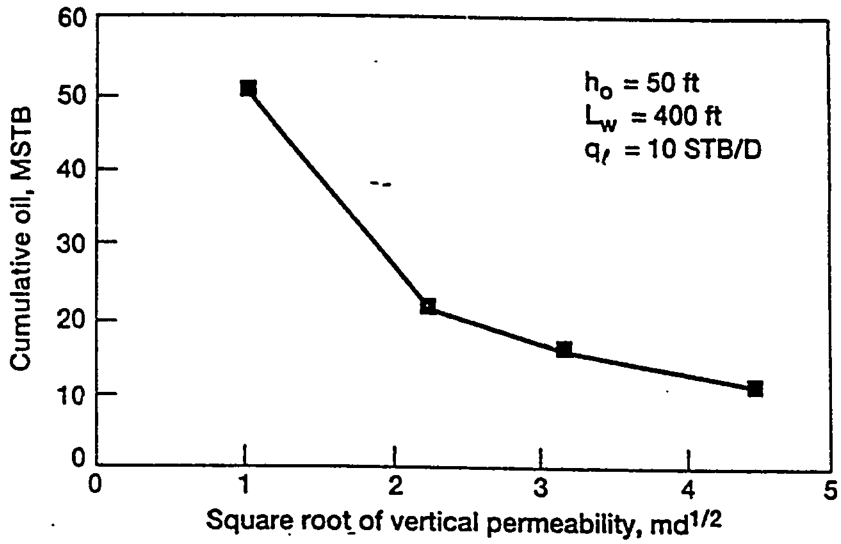


Figure 3.23: Cum oil at 95% water vs square root of vertical permeability in a constant pressure, bottom water system [12]

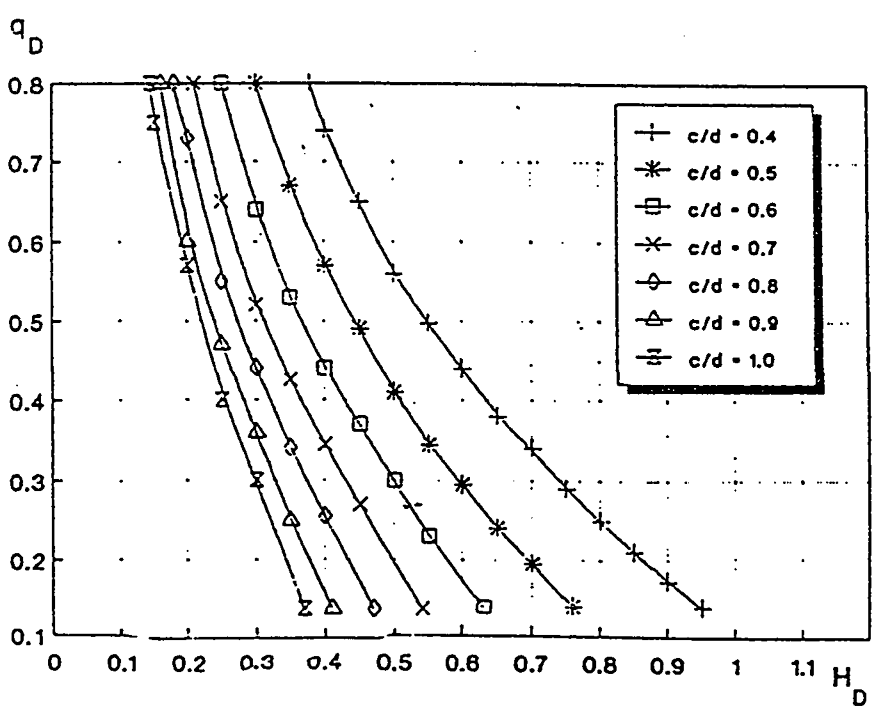


Figure 3.24: Solution of dimensionless critical rate [22]

CHAPTER 4

CRITICAL RATE DETERMINATION

A literature survey of published results shows that most of the work related to critical rate studies is developed using analytical techniques. However, the correlation by Yang and Wattenbarger [8], which is obtained using extensive numerical simulaton, is an exception. The present study is also based on numerical simulation. Using a numerical model of water coning, a parametric study has been carried out for horizontal and vertical wells to determine the sensitivity of various reservoir parameters to critical rate. A new method to determine the critical rate from simulation results is described. This method is based on tracking the water front as it develops and progresses towards the well. It can be called 'Method of Saturation Function.'

4.1 METHOD OF SATURATION FŨNCTION

There are many ways to define a value of critical rate from the results of simulation. Several variables, such as water-cut can be used to estimate the critical rate. In this study the water saturation is tracked in order to determine the critical rate. The idea behind this approach is to track the water/oil interface movement so that the water saturation build up can be detected. The procedure adopted for tracking the front involves measuring the water saturations in vertical planes perpendicular to the direction of the horizontal well. Note that each grid block in the grid block system is dentified by a set of (i, j, k) indices. These indices identify the position of a grid block in the grid system. As shown in Figure 4.1, a vertical plane XY is defined as one formed by all the grid blocks with the same j index value. In each vertical plane the water saturation is measured at two different positions i.e. in two different grid blocks. One of these grid blocks, A, corresponds to an index value of (i_n, j, k_h), where i_n is the index value of the last grid block in the x-direction, j corresponds to the index value of the grid blocks identified by the vertical plane in the y-direction and the k_h index is the index number in the z-direction corresponding to the z-plane in which the horizontal well is situated. The other grid block, B, corresponds to an index value of (i_h, j, k_h), where i_h corresponds to the index value of the x-directional grid block in which the horizontal well is located. In case of a vertical well the vertical plane is one in which the vertical well is located. After identifying the positions of the two points in which the saturations are measured, the next step is to keep track of the water saturation at these two points with time. As soon as the saturation starts to swell up it is an indication that the water front has arrived. Subsequently an increase in water-cut is always observed. In order to standardize the criteria for setting up an upper limit on water saturation for which coning occurs, a dimensionless *Saturation function, Sf*, is defined as follows:

$$S_f = \Delta S_w \frac{H}{L} \tag{4.1}$$

- S_f = saturation function
- ΔS_w = difference in water saturation between the two points in the vertical plane in which the water saturation is measured.
- H = initial thickness of the oil zone.
- L = length of the reservoir in the y-direction.

At each time interval when the simulator generates a report, the saturation function is calculated using the observed water saturation values. If at the end of the simulation run i.e. after approximately thirty years, it is observed that the saturation function has crossed its' threshold value in any vertical plane in the reservoir then it is assumed that the rate corresponding to that simulation run is a *supercritical rate*. In this case another run is made with a slightly lower rate. A rate is termed as *subcritical* for which the saturation function remains below the threshold limit at the end of thirty years. In this case another run is made at a slightly higher rate. Thus the rate

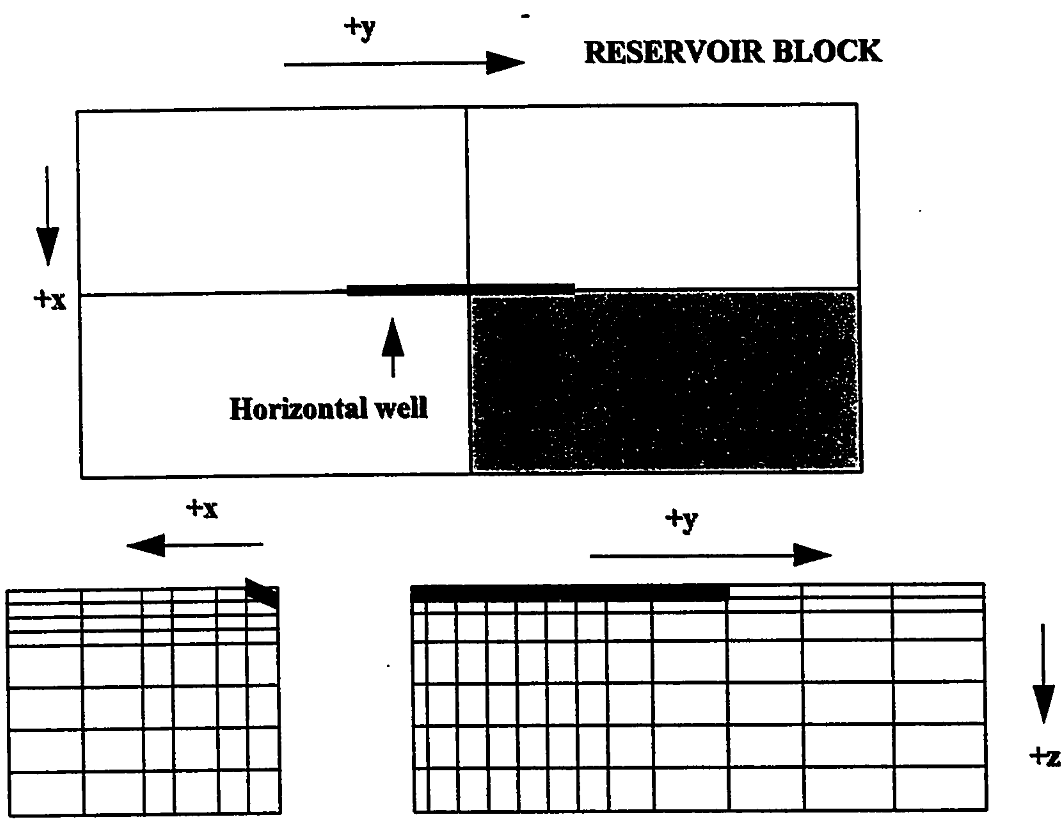


Figure 4.1: An illustration of Saturation Function Measurement

is gradually increased or decreased until a satisfactory value is determined for which the saturation function does not cross its' threshold value even after a long period of thirty years. This value is defined as the critical rate for the given reservoir and well conditions.

The threshold value of the saturation function for this particular study was set at 1.0E-04. A smaller value gives more conservative estimates for critical rates, while a higher value gives optimistic estimates of large critical rate. After trying several values 1.0E-04 was found to be a good compromise.

It is necessary to observe the behavior of the saturation function in all the vertical planes along the length of the horizontal well. The saturation function value in each vertical plane along the horizontal well is observed. The critical rate corresponds to that value for which the saturation function remains within its' threshold limit in all the vertical planes along the horizontal well. However, for a vertical well only one and not all planes needs to be observed: the one in which the well is located.

4.2 BEHAVIOR OF SATURATION FUNCTION WITH TIME

The preliminary research was centered around studying the behavior of the saturation function with time. Figure 4.2 shows how saturation function varies for different rates. Each point corresponds to the saturation function measured at the end of thirty years for a given rate. It can be observed that as the rate is increased from subcritical to a supercritical rate a clear transition occurs. The rate corresponding to the threshold saturation function value at the end of thirty years is selected as the critical rate.

In Figure 4.3 the saturation function is shown as a function of rate for various times. For a supercritical rate a dramatic increase in the saturation function is observed, manifesting that coning occurs suddenly when the rate is higher than a certain value. For subcritical rates even after thirty years the saturation function does not show any substantial rise. The method of saturation function thus provides a reliable way of tracking the water front by observing the water saturation and the change in it a soon as the water crest reaches the well.

4.3 RESERVOIR MODEL

The commercial simulator ECLIPSE, version 93/A was used for this research. All the runs were made on a SUN SPARC10 workstation in the Petroleum Engineering section, KFUPM Research Institute, Dhahran, SaudiArabia.A 3D reservoir model was used in this study. The model selected for this study was basically based on a

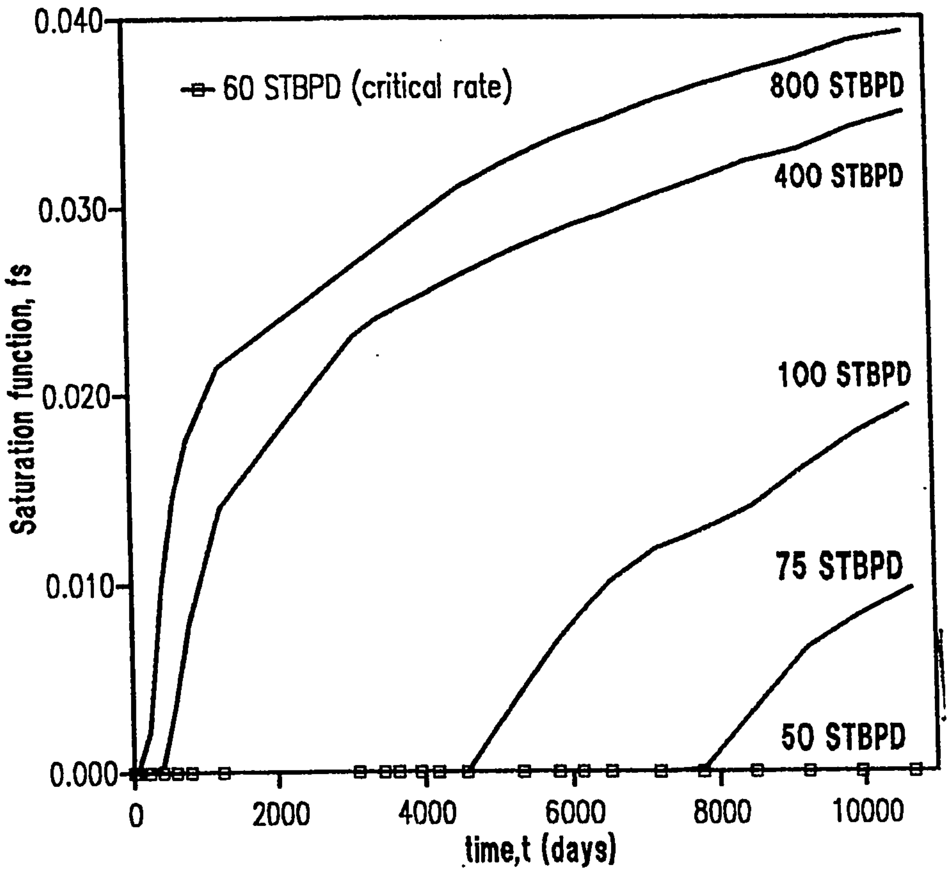


Figure 4.2: Development of saturation function with time.

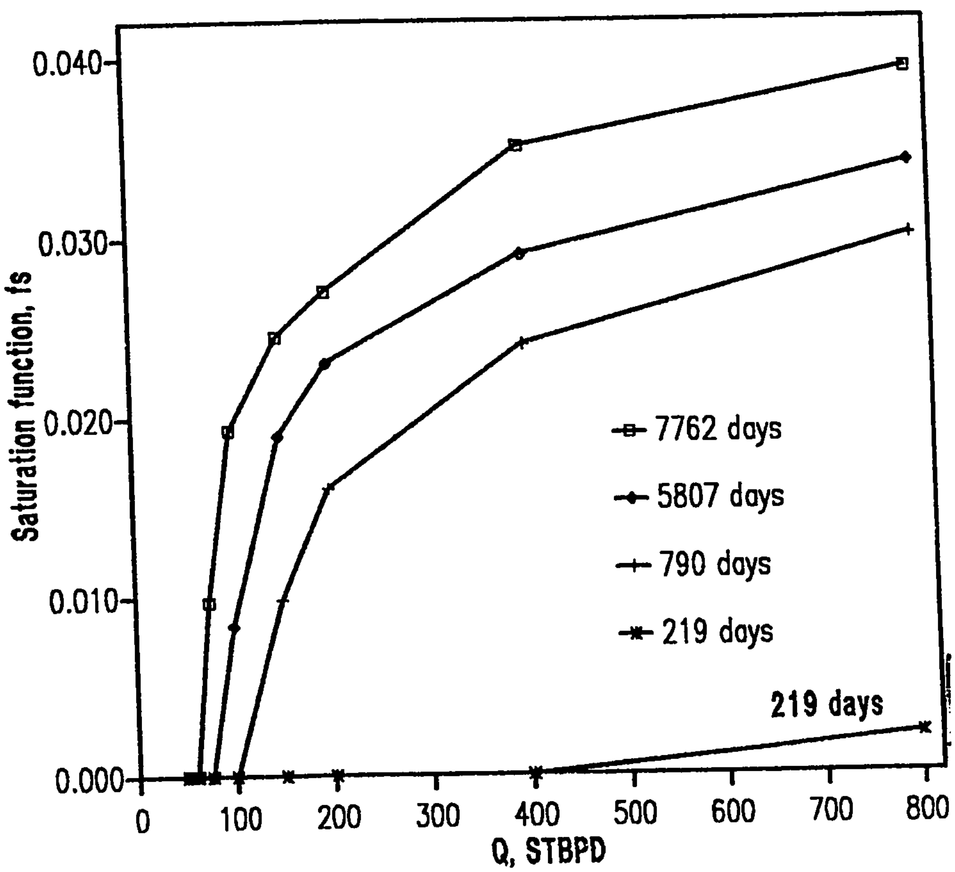


Figure 4.3: Saturation function vs Rate.

reservoir lying in a tilted plane. Table 4.1 and Table 4.2 provide basic information about the model. A schematic diagram is given in Figure 4.4. It is a stratified reservoir model with several layers of varying porosity and permeability differing in both horizontal and vertical direction.This model was used for history matching purposes and for preliminary study of a stratified reservoir. The tilt was removed for the parametric study, which was carried out for a horizontal reservoir.In order to simulate the tilt it was assumed that the surface of the reservoir is composed of a series of grid blocks stepping downwards. The numerical simulation model contains only a quarter of the actual reservoir. By virtue of symmetry, it is not necessary to simulate the entire reservoir thereby considerably reducing the computer time by the use of fewer grid blocks. In accordance with the standard definition, the horizontal well is assumed to be located parallel to the bedding plane. All the simulation runs were made for a quarter block of the actual reservoir to reduce data storage requirements.

4.4 GRID SYSTEM

Designing of the grid system is a fundamental step in developing a simulation model. For coning studies it is necessary to have a grid system which gradually refines as the well-bore is approached. In this study a sensitivity analysis was carried out to

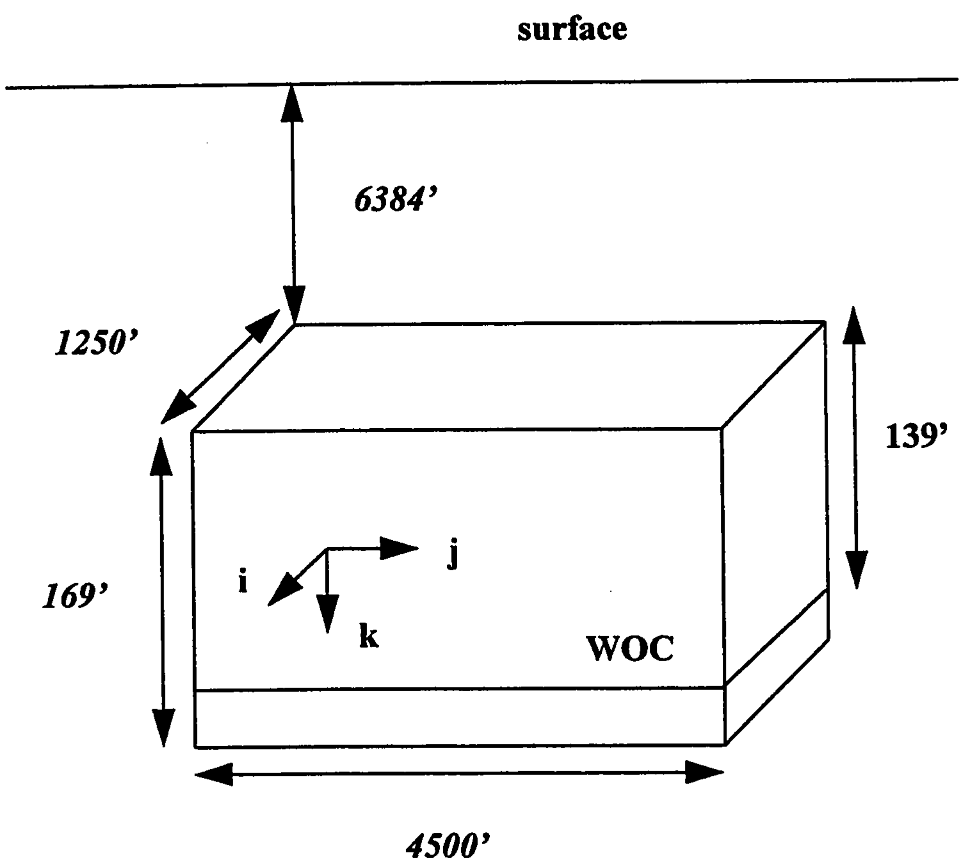


Figure 4.4: A schematic diagram of the reservoir model

Table 4.1: Reservoir Dimensions

DIMENSION	FEET
length	4500.0
width	1250.0
thickness	169.0
depth of the reservoir	6384.0
thickness of the aquifer	30.0
tilt angle (tilted reservoir)	5°

Table 4.2: Rock Properties of the Stratified Reservoir

Layer	Porosity (%)	k_h (md)	k_v (md)	Thickness
1	11.5	35.2	9.0	15.3
2	20.8	169.0	42.0	38.7
3	16.5	58.0	14.0	5.0
4	15.8	126.5	31.0	35.7
5	15.8	53.0	13.0	24.3
6	15.8	53.0	13.0	20.0
7	15.8	53.0	13.0	30.0

determine the optimum grid distribution. For this purpose the Local Grid Refinement (LGR) option available in ECLIPSE was also used. It was found that the increased storage requirement and running time did not warrant the use of extra refined grid blocks near the well-bore. The grid system had to be modified for runs with different well positions in the reservoir. Table 4.3 describes the grid system selected for various simulation runs. The **base case** refers to the simulation runs carried out for the stratified reservoir.

4.5 WELL REPRESENTATION

The version 93/A of ECLIPSE used in this study allows the user to describe a tilted or a horizontal well by making use of a COMPLETION key word in which the user provides the index values, (i, j, k), of the grid blocks in which the well is completed. Thus it is possible to complete the well in any set of inter-connected grid blocks making it possible to easily describe a vertical, horizontal or deviated well. In this study the horizontal well was completed in the second grid block in the x direction and third in the z direction. Table 4.3 gives index numbers of grid blocks in which the horizontal well is completed. Since the well is very close to the edge the symmetry requirements are not affected by not completing the well in the first x and y block.

Table 4.3: Completion Data for the Horizontal Well

Well	Grid	Block	Index
Length	X	Y	Z
500'	2	2-15	3
1000'	2	2-17	3
2000'	2	2-17	3
3000'	2	2-15	3

4.6 PVT AND FLUID DATA

The PVT data given in Table 4.4 to Table 4.7 for this study is taken from PVT data suggested for the Wafra Ratawi Oolite reservoir study available in the published literature [13]. This set of data has been selected not merely for the sake of convenience. In fact it only adds to the credibility of the results in that, it comes from an existing reservoir. The simulation runs carried out for the purpose of this study can be conveniently divided into following phases:

1. The history matching
2. Study of a tilted stratified reservoir
3. Study of a horizontal reservoir with user defined properties
4. Study of a tilted reservoir with user defined geometries.

4.7 HISTORY MATCHING

Using the above mentioned PVT data and reservoir properties a numerical model was developed and validated by carrying out history match using field production schedule data from published literature [13]. The water coning model for horizontal wells for the Ratawi Oolite Reservoir study was setup using the ECLIPSE 93/A version. An example of the ECLIPSE Input file is given in Appendix A.

History matching is an important part of any simulation study. It provides the only practical test of the validity of the computer model of the reservoir.The quality of the match and therefore the amount of confidence that one can have in a computer model depends upon the amount of data available for the history match. Matching parametres were reservoir pressure and cumulative production.

The results obtained from the history match are given in Figure 4.5 and Figure 4.6. The results obtained are compared with field data as well as the history match carried out in a previous study by Menouar et al. [13]. In Figure 4.6 the sudden increase in production at 10684 days is apparent after replacing the vertical well with a horizontal well. The results of the history match show that the simulator model for water coning gives result that match with not only field data but also with results obtained from previous history match. This validates

Table 4.4: Reservoir Data

Gas surface density	0.04104 lbm/cu.ft.
Oil surface density	56.85 lbm/cu.ft.
Water surface density	65.55 lbm/cu.ft.
Water viscosity (V_W)	0.50 cp
Water viscosibility (C_V)**	3.0E-06 psi^{-1}
Water FVF (B_W)	1.0 RB/STB
Water compressibility (C)*	3.0E-06 psi^{-1}
datum depth	6384 ft.
GOC depth	6384 ft.
WOC depth	6535 ft.
Rock compressibility	4.0E-06 psi^{-1}
Initial datum pressure	2756 psi
Oil zone thickness	139 ft.
Aquifer datum depth	6535 ft.
Initial water volume in aquifer	10.5E11 STB
Total (water + rock) compressibility	7.0E-06 psi^{-1}

$*C = -\left(dB_W / B_W dP \right)$ $\qquad$ $**C_V = \left(dV_W / V_W dP \right)$

Table 4.5: Oil Relative Permeability Data

Water Sat. (S_w)	k_{rw}	k_{row}	P_{cow}
0.206	0.00000	1.00000	0.0
0.250	0.00565	0.82296	0.0
0.300	0.01766	0.64270	0.0
0.350	0.03348	0.48469	0.0
0.400	0.05236	0.34894	0.0
0.450	0.07386	0.23545	0.0
0.500	0.09769	0.14420	0.0
0.550	0.12365	0.07521	0.0
0.600	0.15156	0.02848	0.0
0.650	0.18131	0.00400	0.0
0.680	0.20000	0.00000	0.0

Table 4.6: Gas Relative Permeability Data

Gas Relative Permeability			
Gas Sat. (S_g)	k_{rg}	k_{rog}	P_{cog}
0.000	0.00000	1.00000	0.0
0.030	0.00000	0.92520	0.0
0050	0.00020	0.87643	0.0
0.100	0.00251	0.75842	0.0
0.150	0.00740	0.64624	0.0
0.200	0.01485	0.54021	0.0
0.250	0.02487	0.44071	0.0
0.300	0.03746	0.34821	0.0
0.350	0.05263	0.26327	0.0
0.400	0.07036	0.18664	0.0
0.450	0.09066	0.11936	0.0
0.500	0.11353	0.06295	0.0
0.550	0.13897	0.02016	0.0
0.600	0.16698	0.00000	0.0
0.650	0.19756	0.00000	0.0
0.700	0.23071	0.00000	0.0
0.750	0.26643-	0.00000	0.0
0.794	0.30000	0.00000	0.0

Table 4.7: FVF and Viscosity of Reservoir Fluids

(a) Dry Gas		
Gas Press. psia	B_g RB/MSCF	μ_g cp
14.70	208.974	0.01280
500.00	5.86600	0.01320
1000.0	2.81000	0.01390
1470.00	1.85300	0.01480
1500.00	1.81300	0.01490
2000.00	1.33400	0.01610
2500.00	1.06400	0.01750
3000.00	0.89700	0.01900
3500.00	0.78600	0.02050
4000.00	0.70800	0.02200
4500.00	0.65200	0.02350
5000.00	0.60900	0.02500

(b) Live oil with dissolved gas			
R_S MSCF/STB	Oil Pressure psia	B_O RB/STB	μ_O cp
0.0012250	14.70	1.04	18.578
0.0602210	500.00	1.07	8.2850
0.1285700	1000.0	1.10	5.0520
0.2000000	1470.00	1.13	3.6800
0.2003610	1500.00	1.132	3.6170
0.2744900	2000.00	1.16	2.8210
0.3503000	2500.00	1.19	2.3180
0.4276000	3000.00	1.22	1.9730
0.5000000	3500.00	1.25	1.7220
0.6400000	4000.00	1.28	1.5310
0.7000000	4500.00	1.31	1.3800
0.8000000	5000.00	1.345	1.2590

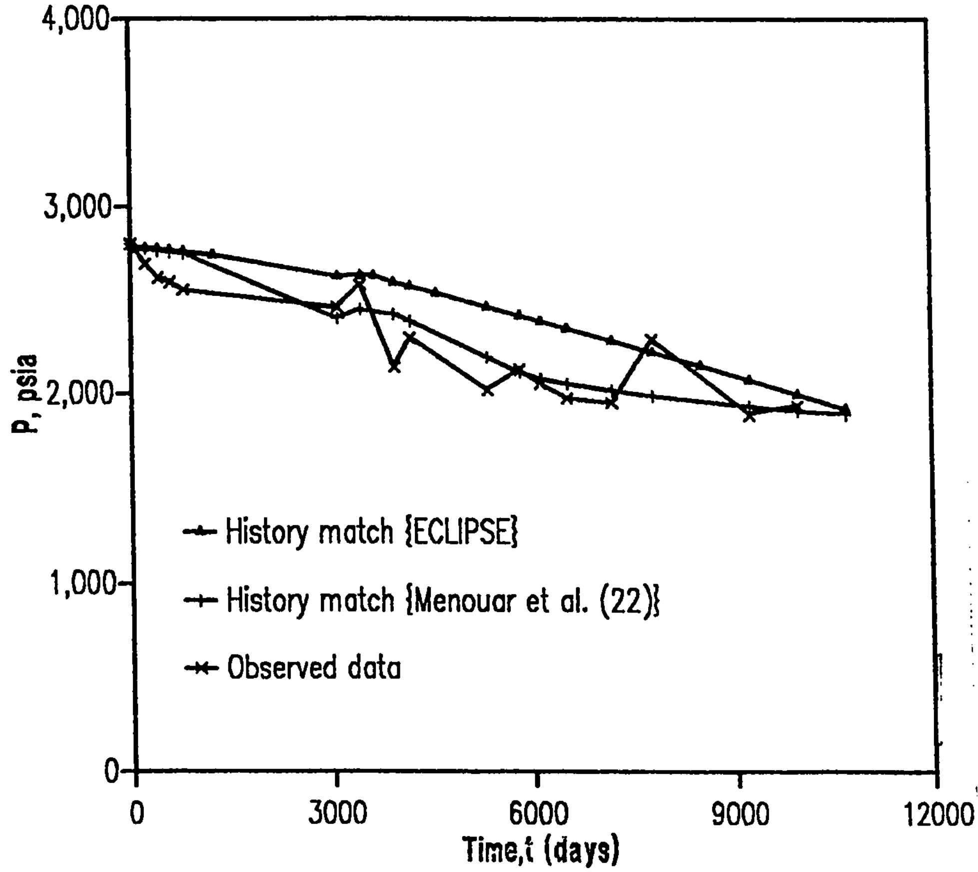


Figure 4.5: History match - Time vs Pressure

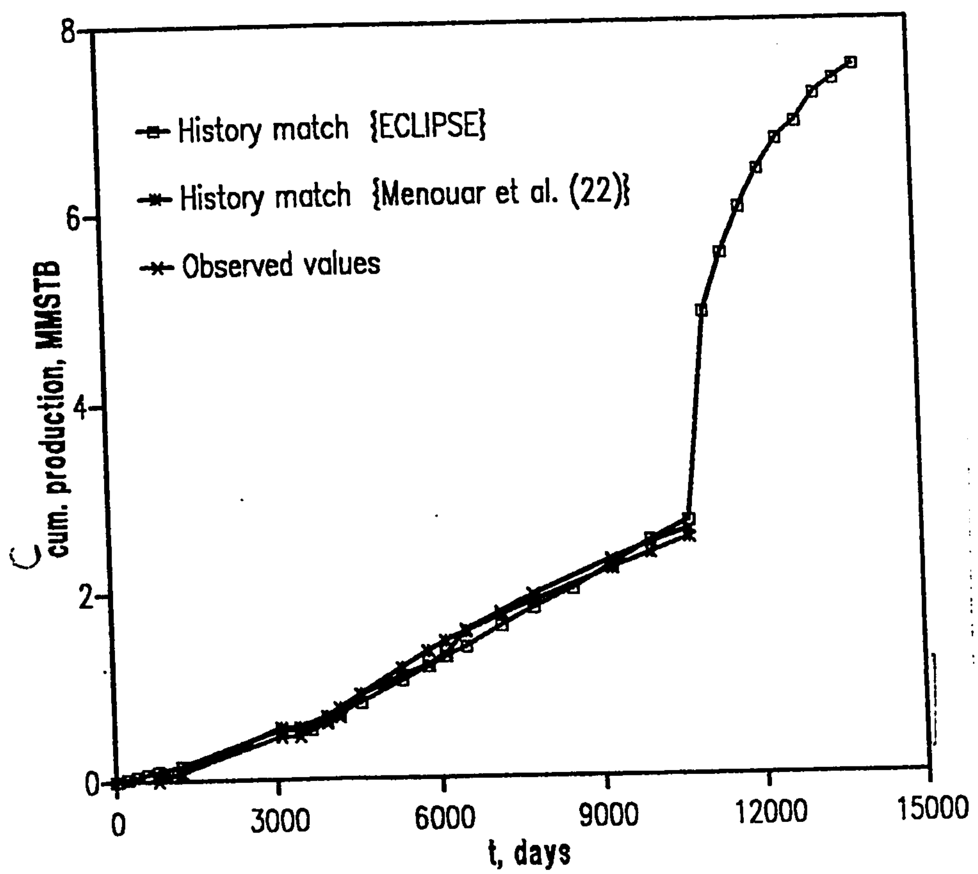


Figure 4.6: History match - Time vs Cum. Production

4.8 STRATIFIED RESERVOIR

After carrying out the hisotry match the same model for a stratified reservoir was run for various production rates to determine which of these rates is the critical rate. The characteristics of this reservoir have already been described in the discussion of history matching in the previous section. As the data for the stratified reservoir represents a real reservoir case, it provides interesting study of how changing the length of a horizontal well affects the critical rate in a real situation. In addition comparison with the performance of a vertical well is also done. The results are shown in Table 4.8 and plotted in Figure 4.7. In addition it is found that the critical rate for the longest horizontal well is as high as 8 times the critical rate for the vertical well for the same position.

Table 4.8: Critical rate as a function of length.

Tilted	***reservoir***
Length (ft.)	**Q (STBPD)**
vertical well	80
500.0	240
2000.0	440
3000.0	600

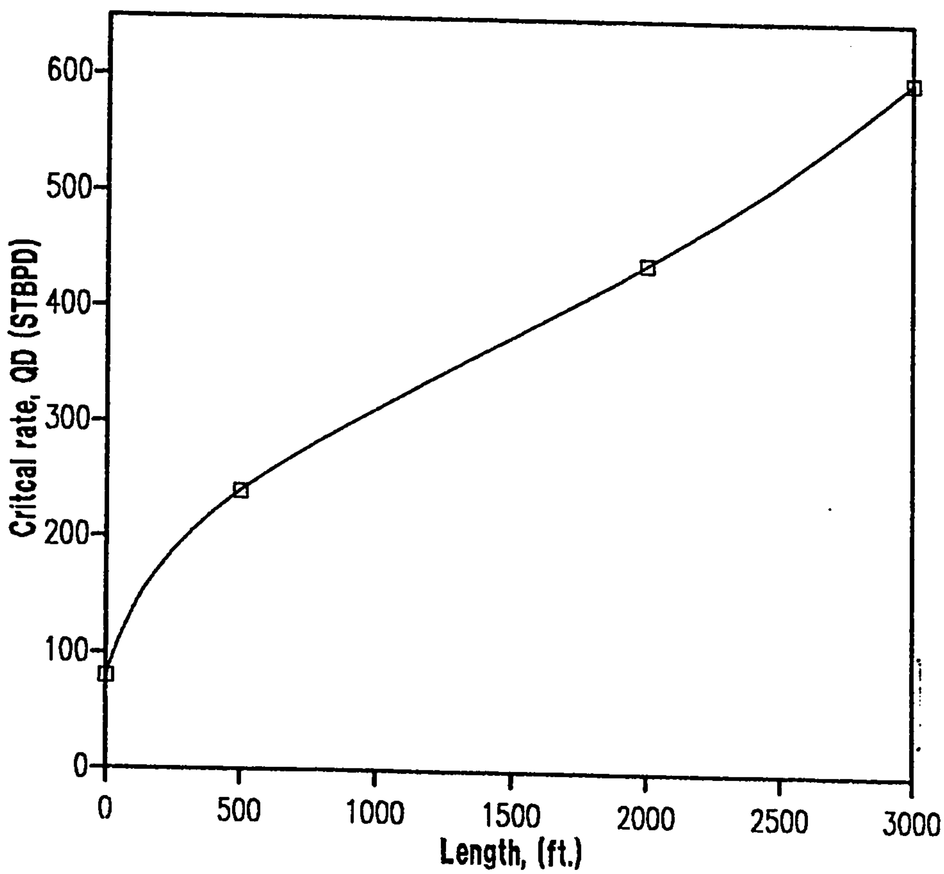


Figure 4.7: Critical rate for stratified reservoir

CHAPTER 5

HORIZONTAL RESERVOIR

After a successful history match which validated the reservoir simulation model followed by the first results for a stratified reservoir the parametric study was carried out for a series of simulation runs. These simulations are made for a horizontal reservoir. The analysis is presented for both vertical as well as horizontal wells and the effect of well position, reservoir anisotropy and geometry, and mobility ratio on horizontal well lengths of 500', 1000', 2000', and 3000' is studied in detail.

5.1 EFFECT OF WELL POSITION

5.1.1 Horizontal Well

The effect of well position upon the critical rate was analysed by determining the critical rate for well positions corresponding to ZD values of 1.0, 0.75, 0.50, 0.25. ZD is a dimensionless number, defined as follows:

$$ZD = \frac{H_t}{H_{oil}} = \frac{H_t}{139}$$

- H_t is the vertical distance from the well to the WOC
- H_{oil} is the vertical depth of WOC from the top of the reservoir

The reservoir is assumed to be homogeneous and isotropic with an absolute permeability of 45.6 md. The PVT properties and reservoir characteristics and geometry are the same as those for the stratified reservoir with the exception that the reservoir is not stratified and tilted. Results are shown in Table 5.1, Figures 5.1 and 5.2.

Figure 5.1 shows the effect of changing the well length for any given position, while Figure 5.2 shows the effect of changing the well position for any given well length upon the critical rate. From Figure 5.1 it can be seen that as the well length increases for a given position, the critical rate increases from a minimum value for a vertical well to a value which is 27 times higher for a 3000' well.

It should be noted that for any given increment in length the percentage increment in critical rate was found to be the same for all positions.

Table 5.1: Critical rate as a function of well length and it's position.

Horizontal Reservoir		**(a=1.0)**		
Length (ft.)	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**
	ZD = 1.0	**ZD =0.75**	**ZD =0.50**	**ZD =0.25**
500.0	120	100	80	40
1000.0	220	200	140	80
2000.0	380	340	240	140
3000.0	540	480	340	200

5.1.2 VERTICAL WELLS

Similar analysis was also carried out for vertical well. The perforated interval was placed at the same positions, ZD, that were used for the analysis of horizontal wells. The thickness of the perforated interval in this study remains 20.0'. See Table 5.2 and Figures 5.1 and 5.2. It can be observed from Figure 5.2 that as the well is brought closer to the WOC the critical rate decreases from a maximum to a minimum value with a 60% drop with respect to the critical rate for the ZD=1.0 position. In addition it is observed that the

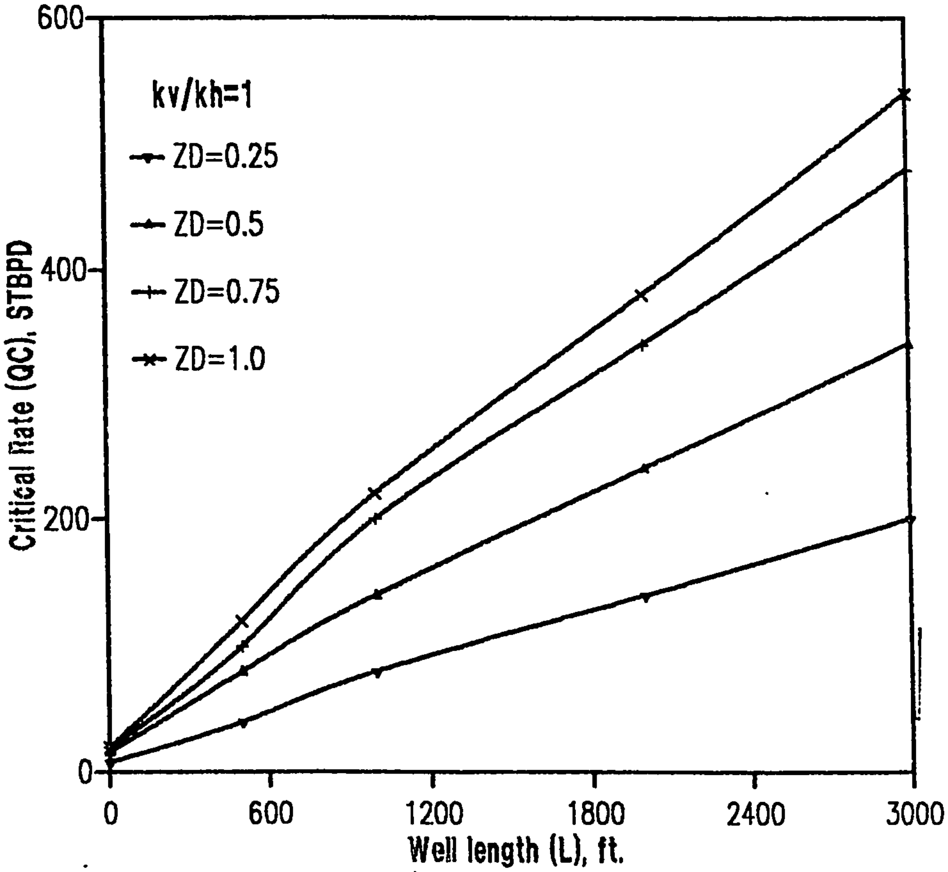


Figure 5.1: Variation with length for different well positions.

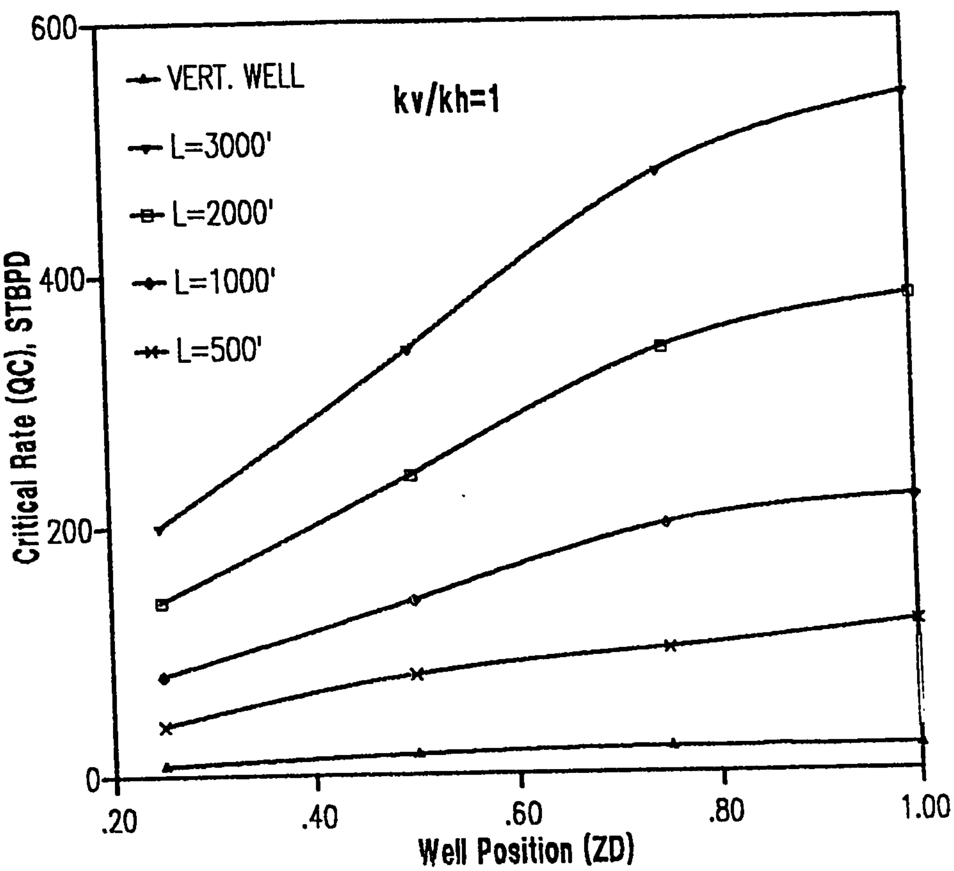


Figure 5.2: Variation with position for different well lengths.

critical rate for the longest horizontal well is as high as 27 times the critical rate for the vertical well at the same position.

Table 5.2: Critical rate as a function of ZD for a vertical well.

Horizontal	***Reservoir***
Anisotropy	**Ratio = 1.0**
ZD	**Qc (STBPD)**
1.0	20
0.75	20
0.50	16
0.25	8

5.2 EFFECT OF RESERVOIR ANISOTROPY

The effect of reservoir anisotropy was studied using anisotropy ratios of 1.0, 0.5, 0.2 and 0.1 for the four well positions, ZD.

5.2.1 HORIZONTAL WELL

The results for the horizontal well are shown in Tables 5.3 to 5.6. For this study only the vertical permeability is changed while the horizontal permeability is kept at the base case value of 45.6 md. It is observed that:

1. As the well position is changed from ZD=1 to ZD=0.25, it is found that the drop in critical rate increases progressively.
2. For well in ZD=1.0 position, the critical rate increases with length but the percentage increase keeps on decreasing for each increment in length.
3. Irrespective of the well position, ZD, as shown in Figure 5.3 to 5.6 and presented in Tables 5.7 to 5.10, the critical rate tends to increase slightly as the anisotropy ratio decreases from a maximum value of 1.0 to a minimum value of 0.1. However as the length increases the trend tends to change.

An analysis of the behavior of critical rate for different positions of any well length was also done. The results are plotted in Figures 5.7 to Figure 5.10. The results are presented in Tables 5.11 to 5.14. As shown in Tables 5.11 to 5.14, the drop in the critical rate at ZD=0.25 with respect to its' value at ZD=1 increases with decrease in anisotropy ratio. It can also be observed that for a given anisotropy ratio the percentage drop in critical rate does not change for any well length.

5.2.2 VERTICAL WELL

The effect of anisotropy ratio was studied for the case of a

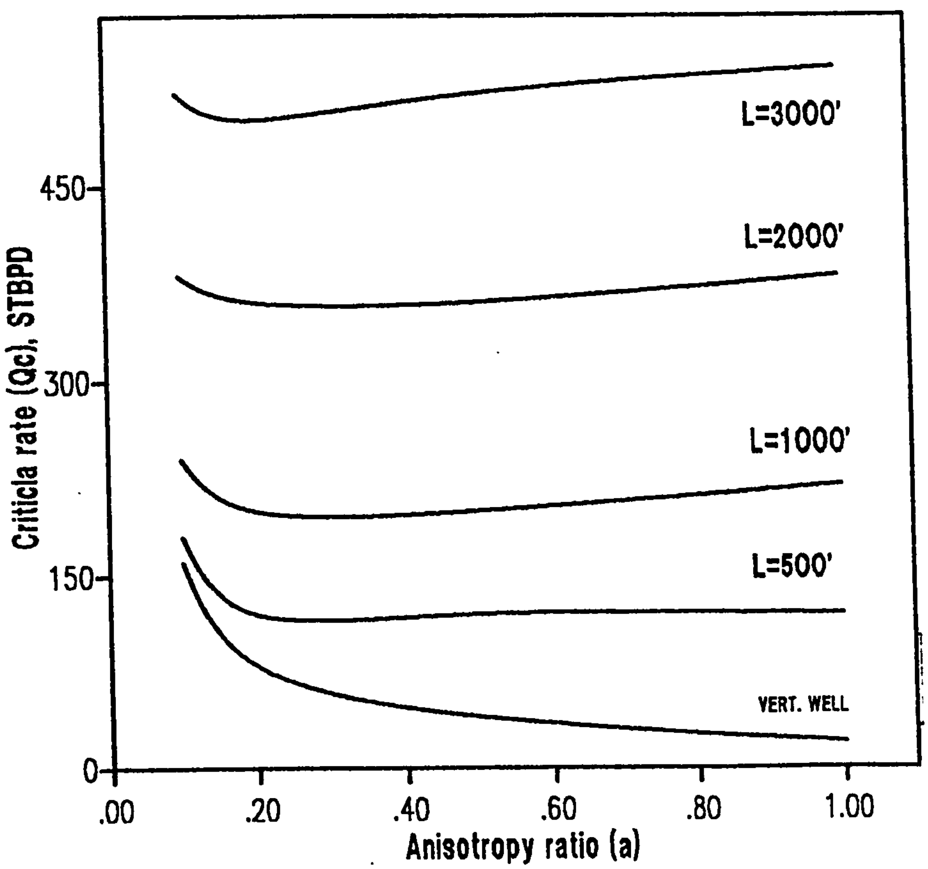


Figure 5.3: Effect of anisotropy ratio for a well when ZD=1.

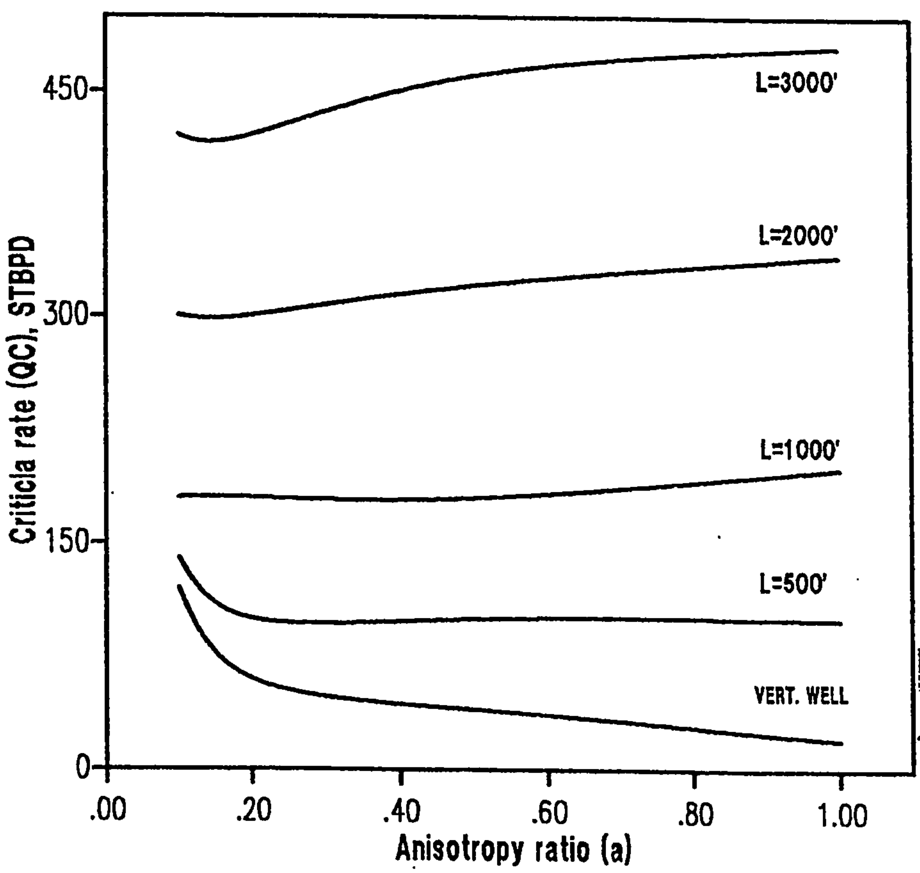


Figure 5.4: Effect of anisotropy ratio for a well when ZD=0.75.

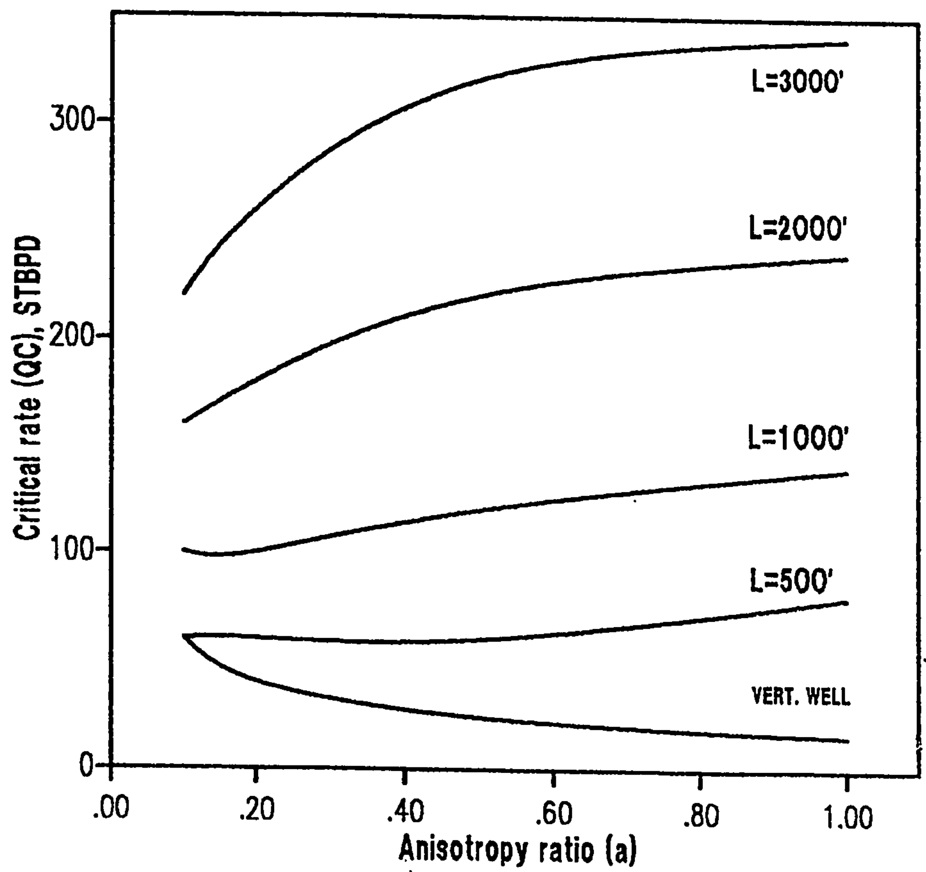


Figure 5.5: Effect of anisotropy ratio for a well when ZD=0.5.

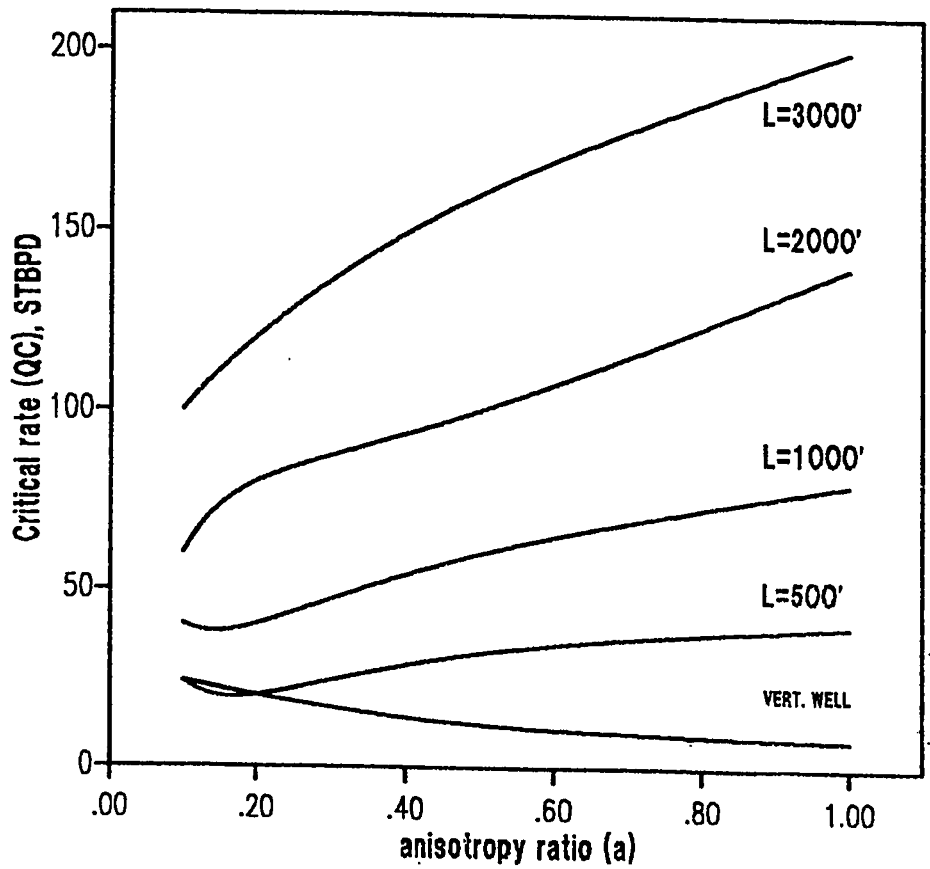


Figure 5.6: Effect of anisotropy ratio for a well whenZD=0.25.

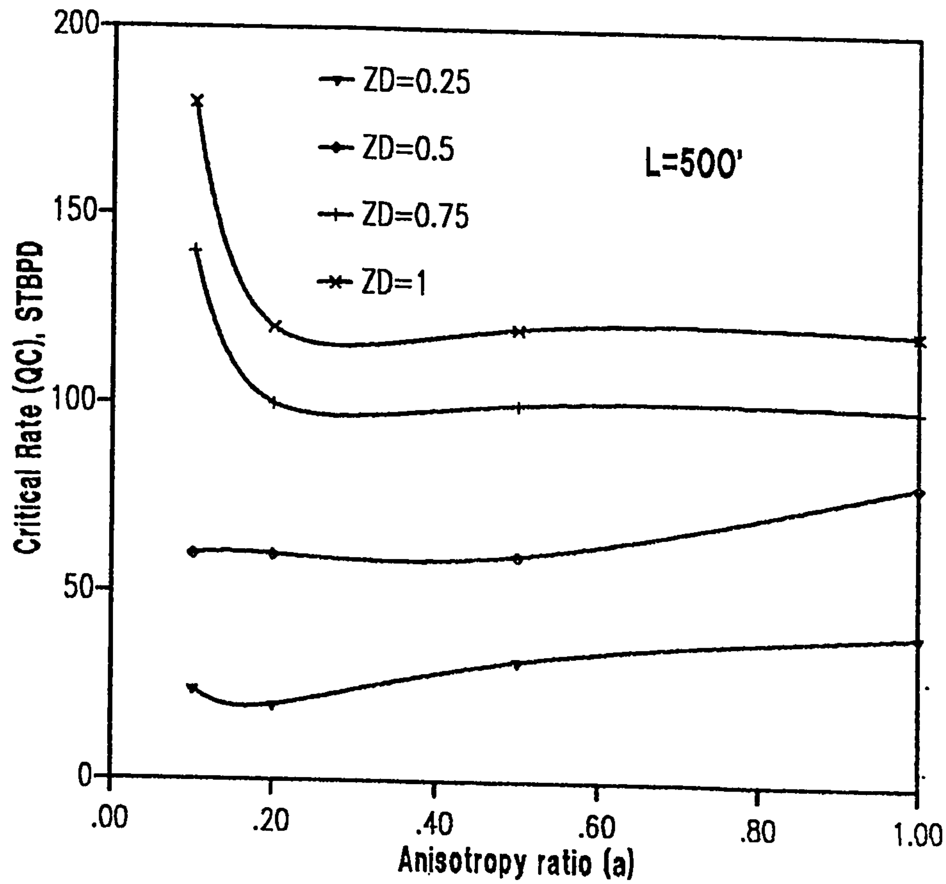


Figure 5.7: Effect of anisotropy ratio on L=500' well for all positions.

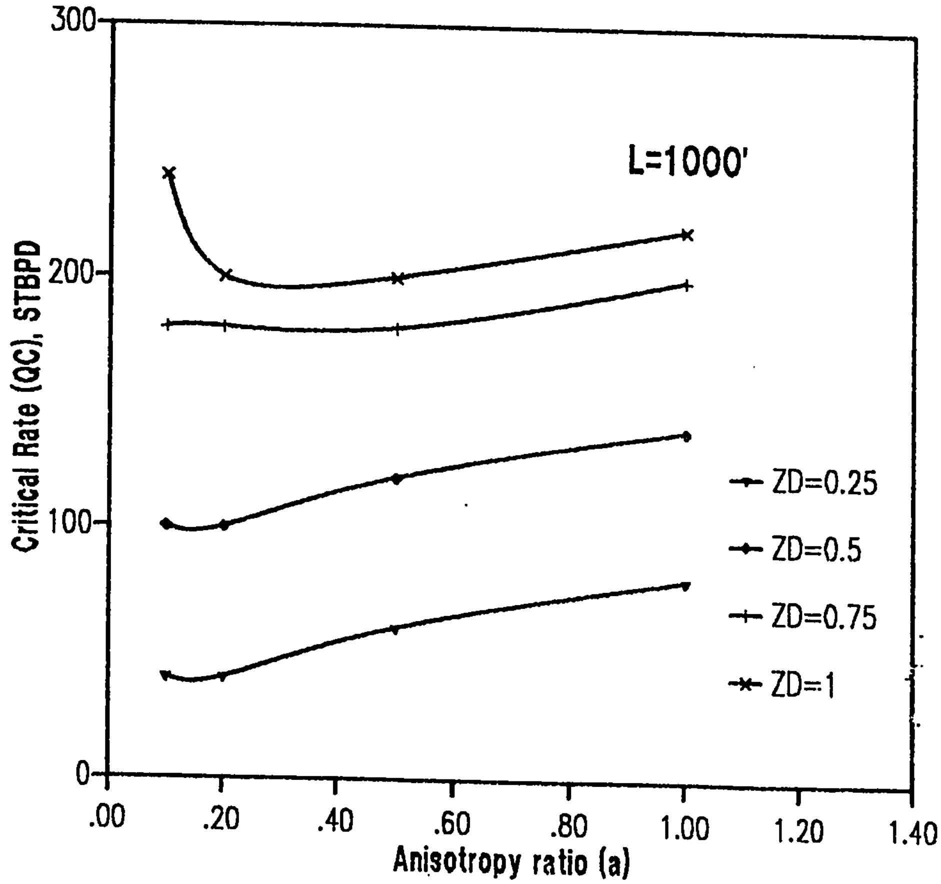


Figure 5.8: Effect of anisotropy ratio on L=1000' well for all positions.

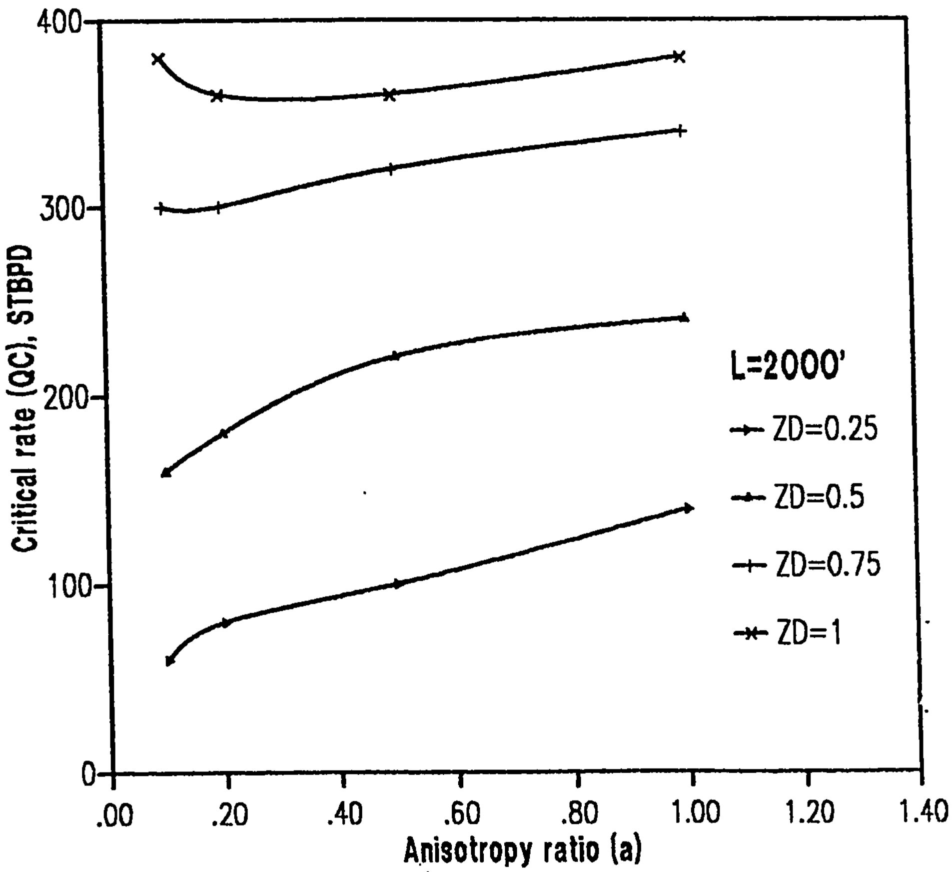


Figure 5.9: Effect of anisotropy ratio on L=2000' well for all positions.

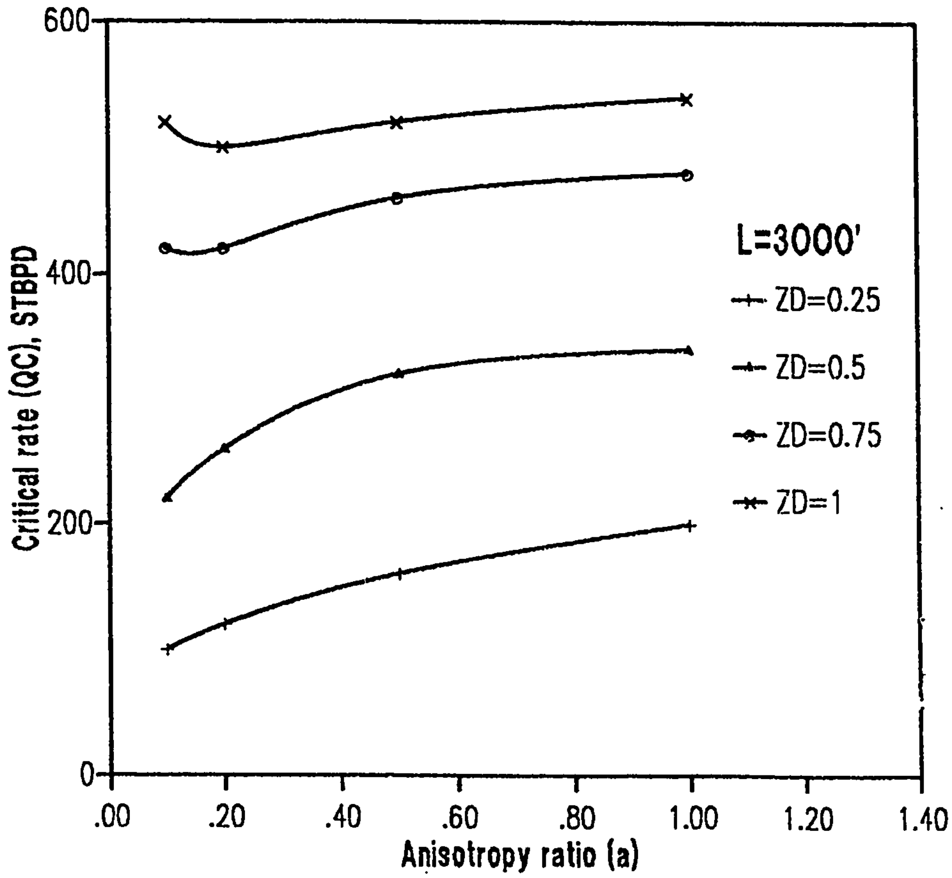


Figure 5.10: Effect of Anisotropy ratio on L=3000' well for all positions

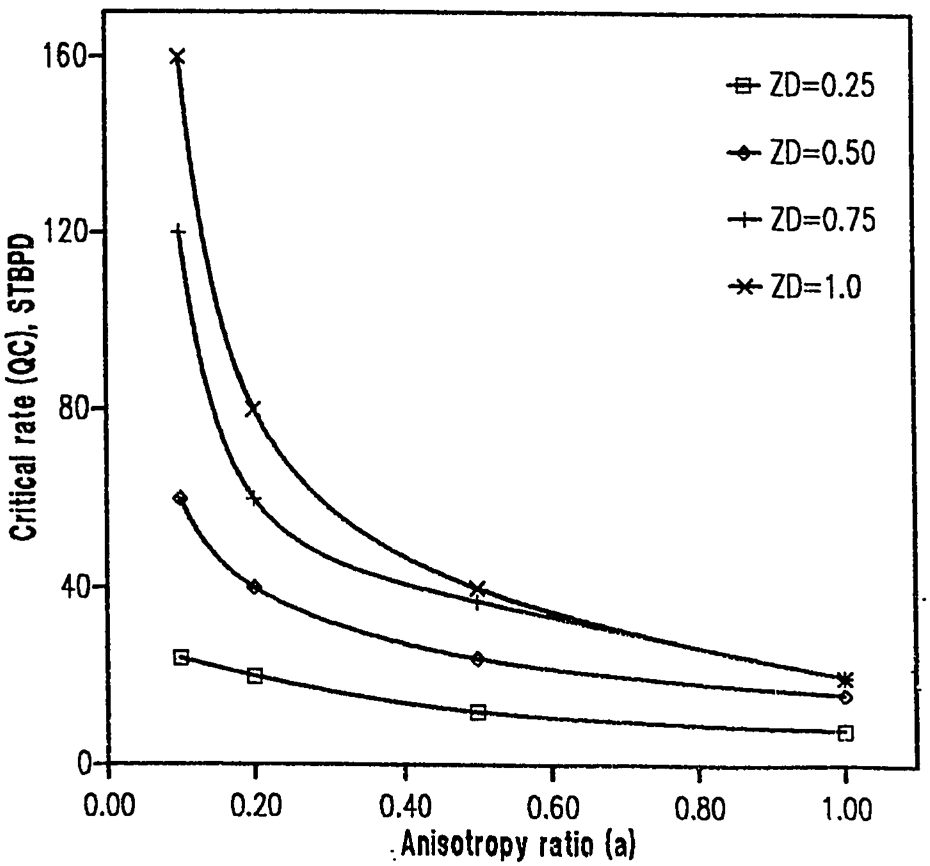


Figure 5.11: Effect of anisotropy ratio on QC for a vertical well.

Table 5.3: Effect of Anisotropy ratio on Critical Rates (ZD=1.0)

	a= 1.0	a= 0.5	a= 0.2	a= 0.1
Well Length (ft.)	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**
500.0	120	120	120	180
1000.0	220	200	200	240
2000.0	380	360	360	380
3000.0	540	520	500	520

Table 5.4: Effect of Anisotropy ratio on Critical Rates (ZD=0.75)

Horizontal	***Reservoir***			
	a= 1.0	**a= 0.5**	**a= 0.2**	**a= 0.1**
Well Length (ft.)	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**
500.0	100	100	100	140
1000.0	200	180	180	180
2000.0	340	320	300	300
3000.0	480	460	420	420

Table 5.5: Effect of Anisotropy ratio on Critical Rates (ZD=0.5)

	a= 1.0	a= 0.5	a= 0.2	a= 0.1
Well Length (ft.)	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**
500.0	80	60	60	60
1000.0	140	120	100	100
2000.0	240	220	180	160
3000.0	340	320	260	220

Table 5.6: Effect of Anisotropy ratio on Critical Rates (ZD=0.25)

Horizontal Reservoir				
	a= 1.0	a= 0.5	a= 0.2	a= 0.1
Well Length (ft.)	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**
500.0	40	32	20	24
1000.0	80	60	40	40
2000.0	140	100	80	60
3000.0	200	160	120	100

Table 5.7: Effect of anisotropy ratio on critical rate for ZD=1.0

Well Length (ft.)	$\frac{Q_c\|_{a=0.1}}{Q_c\|_{a=1.0}}$
500	1.5
1000	1.1
2000	no change
3000	0.95

Table 5.8: Effect of anisotropy ratio on critical rate for ZD=0.75

Well Length (ft.)	$\frac{Q_c\|_{a=0.1}}{Q_c\|_{a=1.0}}$
500	1.4
1000	0.9
2000	0.88
3000	0.88

Table 5.9: Effect of anisotropy ratio on critical rate for ZD=0.5

Well Length (ft.)	$\frac{Q_c\|_{a=0.1}}{Q_c\|_{a=1.0}}$
500	0.75
1000	0.70
2000	0.66
3000	0.65

Table 5.10: Effect of anisotropy ratio on critical rate for ZD=0.25

Well Length (ft.)	$\frac{Q_c\|_{a=0.1}}{Q_c\|_{a=1.0}}$
500	0.6
1000	0.5
2000	0.4
3000	0.4

Table 5.11: Effect of change in well position on horizontal well:

L=500'

Anisotropy ratio	% drop in Qc
1.0	67%
0.5	73%
0.2	83%
0.1	87%

Table 5.12: Effect of change in well position on horizontal well:

L=1000'

Anisotropy ratio	% drop in Qc
1.0	64%
0.5	70%
0.2	80%
0.1	83%

Table 5.13: Effect of change in well position on horizontal well: L=2000'

Anisotropy ratio	% drop in Qc
1.0	63%
0.5	72%
0.2	78%
0.1	84%

Table 5.14 : Effect of change in well position on horizontal well: L=3000'

Anisotropy ratio	% drop in Qc
1.0	63%
0.5	70%
0.2	76%
0.1	81%

vertical well. Table 5.15 gives the results for a vertical well. The results are also presented in Figure 5.11. It can be observed that for a given anisotropy ratio the critical rate drops as the well approaches the OWC from ZD=1.0. This drop expressed as a fraction of the critical rate for the top position of well increases as anisotropy ratio increases. This is given in Table 5.16. Another observation made for horizontal well is related to the behavior of the critical rate as the anisotropy ratio changes from 1.0 to 0.1 for different well positions. As shown in Table 5.17 and Figures 5.3 to 5.6, increase in critical rate for vertical well decreases with position of well.

5.2.3 DETAILED ANALYSIS OF WELL: L=2000'

In order to study the behavior of critical rate with respect to the anisotropy ratio in more detail specifically for very small anisotropy ratios, a detailed analysis of the effect of anisotropy ratio was carried out by determining the critical rates for additional values of the anisotropy ratio, and plotting the results to identify the exact behavior over a still larger range of the anisotrooy ratio. The analysis was carried out for ZD=1 and ZD=0.5 positions only and for one well length of 2000'. The results presented in Table 5.18 are also shown in Figure 5.12.

Table 5.15: Effect of Anisotropy ratio on Vert. well for various ZD.

Horizontal Reservoir			
	a= 0.5	a=0.2	a=0.1
ZD	**Qc**	**Qc**	**Qc**
1.0	40	80	160
0.75	40	60	120
0.5	24	40	60
0.25	12	20	24

The following results are concluded from these observations :

1. As anisotropy ratio changes from 1.0 to 0.1 critical rate remains unchanged for ZD=1 and drops by 33% for ZD=0.5 with respect to higher critical rate.
2. As anisotropy ratio changes from 0.1 to 0.032 critical rate increases by 41% for the ZD=1 case and by 33% for ZD=0.5 case.

5.3 EFFECT OF RESERVOIR GEOMETRY

After investigating the effect of anisotropy ratio, the following reservoir geometries are studied:

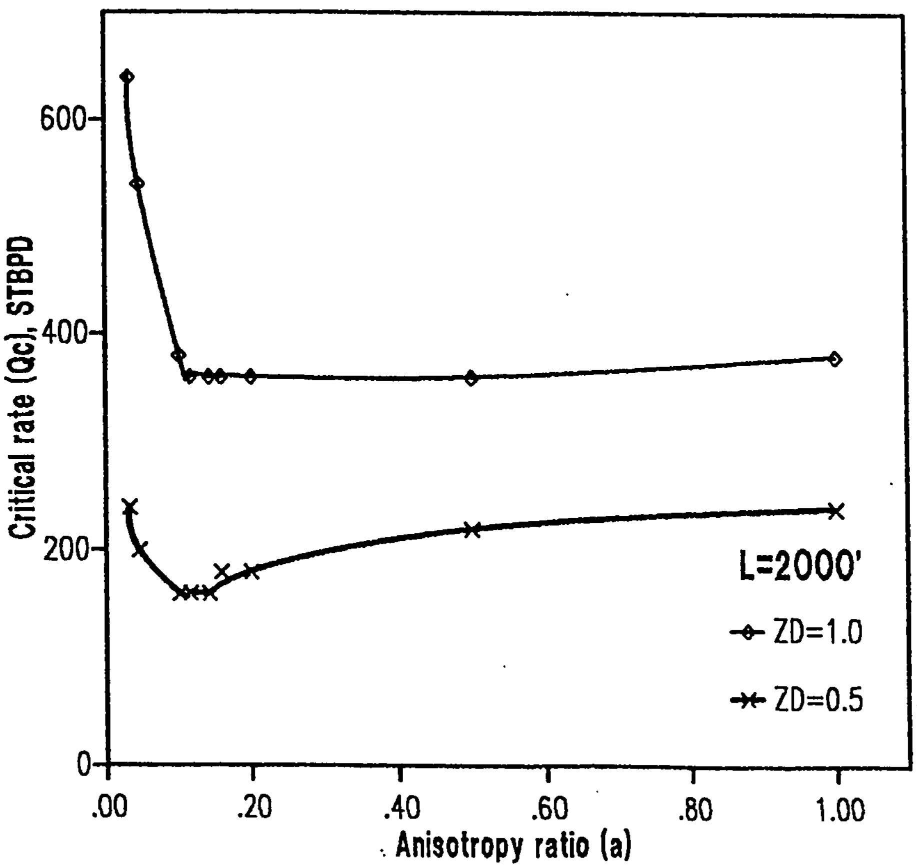


Figure 5.12: A detailed analysis of the effect of anisotropy ratio.

Table 5.16: Critical Rate % drop with anisotropy ratio (vert. well)

Anisotropy ratio	% Drop in Qc
1.0	60%
0.5	70%
0.2	75%
0.1	85%

Table 5.17: Effect of anisotropy ratio on vertical well Qc for all ZD

ZD	$Q_c\vert_{a=0.1}/Q_c\vert_{a=1.0}$
1.0	8
0.75	7
0.50	4
0.25	3

Table 5.18: Detailed Analysis for Anisotropy on well: L=2000'

Horizontal reservoir		
L = 2000'	**ZD=1**	**ZD=0.5**
Anisotropy ratio	**Qc (STBPD)**	**Qc (STBPD)**
1.0000	380	240
0.5000	360	220
0.2000	360	180
0.1580	360	180
0.1414	360	160
0.1155	360	160
0.1000	380	160
0.0450	540	200
0.0316	640	240

1. A square reservoir of dimensions 4500*4500 sq.ft. **(Case A)**
2. A rectangular reservoir of dimensions 2250*4500 sq.ft. **(Case B)**
3. The base case reservoir of dimensions 1250*4500 sq.ft. **(Case C).**

The analysis is carried out for case A and case B for only two well positions: ZD=1.0 and ZD=0.5. All the runs are made for the case of a homogeneous, isotropic reservoir. In addition to the vertical well well lengths of 1000', 2000' and 3000' were considered too.

5.3.1 HORIZONTAL WELL

In the case of horizontal wells it is observed that increasing the area of the reservoir results in an increase in the critical rate. Table 5.19 presents the results. The effect of geometry is presented in Figure 5.13, Figure 5.14 and in Tables 5.20 to 5.22. The percentage drop in critical rate with respect to the higher value for all lengths is presented. It is evident that longer well length shows higher drop in critical rate and this drop is higher if the well position, ZD, is closer to the OWC.

5.3.2 VERTICAL WELL

The effect of geometry on vertical well has also been studied. Table 5.23, Figure 5.13 and Figure 5.14 show the results obtained for vertical wells. The effect of reservoir geometry is also presented in Tables 5.24 and 5.25. It can be observed that the effect of reducing the size of the reservoir is to decrease the critical rate value. This drop increases as distance from OWC increases.

5.4 EFFECT OF RESERVOIR MOBILITY RATIO

A dimensionless mobility ratio, M_D, has been defined as the ratio of any given mobility ratio to the mobility ratio for the base case. The base case mobility ratio has been found to be 1.25. The mobility ratios 12.15 (10 times the mobility ratio of the base case), 6.075 (5 times the mobility ratio of the base case) and 0.243 (0.2 times the mobility ratio of the base case) were used:

1. $M_{10} = 10$
2. $M_5 = 5$
3. $M_{0.2} = 1/5$ respectively.

The mobility ratio was changed by changing the viscosity of the oil. The purpose of defining this dimensionless variable is to demonstrate the degree of change in mobility ratio. For the sake of brevity this ratio will be referred to as the mobility ratio (M_D). The effect of mobility ratio (M_D) has been studied for the case of a homogeneous and isotropic reservoir for the well position ZD=1 and ZD=0.5 with well lengths, 1000', 2000', 3000' and a vertical well:

5.4.1 HORIZONTAL WELL

Table 5.26 and Figures 5.15 to 5.18 present the results obtained for the case of a horizontal well. The following interesting conclusions can be made from these observations:

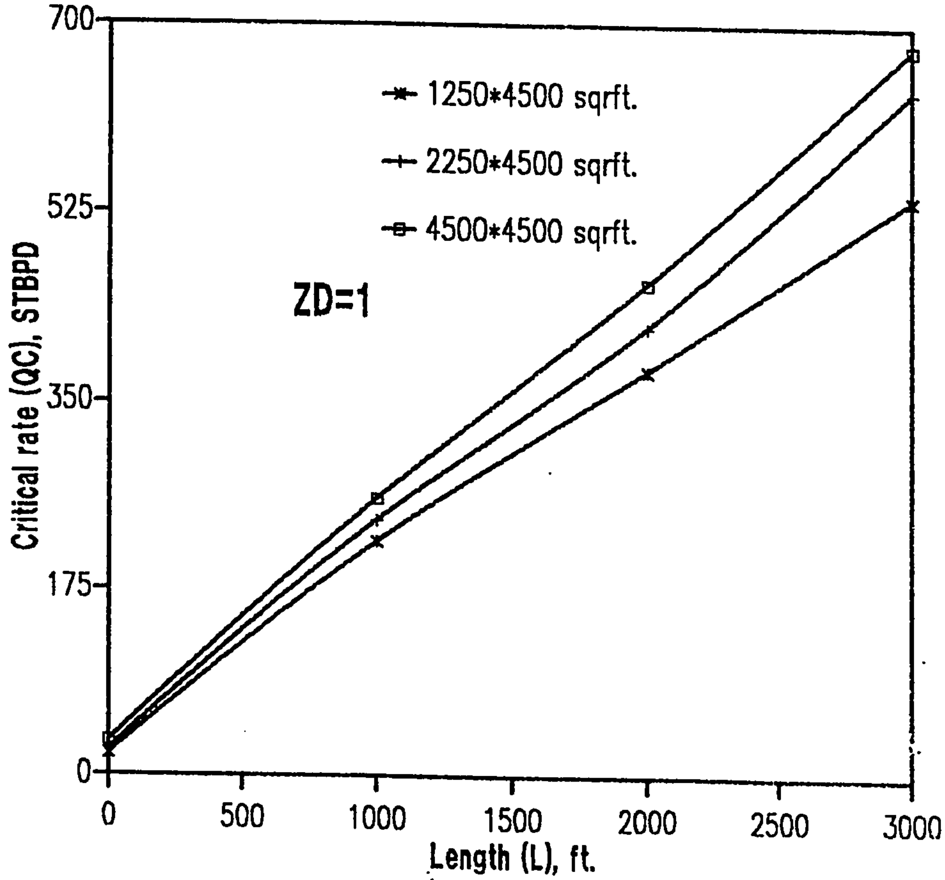


Figure 5.13: Effect of reservoir geometry for different well lengths.

Table 5.19: Effect of Reservoir Geometry on Critical Rate

Horizontal	*Reservoir*			
	ZD=1	*plane*	ZD=0.5	*plane*
	4500'*4500'	2250'*4500'	4500'*4500'	2250'*4500'
Well length	Qc (STBPD)	Qc (STBPD)	Qc (STBPD)	Qc (STBPD)
1000.0'	260	240	160	160
2000.0'	460	420	300	260
3000.0'	680	640	440	400

Table 5.20: Critical Rate % drop with reservoir geometry:

L=1000'

Res. Geometry	% Drop in Qc	Res. Geometry	% Drop in Qc
ZD=1		ZD=0.5	
A-C	15%	A-C	13%
A-B	8%	A-B	no change
B-C	8%	B-C	13%

Table 5.21: Critical Rate % drop with reservoir geometry: L=2000'

Res. Geometry	% Drop in Qc	Res. Geometry	% Drop in Qc
ZD=1		**ZD=0.5**	
A-C	17%	A-C	20%
A-B	9%	A-B	13%
B-C	9%	B-C	8%

Table 5.22: Critical Rate % drop with reservoir geometry: L=3000'

Res. Geometry	% Drop in Qc	Res. Geometry	% Drop in Qc
ZD=1		**ZD=0.5**	
A-C	21%	A-C	23%
A-B	6%	A-B	9%
B-C	6%	B-C	15%

Table 5.23: Effect of Geometry on Vertical Well

ZD=1	
Geometry (ft^2)	**Qc (STBPD)**
4500*4500	32
2250*4500	24
ZD=0.5	
4500*4500	20
2250*4500	20

Table 5.24: Critical Rate % drop with reservoir geometry for vertical wells (ZD=1)

Reservoir Geometry	% Drop in Qc
A-C	38%
A-B	25%
B-C	17%

Table 5.25: Critical Rate % drop with reservoir geometry for vertical wells (ZD=0.5)

Reservoir Geometry	% Drop in Qc
A-C	20%
A-B	no change
B-C	20%

1. As the value of M_D increases for horizontal wells from M_D=0.2 to M_D=1.0, the value of critical rate rises but thereafter for M_D>1 it keeps on decreasing irrespective of well position.
2. Shifting a well's position displays the following results:
   - For $0.2 \leq M_D \leq 5.0$ the value of critical rate rises for the horizontal well ,while
   - For $5.0 \leq M_D \leq 10.0$ the value of critical rate decreases for the horizontal well.
3. In Table 5.27 the effect of mobility ratio on the percentage increase in critical rate, if a vertical well is replaced by a 3000' horizontal well is presented for various mobility ratios.

It can be observed that as the mobility ratio increases the percentage increase in critical rate by replacing a vertical well with a horizontal well increases.

5.4.2 VERTICAL WELL

The effect of mobility ratio for the case of a vertical well was also studied for the above mentioned mobility ratios. The results are given in Table 5.28. The results are also shown in Figures 5.15 to 5.18. The following interesting conclusions can be made:

1. As the value of M_D increases for a vertical well, in contrast to the behavior of a horizontal well, the value of critical rate decreases irrespective of the range of M_D and well position.
2. Shifting a well's position gives the following results:
   - In the range: $0.2 \leq M_D \leq 5.0$, value of critical rate decreases for a vertical well, while
   - In the range: $5.0 \leq M_D \leq 10.0$, value of critical rate increases for vertical well.

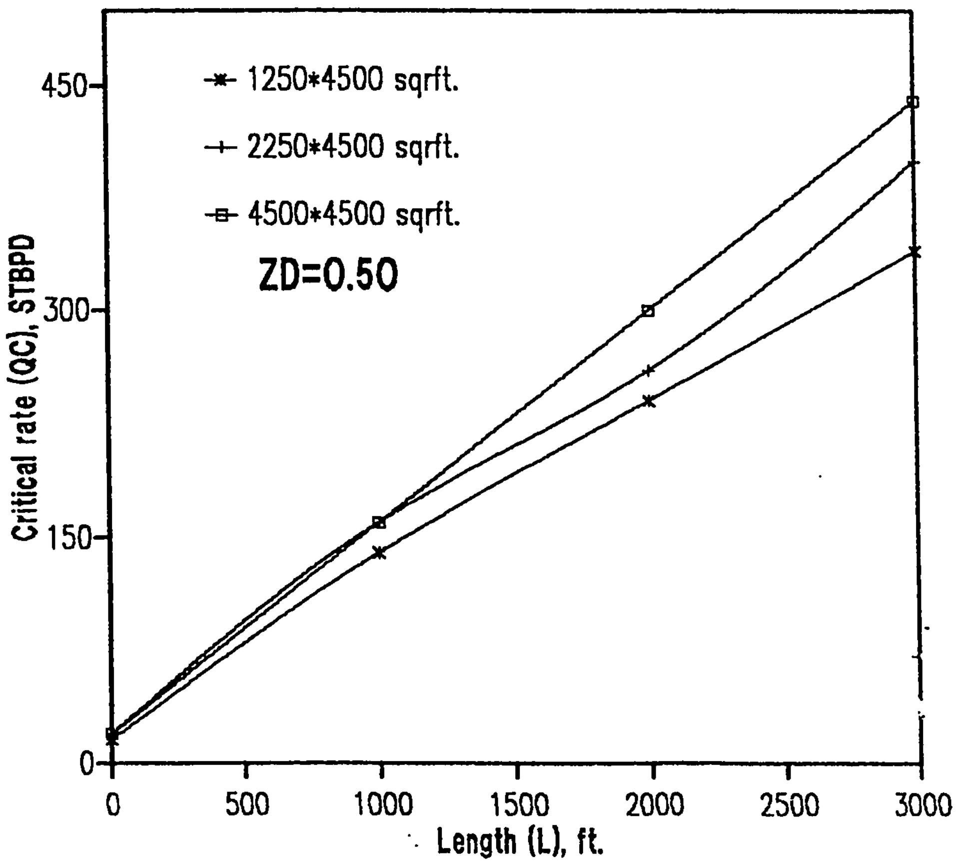


Figure 5.14: Effect of reservoir geometry for different well lengths.

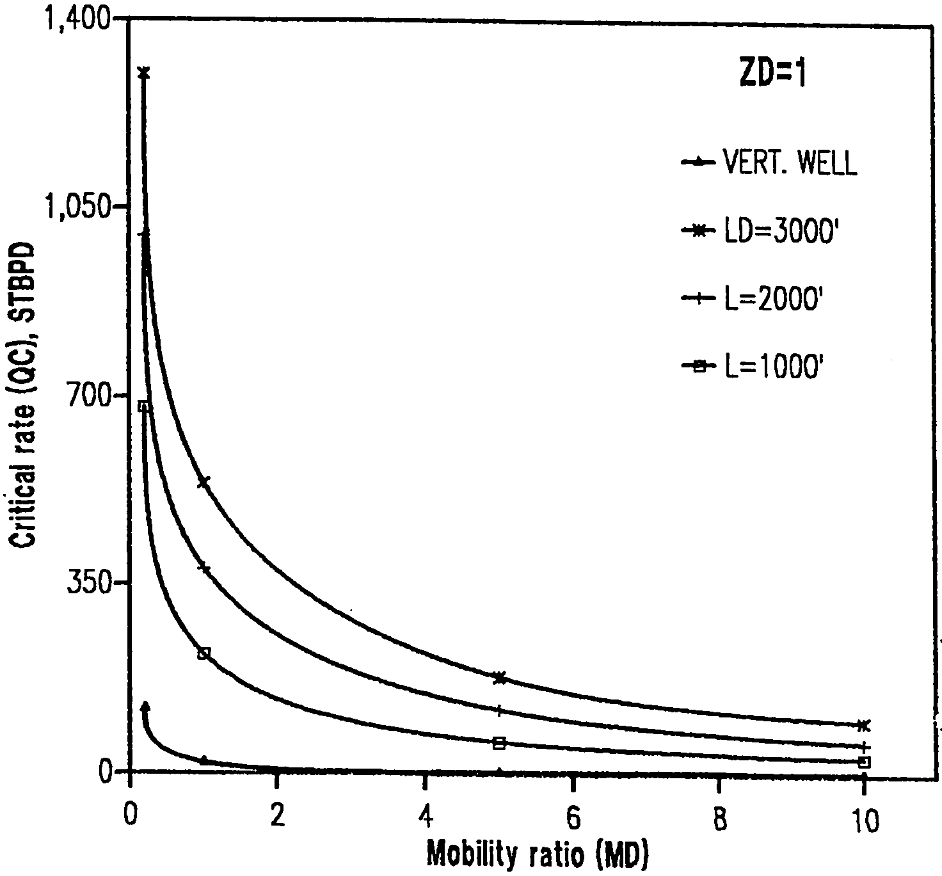


Figure 5.15: Effect of mobility ratio for different well lengths.

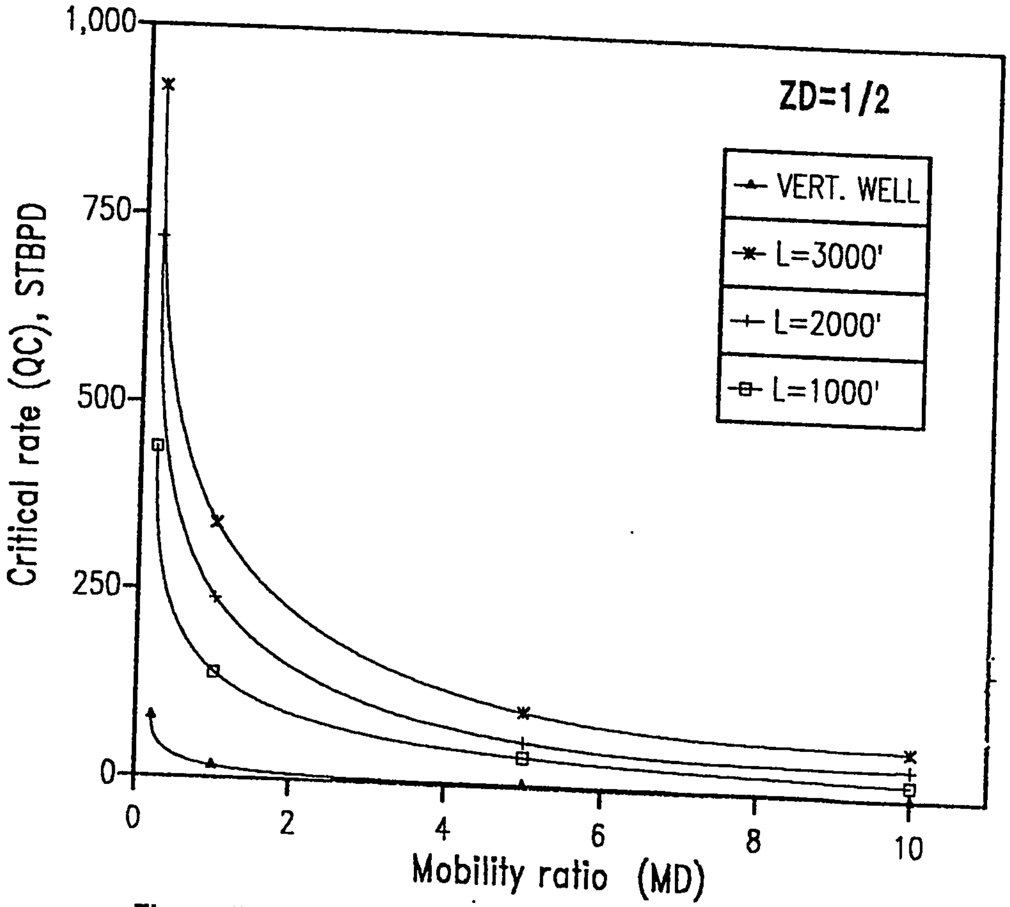


Figure 5.16: Effect of mobility ratio for different well length.

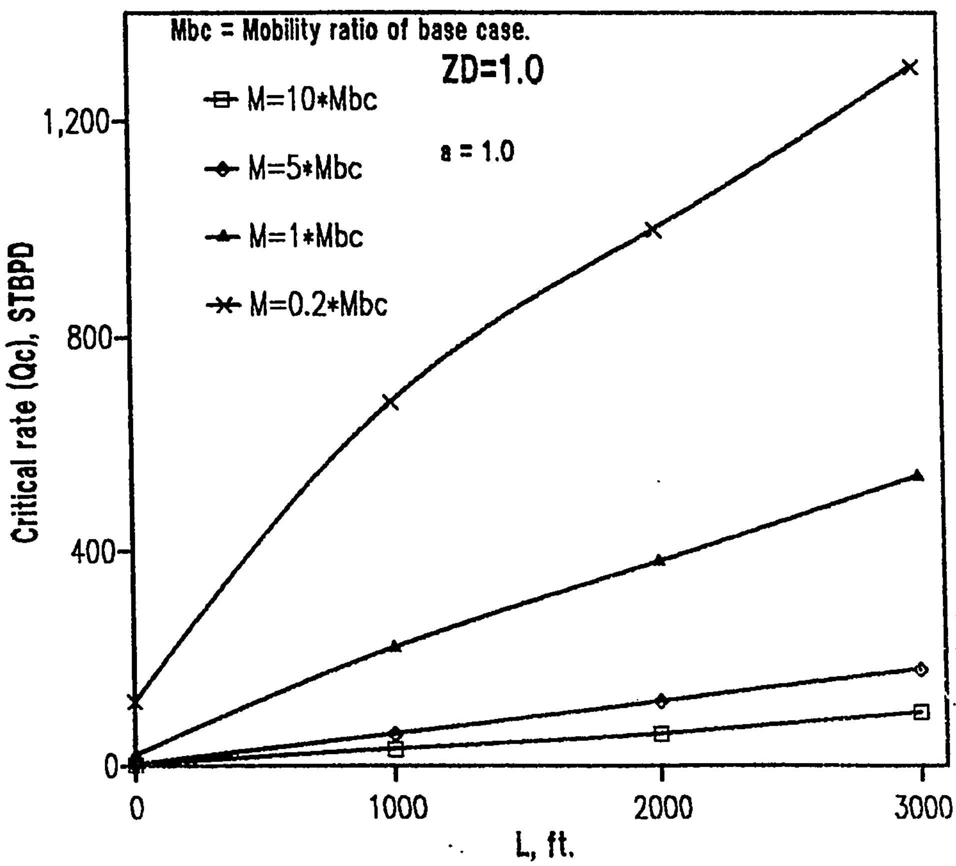


Figure 5.17: Variation with length for different mobility ratios.

Table 5.26: Effect of Mobility Ratio (M_D) on Critical Rate

Horizontal	*Reservoir*		
	ZD=1	**ZD=1**	**ZD=1**
	M_{10} =10.0	**M_5=5.0**	**$M_{0.2}$ =0.2**
Well Length	**Qc, STBPD**	**Qc, STBPD**	**Qc, STBPD**
1000'	32	60	680
2000'	60	120	1000
3000'	100	180	1300
	ZD=0.5	**ZD=0.5**	**ZD=0.5**
	M_{10} =10.0	**M_5 =5.0**	**$M_{0.2}$ =0.2**
Well Length	**Qc, STBPD**	**Qc, STBPD**	**Qc, STBPD**
1000'	20	40	440
2000'	40	60	720
3000'	64	100	920

Table 5.27: Effect of M_D on % drop in Critical rate for various M_D.

	ZD=1	ZD=0.5
Mobility ratio (M_D)	**% drop in Qc**	**% drop in Qc**
0.2	96%	95%
1.0	91%	91%
5.0	98%	96%
10.0	97%	97%

Table 5.28: Effect of Mobility Ratio, M_D on Qc in Vertical Wells.

	ZD=1	ZD=0.5
Mobility ratio	**Qc (STBPD)**	**Qc (STBPD)**
M_{10} =10	3.6	2.0
M_5 =5	4.0	4.0
$M_{0.2}$ =0.2	120.0	80.0

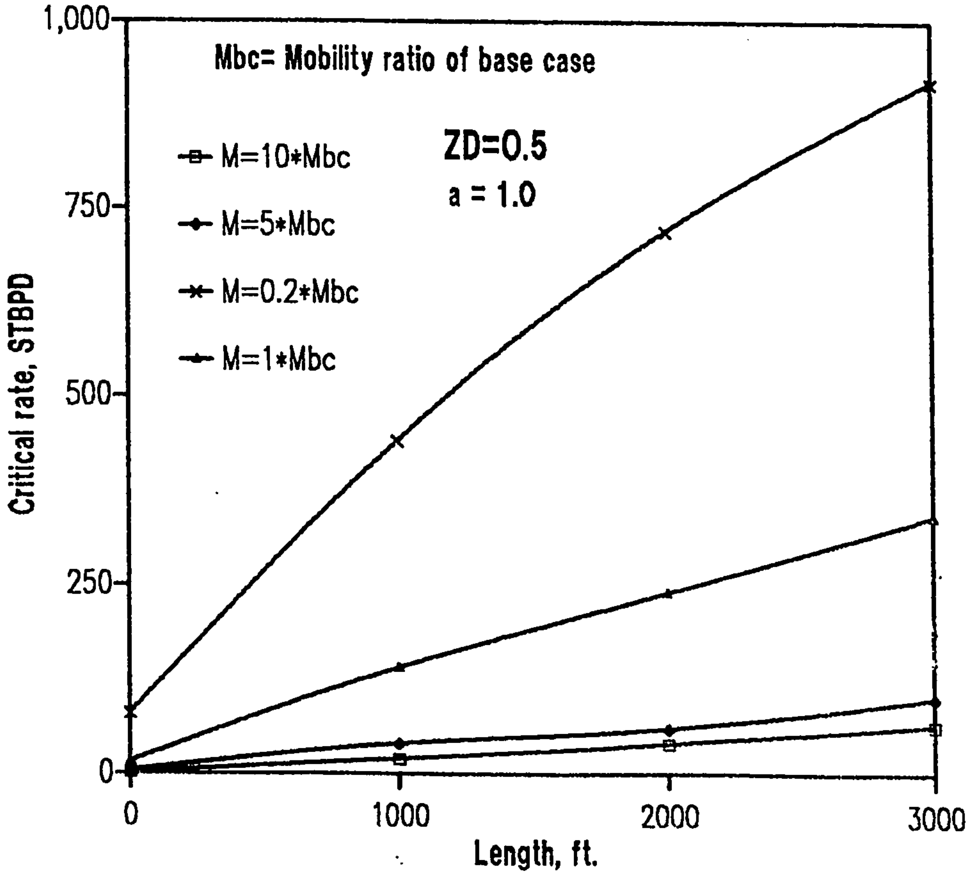


Figure 5.18: Variation with length for different mobility ratios.

CHAPTER 6

RESULTS AND COMPARISON

The previous chapter presented the results of the parametric study. These results which have been shown in tabular and graphical form illustrate the behavior of the critical rate as a function of various well and reservoir parameters. The objective of this chapter is to introduce dimensionless variables for the generalisation of the results.

6.1 DEFINING DIMENSIONLESS PARAMETERS

In order to generalise the results obtained in this study five dimensionless numbers have been defined below. See Figure 6.1.

1. Dimensionless Critical Rate, QD:

$$QD = \frac{Q}{Q_g} \tag{6.1}$$

- Q is the critical rate (STBPD)

- Q_g is the flow due to gravity, defined as follows:

$$Q_g = \frac{2.5E-07k}{\mu_o B_o}(\Delta\rho_{ow})gHL$$

(6.2)

In our case:

- k = 45.6 md. (absolute base case permeability)
- B_o =1.15 (av. oil FVF corresponding to pressure range for this study)
- μ_o = 2.5 cp (corresponding to pressure range for this study)
- $\rho_{ow} = (\rho_{water} - \rho_{oil}) = 65.55 - 56.85 = 8.7$ lb_m/cu.ft.
- H = 169 ft. (thickness of the reservoir)
- L = 4500 ft. (length of the reservoir)
- g = 32.2 ft./s^2, so that:

$$QD = \frac{Q}{833.93}$$

(6.3)

2. Dimensionless well position, Z_D:

The dimensionless well position, ZD, is defined as follows:

$$ZD = \frac{H_t}{H_{oil}} = \frac{H_t}{139}$$

(6.4)

- H_t is vertical distance from the well to the WOC
- H_{oil} is vertical depth of WOC from the top of the reservoir

3. Dimensionless Anisotropy ratio, a:

The dimensionless anisotropy ratio, a, is defined as:

$$a = \sqrt{\frac{k_v}{k_h}} \qquad (6.5)$$

- k_h = Permeability in the horizontal direction
- k_v = Permeability in the vertical direction

4. Dimensionless well length, LD:

A dimensionless well length, LD, is defined as follows:

$$LD = \frac{L}{H_{oil}} \qquad (6.6)$$

5. Dimensionless Ratio of the Mobility ratios, M_D:

A dimensionless mobility ratio, M_D, was defined as the ratio of any given mobility ratio to the mobility ratio for the base case. The base case mobility ratio was found to be 1.25. For this study four M_D were selected, viz. 0.2, 1, 5, 10. The critical rate data obtained by simulation is presented in Tables 6.1 to 6.8 in dimensionless form. The graphical relationships presented in Chapter 5 are plotted in dimensionless form. (see Figures 6.2 to 6.23).

In Figures 6.12 to 6.15 the dimensionless critical rate has been plotted with respect to a product of dimensionless length, LD and anisotropy ratio, a. It can be observed that lines of different anisotropy ratios seperate themselves into gently sloping curves as the anisotropy ratio increases.

6.2 COMPARISON WITH EXISTING CORRELATIONS

The results of this study were compared to the correlations available in the literatue to determine their consistency and accuracy.

In this regard the exisiting correlations available in literature were applied to the reservoir used in our study. The results are presented in Table 6.9. These results are for a 2000' long horizontal well with ZD=1, in a homogeneous and isotropic reservoir. The result is for the well located in the top position for which ZD=1.0. The same is true for the case of vertical wells.

It can be seen that the results compare favorably with the most recent correlations of Yang/Wattenbarger and Guo/ Molinard and Lee.

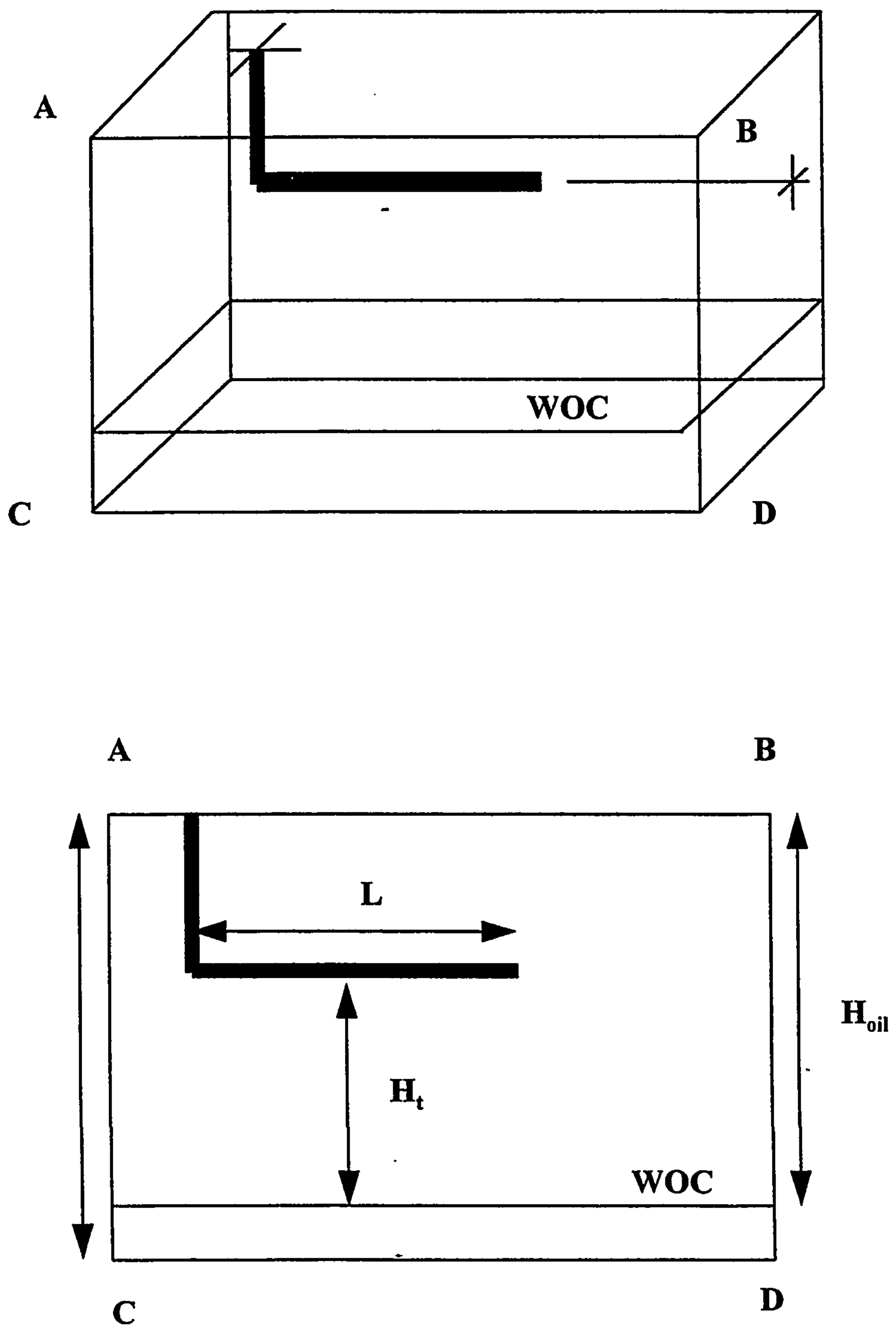


Figure 6.1: Illustration of dimensionless variables

Table 6.1: Effect of Anisotropy ratio on Critical Rates (ZD=1.0)

Well Length (ft.)	LD	QD	Qc (STBPD)
a = 1.0			
500.0	3.6	0.14390	120
1000.0	7.2	0.26381	220
2000.0	14.4	0.45567	380
3000.0	21.6	0.64754	540
a = 0.5			
500.0	3.6	0.14390	120
1000.0	7.2	0.23983	200
2000.0	14.4	0.43169	360
3000.0	21.6	0.62355	520
a = 0.2			
500.0	3.6	0.14390	120
1000.0	7.2	0.23983	200
2000.0	14.4	0.43169	360
3000.0	21.6	0.59957	520
a = 0.1			
500.0	3.6	0.21585	120
1000.0	7.2	0.28779	200
2000.0	14.4	0.45567	360
3000.0	21.6	0.62355	500

Table 6.2: Effect of Anisotropy ratio on Critical Rates (ZD=0.75)

a = 1.0			
Well Length (ft.)	**LD**	**QD**	**Qc (STBPD)**
500.0	3.6	0.11991	100
1000.0	7.2	0.23983	200
2000.0	14.4	0.40771	340
3000.0	21.6	0.57559	480
a = 0.5			
500.0	3.6	0.11991	100
1000.0	7.2	0.21585	180
2000.0	14.4	0.38373	320
3000.0	21.6	0.55161	460
a = 0.2			
500.0	3.6	0.11991	100
1000.0	7.2	0.21585	180
2000.0	14.4	0.35974	300
3000.0	21.6	0.50364	420
a = 0.1			
500.0	3.6	0.16788	140
1000.0	7.2	0.21585	180
2000.0	14.4	0.35974	300
3000.0	21.6	0.50364	420

Table 6.3: Effect of Anisotropy ratio on Critical Rates (ZD=0.5)

a = 1.0			
Well Length (ft.)	**LD**	**QD**	**Qc (STBPD)**
500.0	3.6	0.09593	80
1000.0	7.2	0.16788	140
2000.0	14.4	0.28779	240
3000.0	21.6	0.40771	340
a = 0.5			
500.0	3.6	0.07195	60
1000.0	7.2	0.14390	120
2000.0	14.4	0.26381	220
3000.0	21.6	0.38373	320
a = 0.2			
500.0	3.6	0.07195	60
1000.0	7.2	0.11991	100
2000.0	14.4	0.21585	180
3000.0	21.6	0.31178	260
a = 0.1			
500.0	3.6	0.07195	60
1000.0	7.2	0.11991	100
2000.0	14.4	0.19186	160
3000.0	21.6	0.26381	220

Table 6.4: Effect of Anisotropy ratio on Critical Rates (ZD=0.25)

a = 1.0			
Well Length (ft.)	**LD**	**QD**	**Qc (STBPD)**
500.0	3.6	0.04797	40
1000.0	7.2	0.09593	80
2000.0	14.4	0.16788	140
3000.0	21.6	0.23983	200
a = 0.5			
500.0	3.6	0.03837	32
1000.0	7.2	0.07195	60
2000.0	14.4	0.11991	100
3000.0	21.6	0.19186	160
a = 0.2			
500.0	3.6	0.02398	20
1000.0	7.2	0.04797	40
2000.0	14.4	0.09593	80
3000.0	21.6	0.14390	120
a = 0.1			
500.0	3.6	0.02878	24
1000.0	7.2	0.04797	40
2000.0	14.4	0.07195	60
3000.0	21.6	0.11991	100

Table 6.5: Effect of Anisotropy ratio on Vert. well for various ZD.

a = 1.0		
ZD	**QD**	**Qc (STBPD)**
1.0	0.02398	20
0.75	0.02398	20
0.50	0.01919	16
0.25	0.00959	8
a = 0.5		
1.0	0.04797	40
0.75	0.04797	40
0.5	0.02878	24
0.25	0.01439	12
a = 0.2		
1.0	0.09593	80
0.75	0.07195	60
0.5	0.04797	40
0.25	0.02398	20
a = 0.1		
1.0	0.19186	160
0.75	0.16788	120
0.5	0.07195	60
0.25	0.02878	24

Table 6.6: Detailed Analysis of Anisotropy for Well: LD=14.4

LD = 14.4	ZD=1	
Anisotropy ratio	**Q_D**	**Qc (STBPD)**
1.0000	0.45567	380
0.5000	0.43169	360
0.2000	0.43169	360
0.1580	0.43169	360
0.1414	0.43169	360
0.1155	0.43169	360
0.1000	0.45567	380
0.0450	0.64754	540
0.0316	0.76745	640
LD=14.4	**ZD=0.5**	
1.0000	0.28779	240
0.5000	0.26381	220
0.2000	0.21585	180
0.1580	0.21585	180
0.1414	0.19186	160
0.1155	0.19186	160
0.1000	0.19186	160
0.0450	0.23983	200
0.0316	0.28779	240

Table 6.7: Effect of Reservoir Geometry on Critical Rate

ZD=1	4500*4500 ft^2		
Well length (ft.)	**LD**	**QD**	**Qc (STBPD)**
vert. well	-	0.03837	32
1000.0	7.1942	0.31178	256
2000.0	14.3885	0.55161	460
3000.0	21.5827	0.81542	680
ZD=1	**2250*4500 ft^2**		
vert. well	-	0.02878	24
1000.0	7.1942	0.28779	240
2000.0	14.3885	0.50364	420
3000.0	21.5827	0.76745	640
ZD=0.5	**4500*4500 ft^2**		
vert. well	-	0.02398	20
1000.0	7.1942	0.19186	160
2000.0	14.3885	0.35974	300
3000.0	21.5827	0.52762	440
ZD=0.5	**2250*4500 ft^2**		
vert. well	-	0.02398	20
1000.0	7.1942	0.19186	160
2000.0	14.3885	0.31178	260
3000.0	21.5827	0.47996	400

Table 6.8: Effect of Mobility Ratio (M_D) on Critical Rate

Well length (ft.)	LD	QD	Qc (STBPD)
ZD=1	**M_{10} =10.0**		
vert. well	-	0.00432	3.6
1000.0	7.19420	0.0384	32
2000.0	14.3885	0.0719	60
3000.0	21.5287	0.120	100
ZD=0.5	**M_{10} =10.0**		
vert. well	-	0.00240	2.0
1000.0	7.19420	0.024	20
2000.0	14.3885	0.048	40
3000.0	21.5287	0.0767	64
ZD=1	**M_5=5.0**		
vert. well	-	0.00480	4.0
1000.0	7.19420	0.0719	60
2000.0	14.3885	0.144	120
3000.0	21.5287	0.216	180

ZD=0.5	M_5 =5.0		
Well Length (ft.)	**LD**	**QD**	**Qc (STBPD)**
vert. well	-	0.00480	4.0
1000.0	7.19420	0.048	40
2000.0	14.3885	0.0719	60
3000.0	21.5287	0.120	100
ZD=1	**$M_{0.2}$ =0.2**		
Well Length (ft.)	**LD**	**QD**	**Qc (STBPD)**
vert. well	-	0.144	120.0
1000.0	7.19420	0.815	680
2000.0	14.3885	1.20	1000
3000.0	21.5287	1.56	1300
ZD=0.5	**$M_{0.2}$ =0.2**		
Well Length (ft.)	**LD**	**QD**	**Qc (STBPD)**
vert. well	-	0.0959	80.0
1000.0	7.19420	0.528	440
2000.0	14.3885	0.863	720
3000.0	21.5287	1.10	920

Table 6.9: Comparison for the reservoir used in this study

Vertical well	
Correlation	**Qc, STBPD**
Meyer and Pirson	7.5
Chaperon	17.35
Schol's	10.75
Hoyland's	12.7
Papatzacos (analytical)	16.4
Yang and Wattenbarger	18.9
This study (simulation)	20

Horizontal well	
Correlation	**Qc, STBPD**
Chaperon	150
Efros	8.3
Giger and Karcher	17
Guo and Lee	644.7
Guo, Molinard and Lee	398.7
Yang and Wattenbarger	459.4
This study (simulation)	380

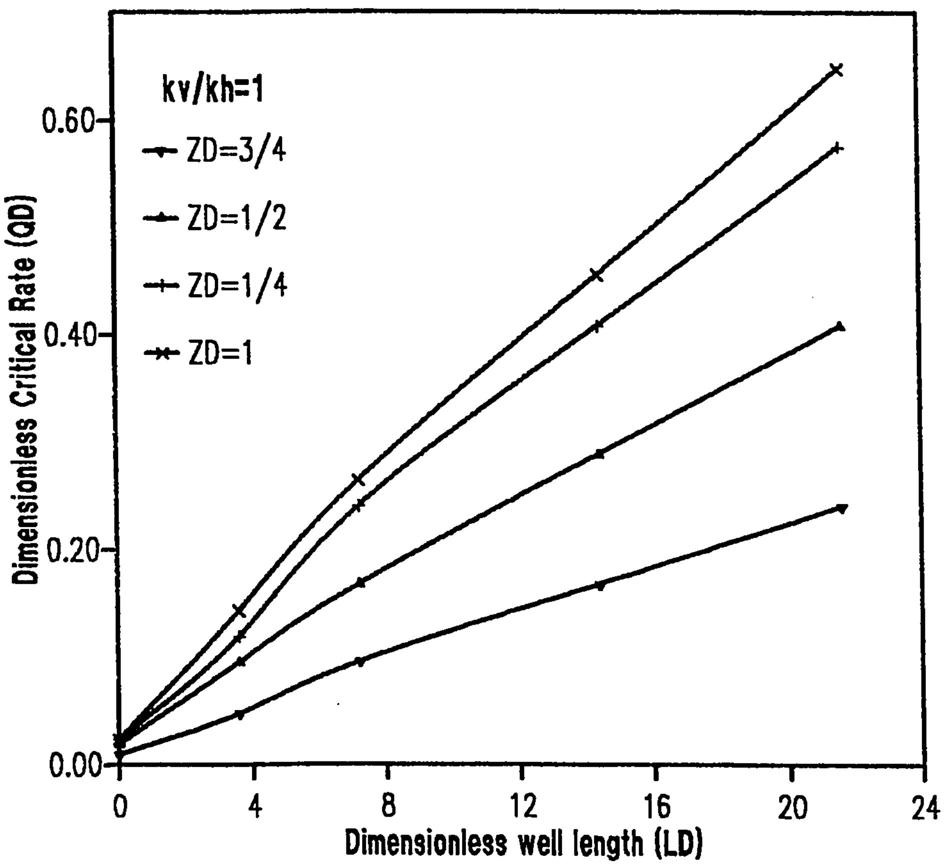


Figure 6.2: Variation of QD with LD for different well positions.

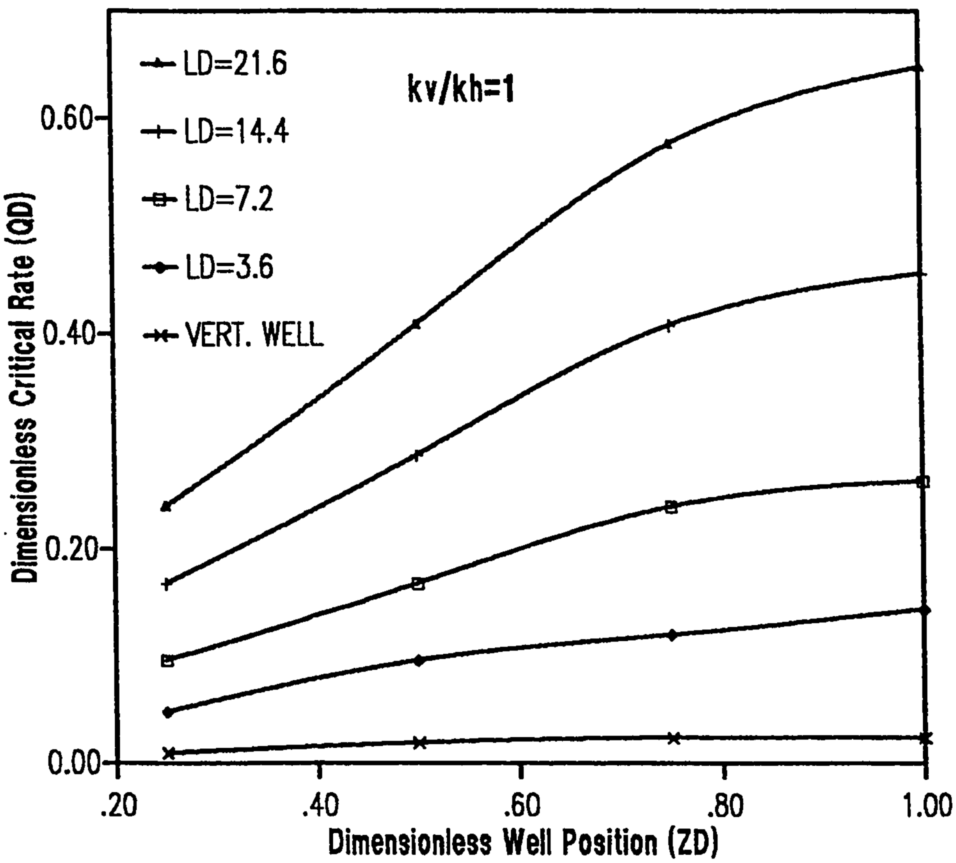


Figure 6.3: Variation of QD with ZD for different well lengths.

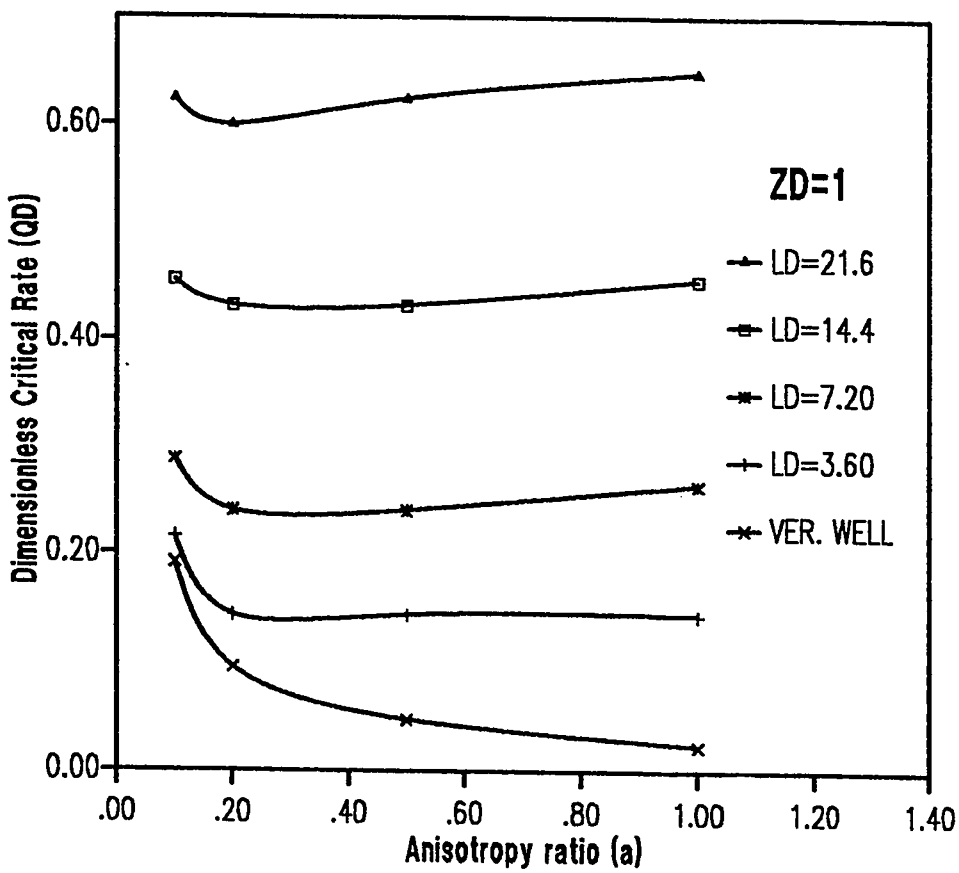


Figure 6.4: Effect of anisotropy ratio for a well when ZD=1.

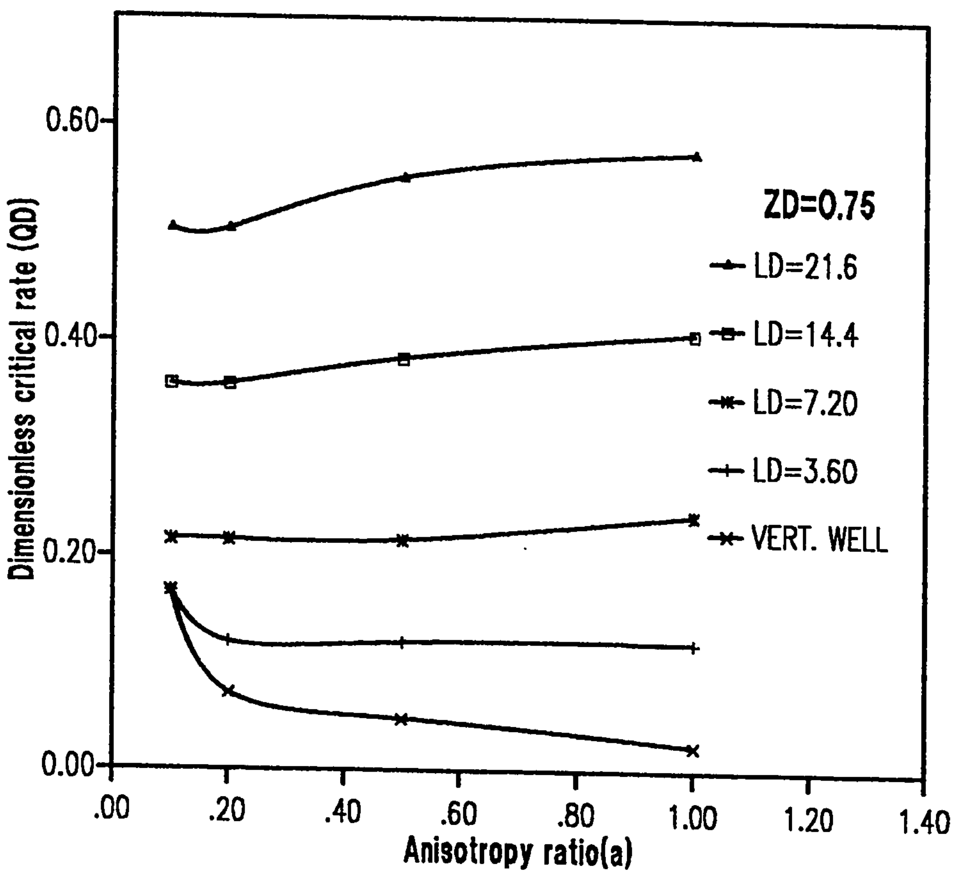


Figure 6.5: Effect of anisotropy ratio for a well whenZD=0.75

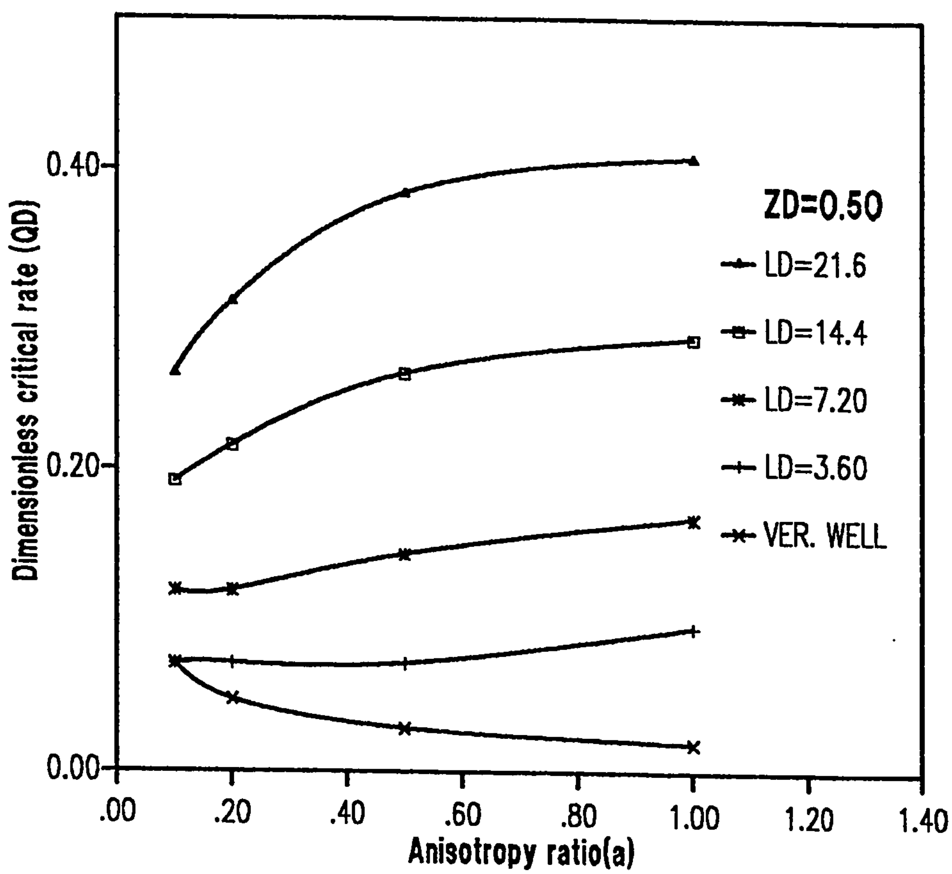


Figure 6.6: Effect of anisotropy ratio for a well when ZD=0.50

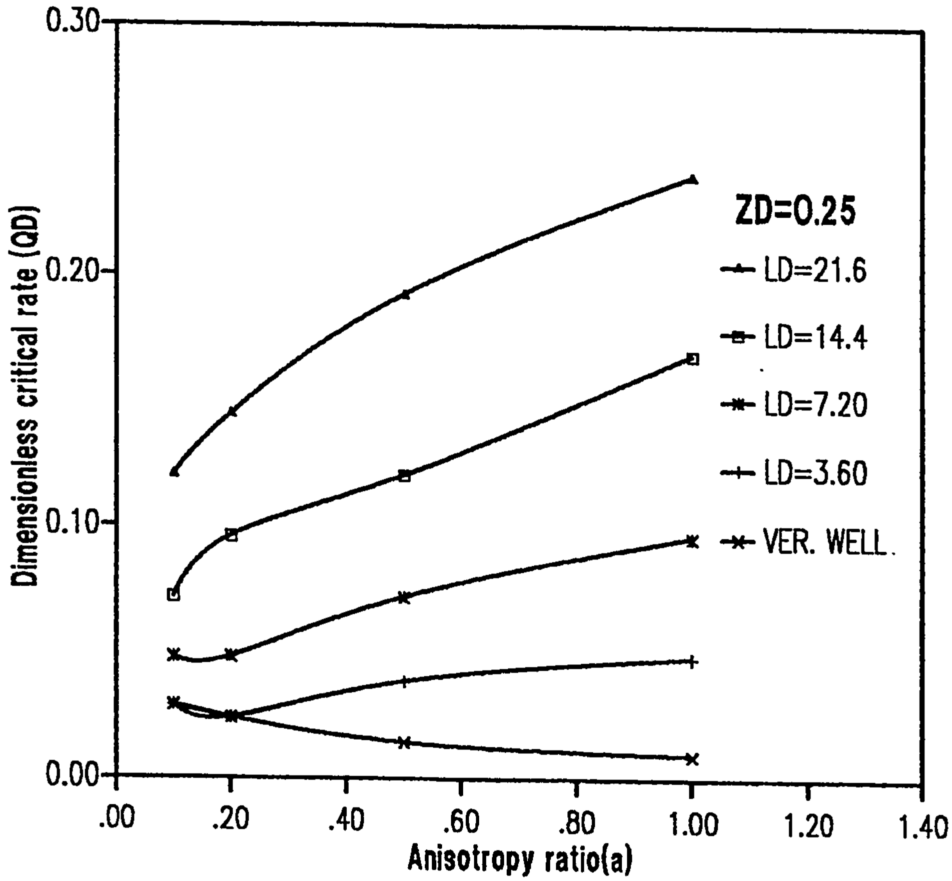


Figure 6.7: Effect of anisotropy ratio for a well when ZD=0.25

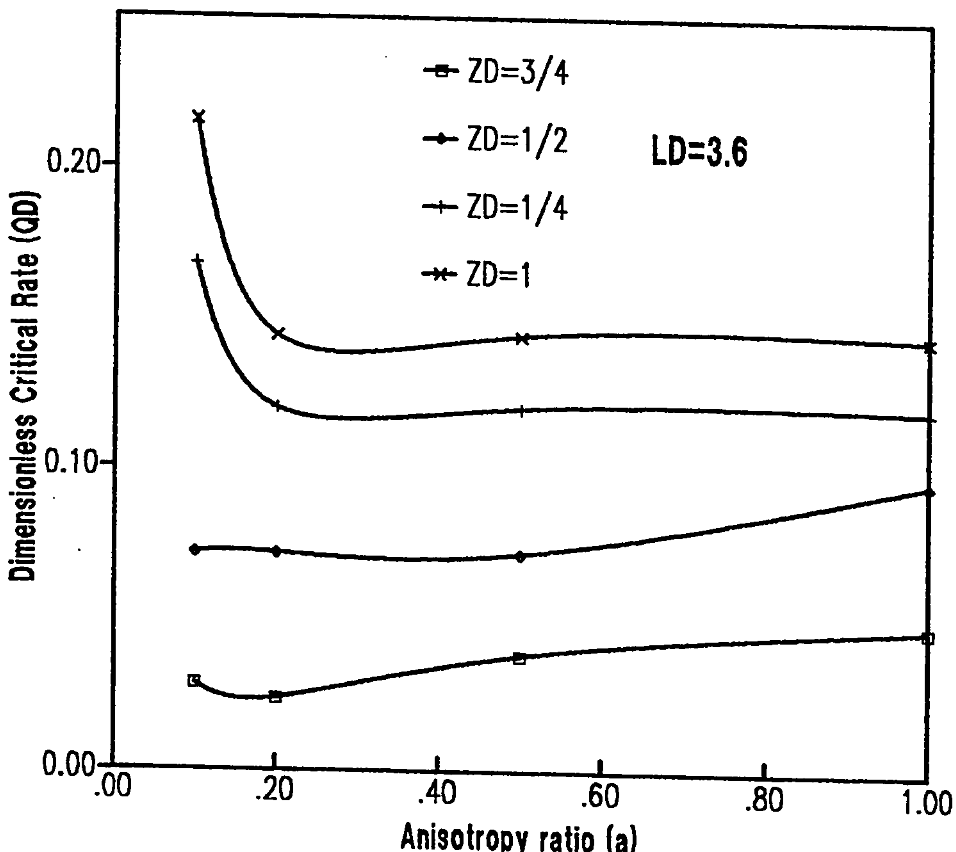


Figure 6.8: Effect of anisotropy ratio for LD=3.6 well for various positions.

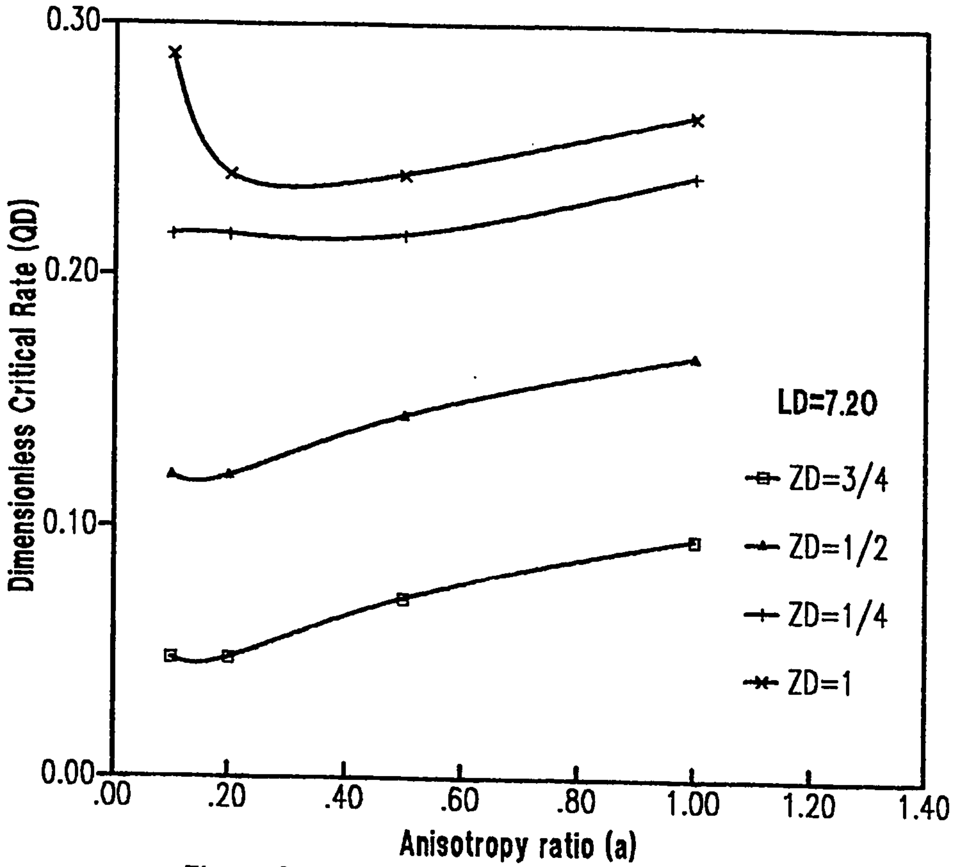


Figure 6.9: Effect of anisotropy ratio for LD=7.20 well for various positions.

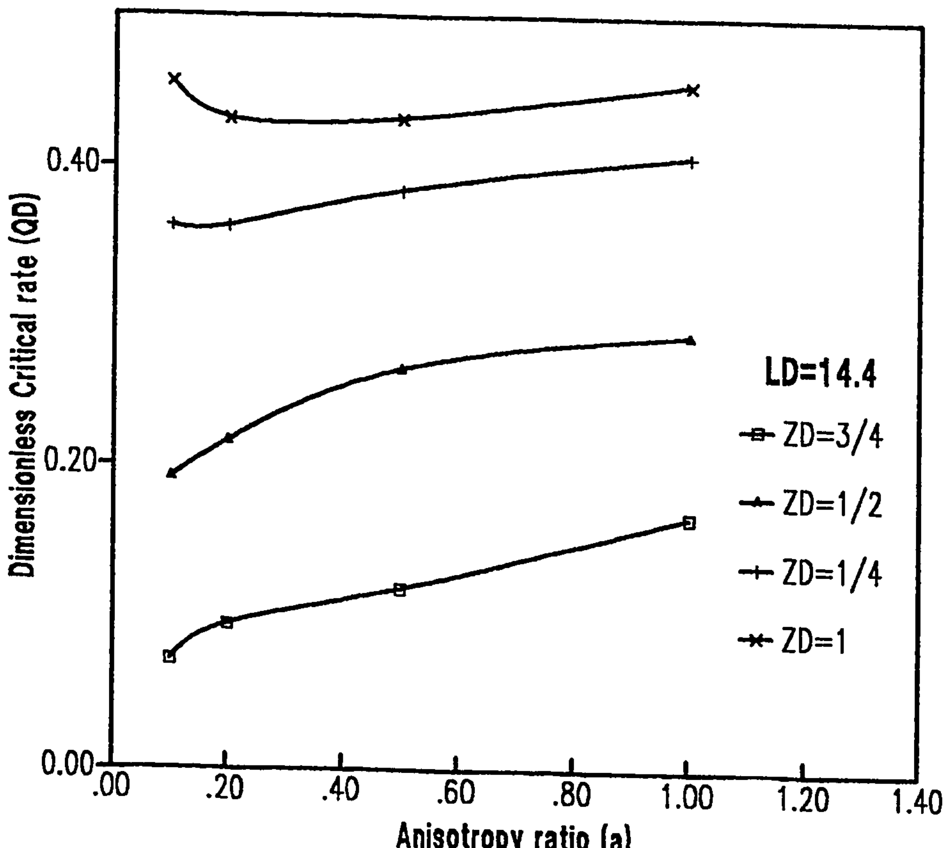


Figure 6.10: Effect of anisotropy ratio for LD=14.4 well for various positions.

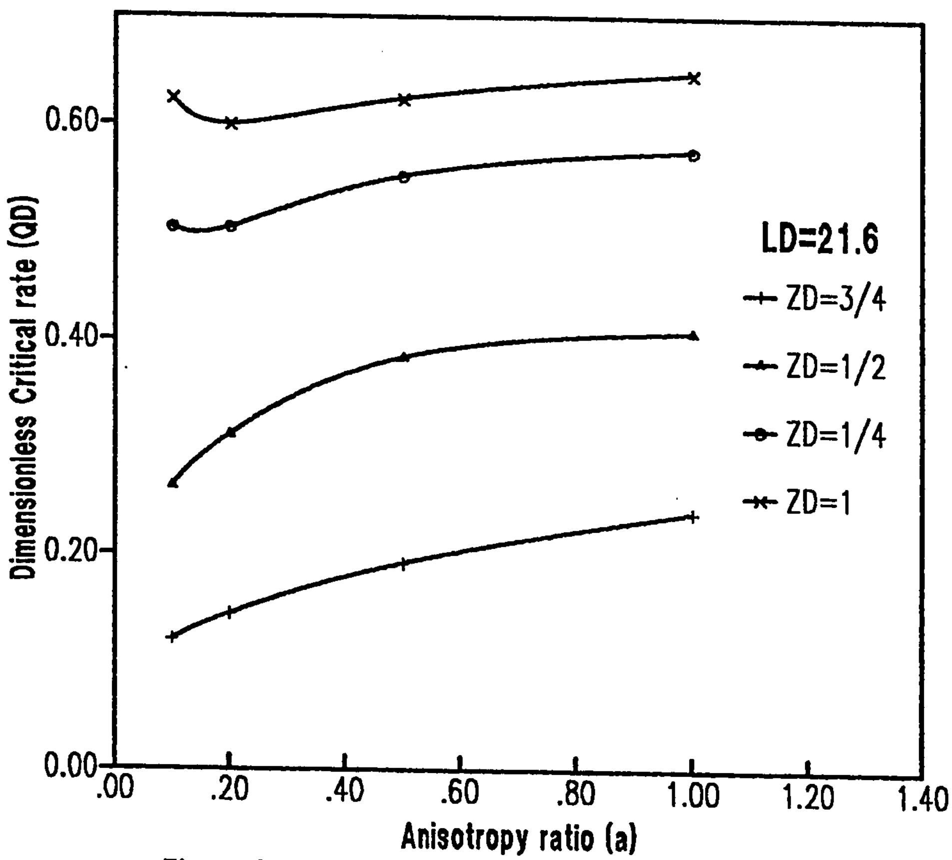


Figure 6.11: Effect of Anisotropy ratio for a LD=21.6 well for various positions

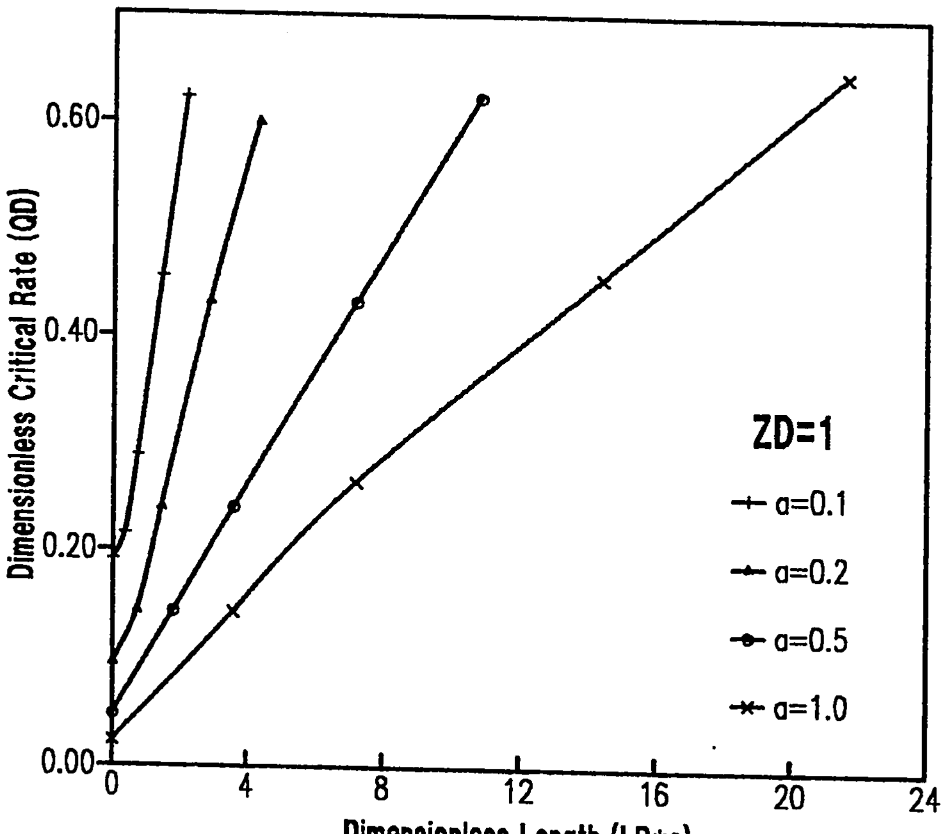


Figure 6.12: Variation of QD with (LD*a) for various anisotropy ratios.

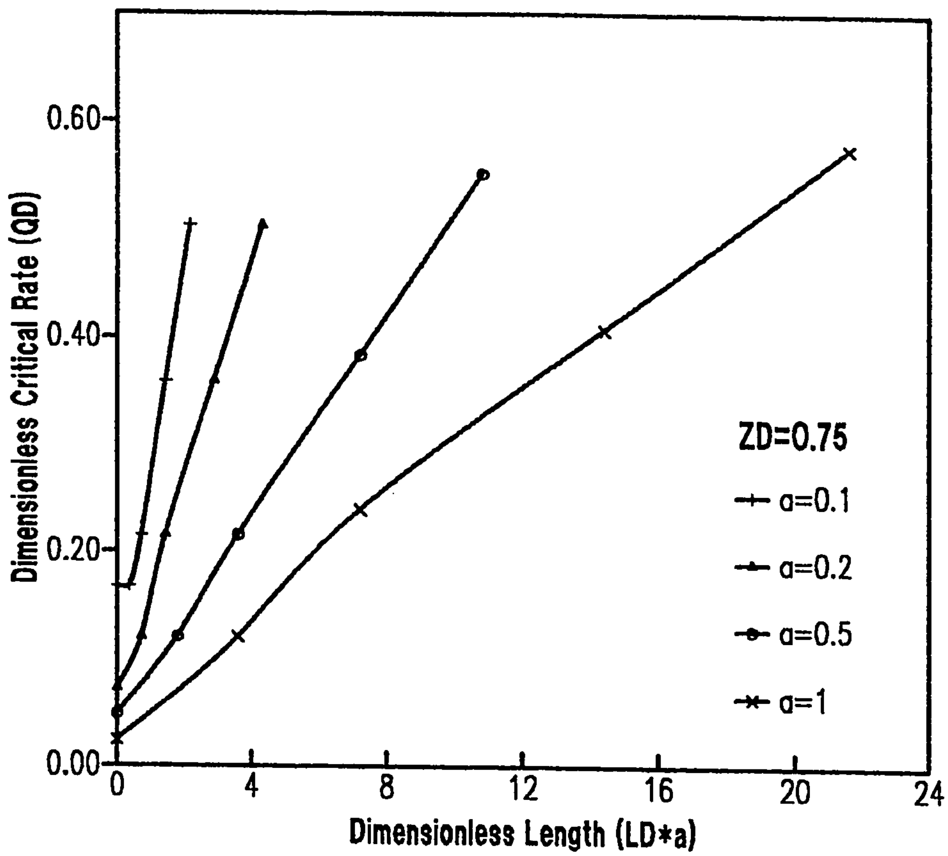


Figure 6.13: Variation of QD with (LD*a) for various anisotropy ratios.

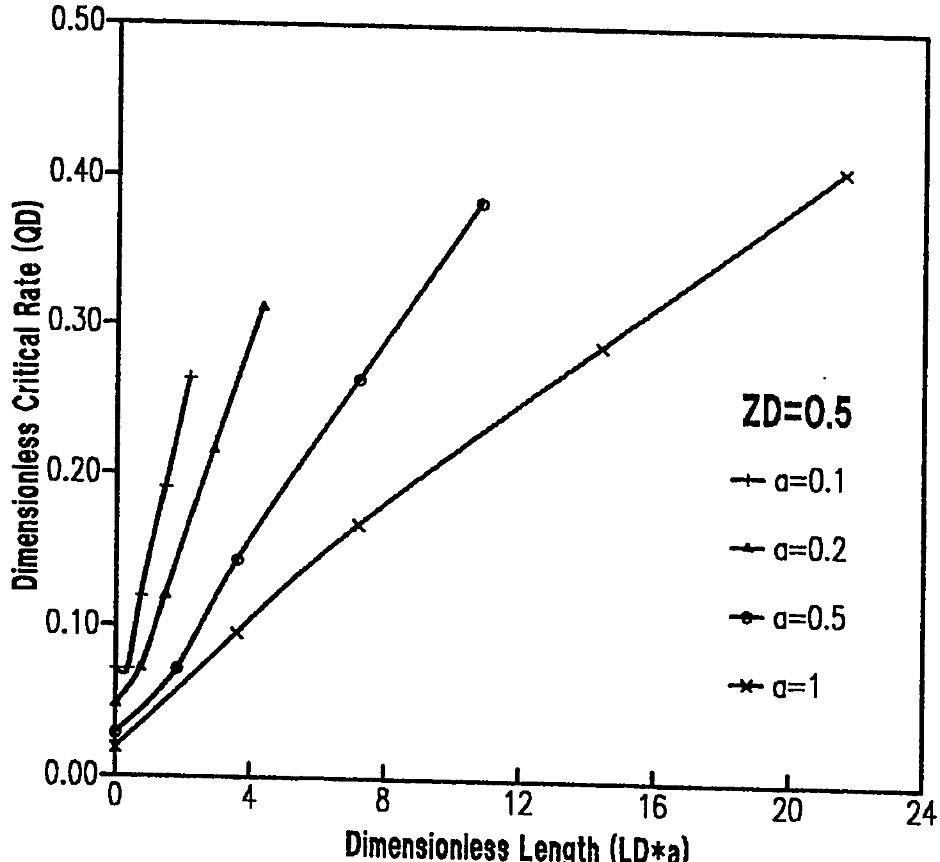


Figure 6.14: Variation of QD with (LD*a) for various anisotropy ratios.

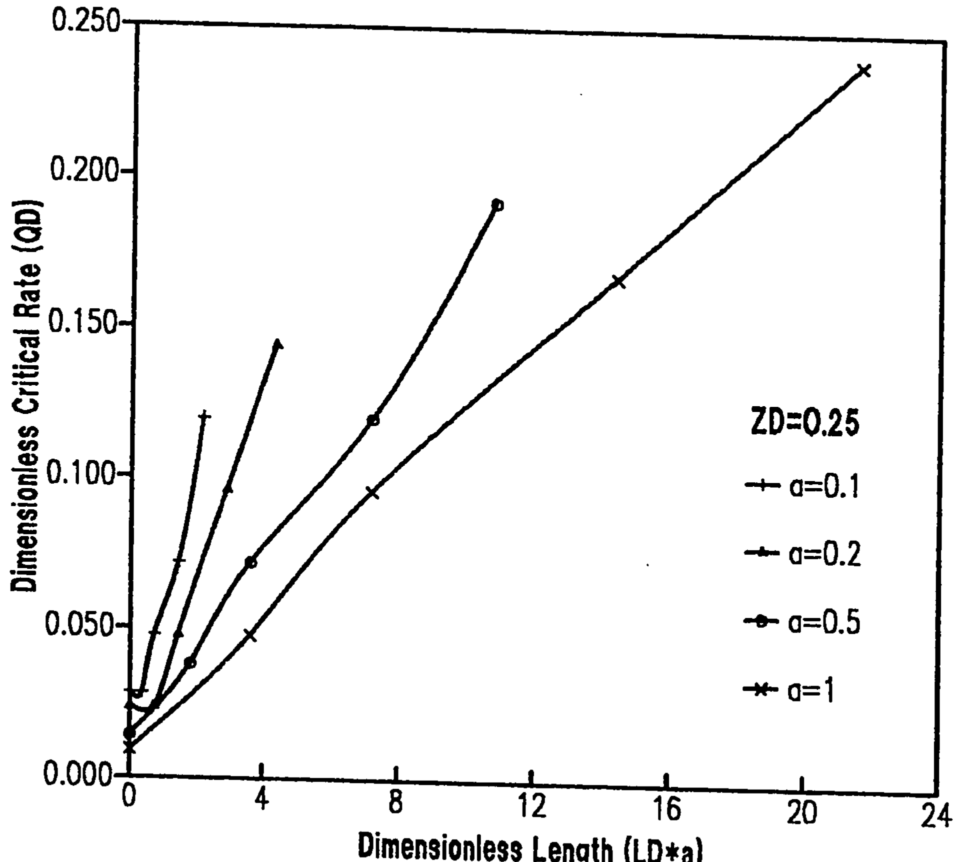


Figure 6.15: Variation of QD with (LD*a) for various anisotropy ratios.

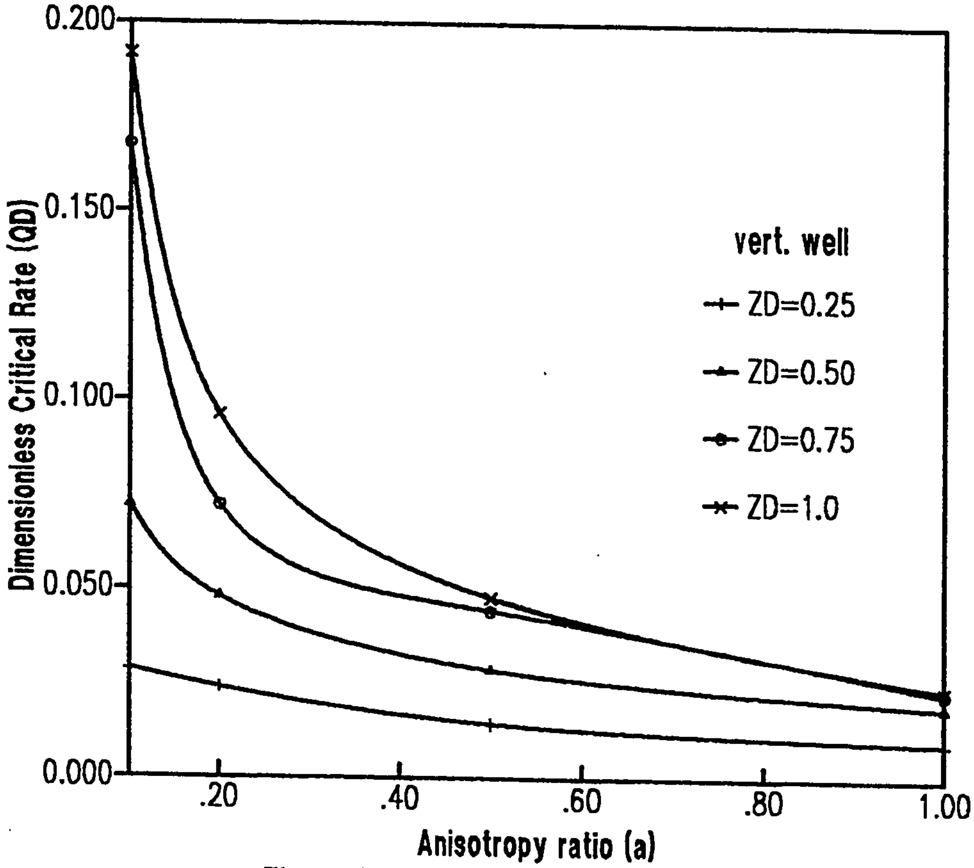


Figure 6.16:Effect of anisotropy ratio on vertical well for various positions.

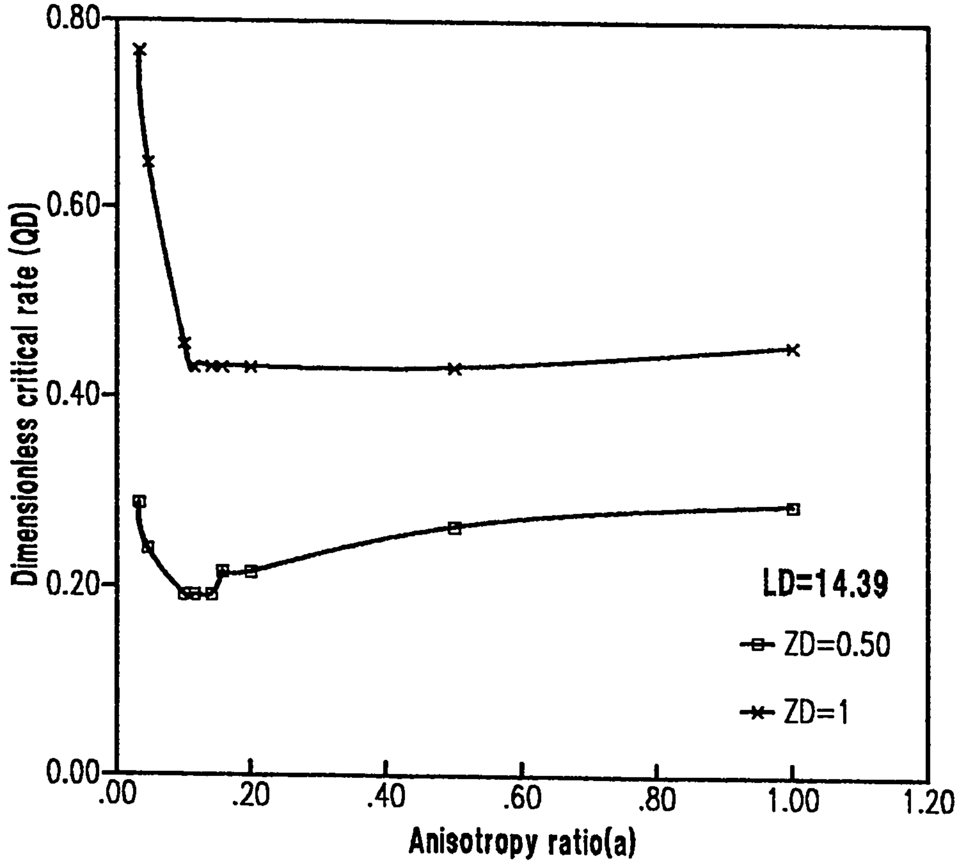


Figure 6.17: A detailed analysis of the effect of anisotropy ratio.

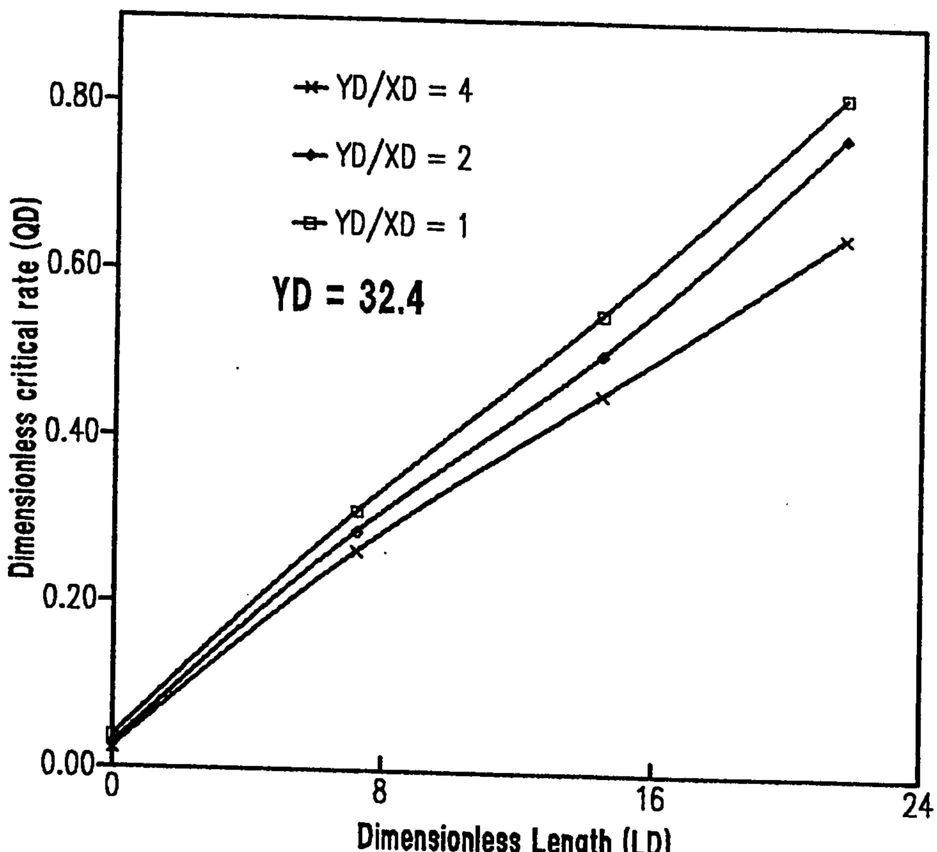


Figure 6.18: Effect of reservoir geometry for different well lengths for ZD=1.0.

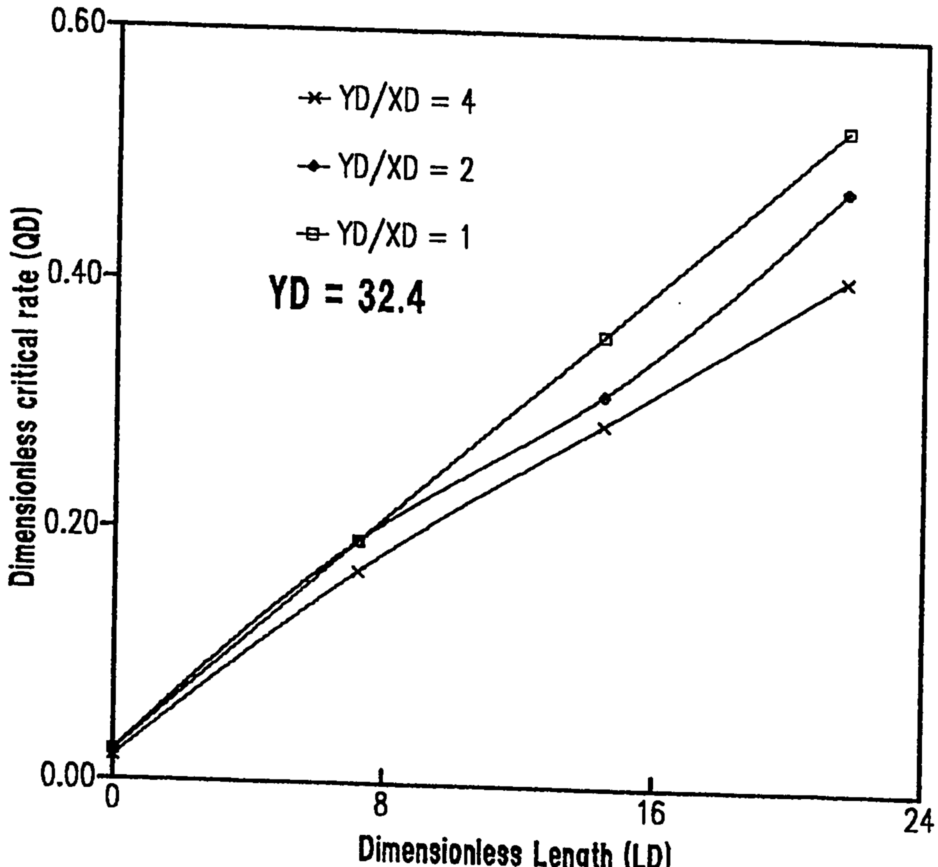


Figure 6.19: Effect of reservoir geometry for different well lengths for ZD=0.50.

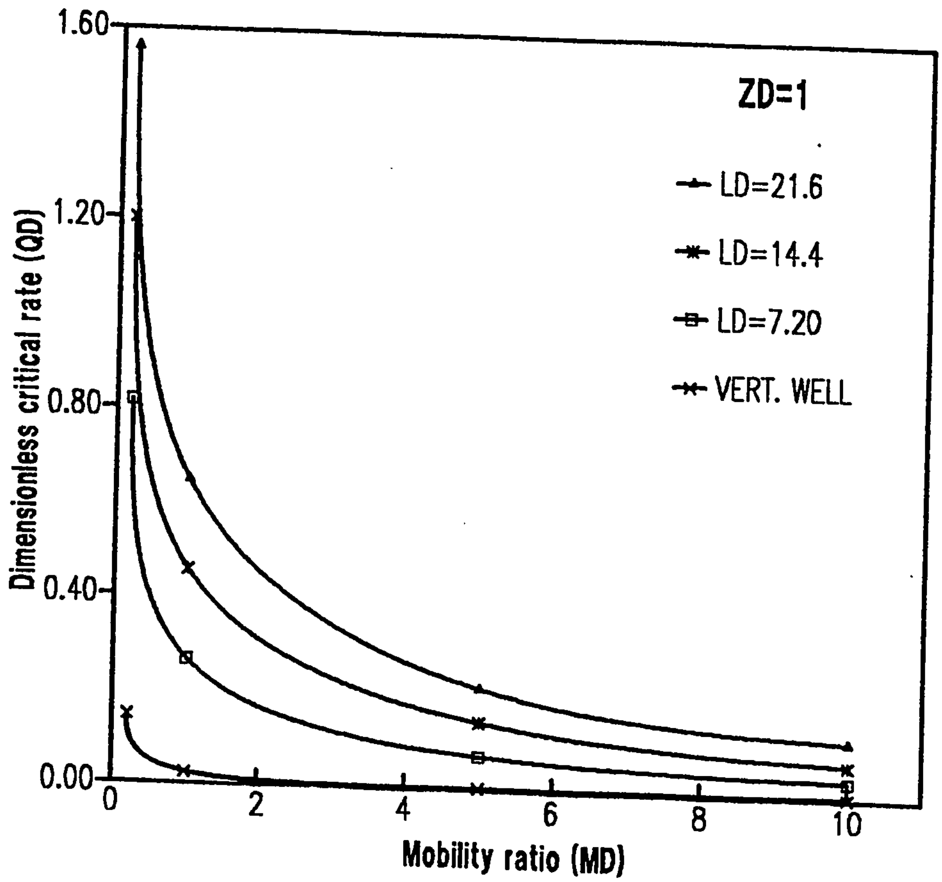


Figure 6.20: Effect of MD for various LD

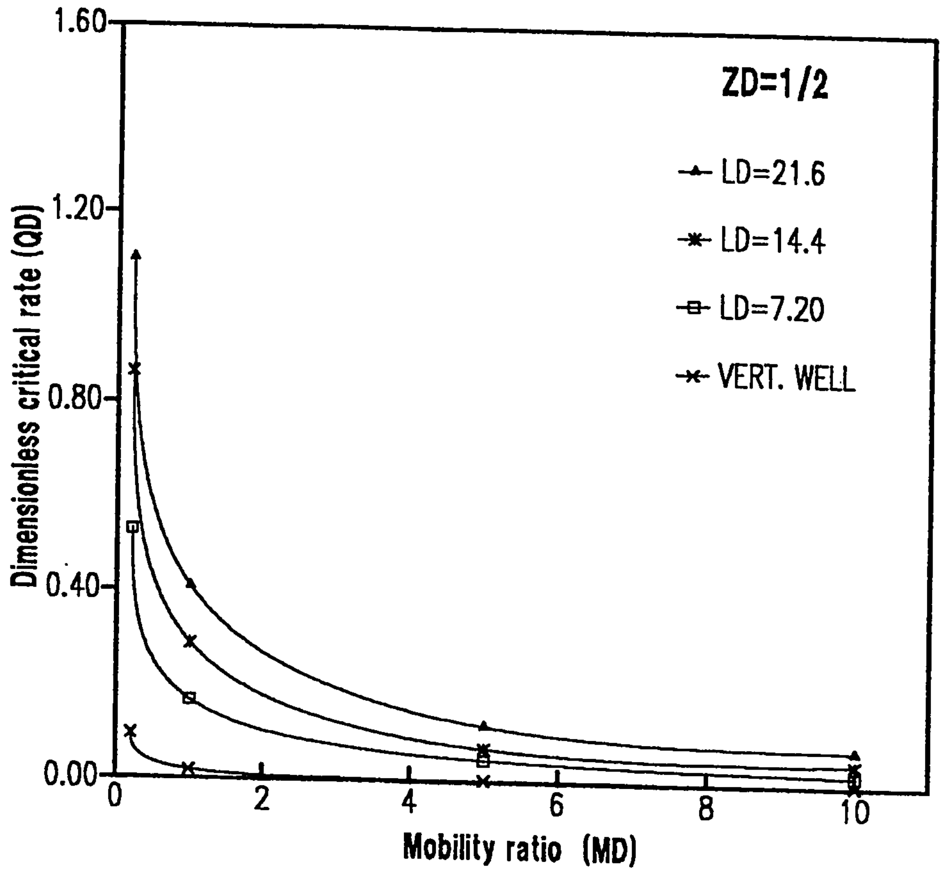


Figure 6.21: Effect of MD for various LD.

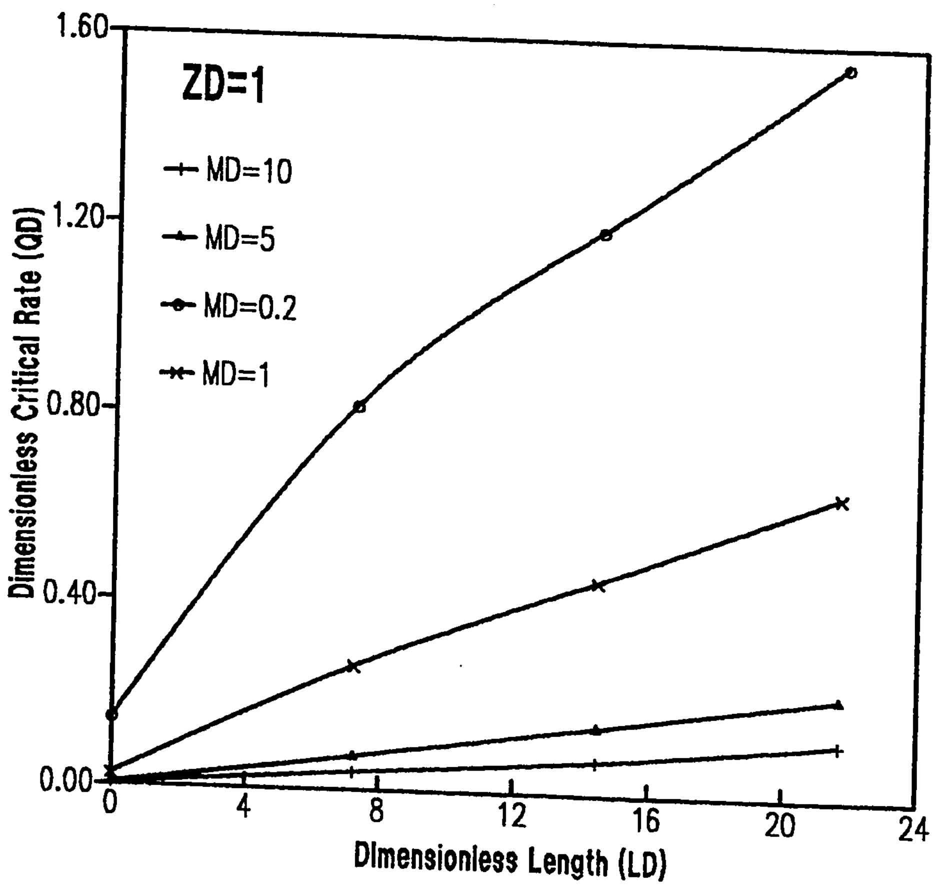


Figure 6.22: Variation of QD with LD for various MD.

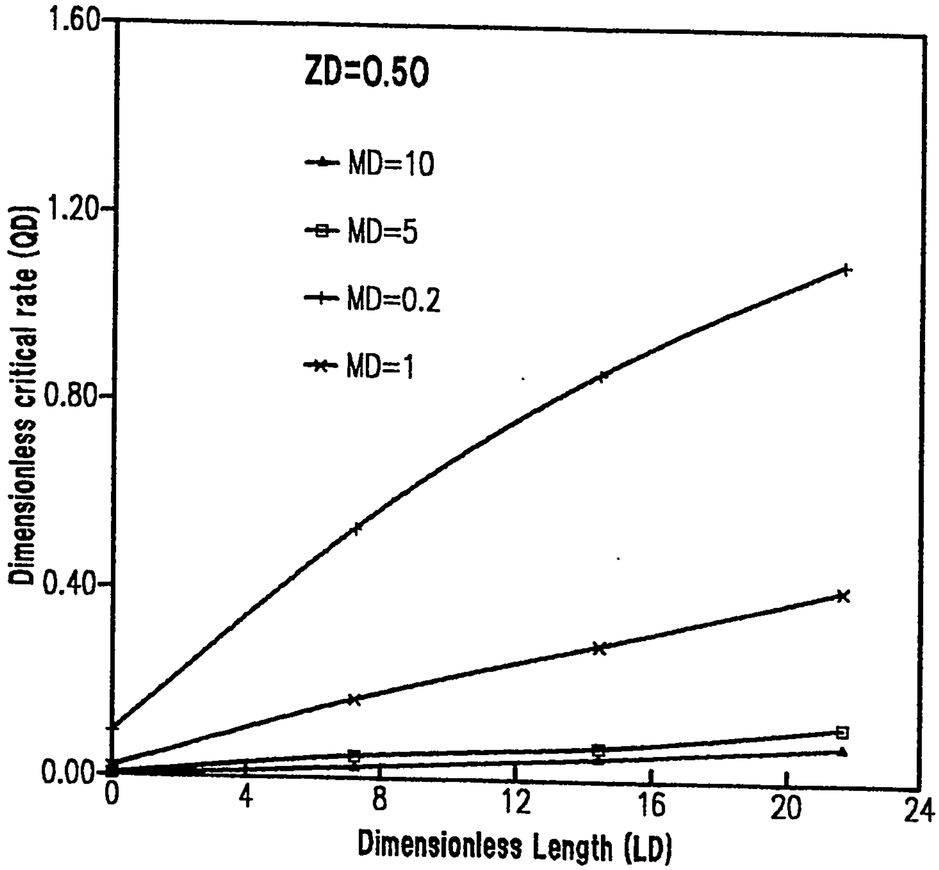


Figure 6.23: Variation of QD with LD for various MD

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

In this work the effect of well length, anisotropy ratio, reservoir geometry and mobility ratio on the critical rate is studied. The results are consistent with the published literature. However, as a result of this detailed study two important observations have been made:

1. For horizontal wells, most of the studies present the critical rate as an increasing function of the anisotropy ratio. The present study shows that this is true only for $0.5<a<1$. In fact, for $0.01<a<0.1$, critical rate is a strongly decreasing function of anisotropy ratio. This is not a mere theoretical case. Many reservoirs with discontinuous thin silt barriers are believed to display very low anisotropy ratios.

2. *M*ost of the studies describe the critical rate for vertical wells as a decreasing function of the anisotropy ratio, opposite in behavior to horizontal wells. Although the present study agrees with the general trend, it shows that there is in fact a harmonious continuity between vertical and horizontal wells and short horizontal wells display a behavior in between.

7.2 RECOMMENDATION

Since this study is based solely on numerical simulation, a check of some of these results using scaled laboratory models would be recommended.

NOMENCLATURE

A	drainage area, ft.
a_l	length of the drainage pattern, ft.
a	anisotropy ratio = $\sqrt{k_V/k_H}$
b	width of the drainage pattern, ft.
B_g	gas FVF, RB/MSCF
B_o	oil FVF, RB/STB
B_w	water FVF, RB/STB
c	distance of the well-bore from bottom of the oil zone, ft.
d	thickness of the oil zone, ft.
g	acceleration due to gravity, 32.2 ft./s^2
GBT	gas breakthrough time,days
GOC	gas oil contact
GOR	gas oil ratio, MSCF/STB
h	reservoir height, ft.
h_l	oil column thickness, ft.
H_D	dimensionless height of water crest
H_C	height of water crest at cusp point, ft.
H_t	vertical distance from well to WOC, ft.
H_{oil}	vertical depth of WOC from the top of the reservoir, ft.
h_{bp}	average oil column height below perforation,ft.

h_{wb}	break through height,ft.
h_{ap}	oil column height above perforations, ft.
h^*	reservoir height adjusted for heterogeneous permeability, ft.
k	permeability, md.
k_x	x-directional permeability, md.
k_y	y-directional permeability, md.
k_h	horizontal permeability, md.
k_v	vertical permeability, md.
k_r	relative permeability.
k_{ro}'	oil relative permeability.
k_{rw}'	water relative permeability.
L_w	c/d, well-bore location index, dimensionless
L	horizontal well length, ft.
m	slope of the straight line equation [8]
M	mobility ratio.
M_D	Mobility ratio over base case.
N	number of wells.
P	average pressure, psia
Pc	capillary pressure, psia
P_w	well pressure, psia
$\overline{P_N}$	normalized pressure
P_N	average normalized pressure

P_s^*	dimensionless pressure drop for vertical convergence
P^*	dimensionless pressure drawdown
Q, q	flow-rate, STBPD
q_{hc}	critical rate for horizontal wells, STBPD
q_{vc}	critical rate for vertical wells, STBPD
Qc, q_{CD}	dimensionless critical rate
q_o	critical rate for oil, STBPD
Qc, q_c	critical rate, STBPD
Qg	flow rate due to gravity, STBPD
q_t	gross production rate for horizontal wells, STBPD
R	recovery ratio
Rs	dissolve gas oil ratio, MSCF/STB
r_w	well radius, ft.
r^*_w	well radius adjusted for reservoir heterogeneities, ft.
r_e	location of actual noflow boundary for pseudosteady state, ft.
r_A	drainage radius for steady state, ft.
S	well spacing for horizontal wells, ft.
Sw	water saturation
So	oil saturation
Sg	gas saturation
T	breakthrough time, days
WC	water-cut
WOR	water-oil ratio

X	cartesian coordinate direction
X_A	distance from the well to the lateral edge of drainage volume, ft.
X_e	actual distance to no-flow boundary, ft.
X_a	drainage width, ft
X_D	dimensionless drainage width
Y	cartesian coordinate direction
y_e	horizontal well spacing, ft.
ZD	dimensionless well position.
Z	cartesian coordinate direction
α	aspect ratio: b/a
$\Delta\rho_{og}$	density difference between gas and oil, lb_m/cu.ft.
μ	kinematic viscosity, cp
μ_o	oil viscosity, cp.
$\Delta\gamma$	difference between th ehydrostatic gradients of water and
oil,	psi/ft.

subscripts

o	oil
w	water
g	gas
ow	oil-water
og	oil-gas
wg	water-gas

BIBLIOGRAPHY

(1) **Muskat, M. and Wyckoff, R. D.:** *An Approximate Theory of Water-Coning in Oil Production,* Trans. AIME, Vol. 114, 1935, pp.144-161.

(2) **Dietz, D. N.:** *A theoretical approach to the problem of encroaching and bypassing edge water,* Konibel. Ned. Akad. Wetenschap, 1953, Proc. B56.

(3) **Kossack, C.A., Kleppe, J. and Aasen, T.:** *Oil Production from the Troll Field: A Comparison of Horizontal and Vertical Well,* Paper SPE 16869, presented at SPE 62nd Annual Technical Conference and Exhibition, Dallas, TX, September 27-30, 1987.

(4) **Butler, R.M.:** *The Potential for Horizontal Wells for Petroleum Production,* J. Can. Pet. Tech. (May-June 1989) 39-47.

(5) **Nghiem, L., Collins, D.A. and Sharma, R.:** *Seventh SPE Comparative Solution Project: Modelling of Horizontal Wells in Reservoir Simulation,* Paper SPE 21221 presented at the 11th SPE

Symposium on Reservoir Simulation, Anaheim, CA, February 17-20, 1991.

(6) **Zagalai, B.M. and Murphy, P.J.:** *Reservoir Simulation of Horizontal wells in the Helder Field,* JPT (August 1991) 906-913.

(7) **Wang, B.:** *A Parametric Study of Gas and Water Coning in Vertical and Horizontal Wells*, Proc. Indonesia Petroleum Association, 20th
Annual Convention, October 1991.

(8) **Yang, W. and Wattenbarger, R.A.:** *Water Coning Calculations for Vertical and Horizontal Wells,* Paper SPE 22931 presented at the 66th Annual Technical Conference and Exhibition, Dallas, TX, October 6-9, 1991.

(9) **Haug, B.T., Ferguson, W.I. and Kydland, T.:** *Horizontal Wells in the Water Zone: The Most Efficient Way of Tapping oil From thin Oil Zones?,* Paper SPE 22929 presented at the 66th Annual Technical Conference and Exhibition, Dallas, TX, October 6-9, 1991.

(10) **Suprunowicz, R. and Butler, R.M.:** *The Productivity and optimum Pattern Shape for Horizontal Wells Arranged in Staggered Rectangular Arrays,* J. Can. Pet. Tech. (June 1992) 41-46.

(11) **Gilman, J.R. and Jargon, J.R.:** *Evaluating Horizontal vs Vertical Well Performance,* World Oil, April 1992, pp 55-60.

(12) **Gilman, J.R. and Jargon, J.R.:** *Evaluating Horizontal vs Vertical Well performance*, World Oil, June 1992, pp 55-60.

(13) **Menouar, H. and Huang, W.S.:** *Horizontal Well Design in Wafra Field, Ratawi Oolite Reservoir,* Paper SPE 25597 presented at the SPE Middle East Oil Technical Conference and Exhibition, Bahrain, April 3-6, 1993.

(14) **Karcher, B.J. and Giger, F.M.:** *Some Practical Formulas To Predict Horizontal Well Behavior*, Paper SPE 15430 presented at the 61st Annual Technical Conference and Exhibition, New-Orleans, LA, October 5-8, 1986.

(15) **Ozkan, E. and Raghavan, R.:** *Performance Of Horizontal Wells Subject To Bottom Water Drive,* Paper SPE 18545 presented at

the SPE Eastern Regional Meeting, Charleston, WV, November 2-4, 1988.

(16) **Lacy, S. and Ding, W., Joshi, S.D.:** *Horizontal Well Applications and Parameters for Economic Success,* Paper SPE 23676 presented at the SPE Second Latin American Petroleum Engineering Conference, Caracas, Venezuela, March 8-11, 1992.

(17) **Suprunowicz, R. and Butler, R.M.:** *Vertical Confined Water Drive to Horizontal Well-Part 1: Water and Oil of equal Densities,* J. Can. Pet. Tech. (January 1992) 32-38.

(18) **Suprunowicz, R. and Butler, R.M.:** *The Choice of Pattern Size and Shape for Regular Arrays of Horizontal Wells*, J. Can. Pet. Tech. (January 1992) 39-44.

(19) **Chaperon, I.:** *Theoretical Study of Coning Towards Horizontal And Vertical Wells in Anisotropic Formations: Subcritical and Critical Rates,* Paper SPE 15377 presented at the 61st Annual Technical Conference and Exhibition, New Orleans, LA, October 5-8, 1986.

(20) **Efros, D.A.:** *Study of multiphase flows in porous media* (in Russian), Gastoptexizdat, Leningrad, 1963.

(21) **Giger, F.M.:** *Analytic 2-D Models Of Water Cresting Before Breakthrough for Horizontal Wells*, Paper SPE 15378 presented at the 61st Annual Technical Conference and Exhibition, New-Orleans, LA, October 5-8, 1986.

(22) **Guo, B. and Lee, R.L.:** *Determination of the Maximum water-free Production Rate of a Horizontal Well with Water/Oil Interface Cresting,* Paper SPE 24324 presented at the SPE Rocky Mountain regional Meeting, Casper, WY, May 18-21, 1992.

(23) **Guo, B., Molinard, J.E. and Lee, R.L.:** *A General Solution of gas/water Coning Problem for Horizontal Wells*, Paper SPE 25050 presented at the European Petroleum Conference, Cannes, France, November 16-18, 1992.

APPENDIX A

A SAMPLE ECLIPSE INPUT FILE

```
=======================================================================
--
=======================================================================
--      THIS IS THE SECOND PROGRAM TO STUDY WATER CRESTING
--             IN HORIZONTAL WELLS.
--       BASED ON DATA FROM RATAWI OOLITE RESERVOIR.
--
--       SIMULATING A HORIZONTAL WELL FROM 1-1-1961
--       UPTO  14336 DAYS
--      2000' HORIZONTAL WELL IN B LAYER  R-101 (R-24)
--
=======================================================================
RUNSPEC
=======================================================================
         RATAWI OIL FIELD 3 PHASE WATER CONING STUDY
= NDIVIX NDIVIY NDIVIZ QRDIAL NUMRES QNNCON MXNAQN MXNAQC QDPORO
QDPERM
 11  18   12   F   1   F    0   0    F    F /
=  OIL  WATER  GAS  DISGAS VAPOIL
  T   T    T    T   F/
= UNIT CONVENTION
  'FIELD'                /
=  NRPVT  NPPVT  NTPVT NTROCC QROCKC QRCREV
 15   20   1   1    F    T /
= NSSFUN NTSFUN QDIRKR QREVKR QVEOPT QHYSTR QSCALE
 20    1    F    T    f    F    F   /
= NDRXVD NTEQUL NDPRVD QUIESC QTHPRS QREVTH
 20    1    100  f     F     T /
=  NTFIP  QGRAID
 1     F /
= NWMAXZ NCWMAX NGMAXZ NWGMAX MAXLGR MAXCLS LSTACK
 1    14  0    0    0    0    /
= QEXGOP NWFRIC NUPCOL
  F   0    3 /
= MXMFLO MXMTHP MXMWFR MXMGFR MXMALQ NMMVFT
 0   0     0   0     0   0 /
= MXSFLO MXSTHP NMSVFT
 0   0     0 /
```

```
= NANAQU NCAMAX
  1   198 /
=  DAY  MONTH  YEAR
   1  'JAN'  1961 /
= QSOLVE NSTACK QFMTOU QFMTIN QUNOUT QUNINP NGDISK  IDYNAM
  T   0  f   f   F    F /

GRID   ====================================================================
--------X-DIRECTION GRID BLOCK SIZES
DXV
6 4 20  40 80 100 200  200  200  200 200  /

---Y-DIRECTION GRID BLOCK SIZES
DYV
800 750 950 190 160 80 40 20 10 10 20 50 350 790 250 20 4 6  /

--INPUT Z-DIRECTION GRID BLOCK SIZES
DZ
2178*5.3
--- Z-DIRECTION PERMEABILITY

PERMZ
2178*13  /

--Y-DIRECTION PERMEABILITY
PERMY
2178*53  /

--X-DIRECTION PERMEABILITY
PERMX
2178*53  /

--GRID BLOCK POROSITIES
PORO
2178*0.158  /


--DEPTH OF TOP OF RESERVOIR
TOPS
198*6384.0  /

INIT

OLDTRAN

RPTGRID
---KY KZ MULT-X Y Z PORO * TPS PRV DPTH TRAN-X Y Z * * * * AQNUM AQCON
6*0    3*0    0  0  0  0  0     3*0   6*  /
```

```
PROPS ==============================================================
--WATER RELATIVE PERMEABILITY AND CAPILLARY-PRESSURE AS FUNCTION
--OF WATER SATURATION.
--SWAT    KRW    KROW    PCOW
SWOF
0.20600  0.0     1.00000  0
0.25000  0.00565 0.82296  1*
0.30000  0.01766 0.64270  1*
0.35000  0.03348 0.48469  1*
0.40000  0.05236 0.34894  1*
0.45000  0.07386 0.23545  1*
0.50000  0.09769 0.14420  1*
0.55000  0.12365 0.07521  1*
0.60000  0.15156 0.02848  1*
0.65000  0.18131 0.00400  1*
0.68000  0.20000 0.00000  0.0 /

--GAS RELATIVE PERMEABILITY
--SGAS    KRG    KROG    PCOG
SGOF
0.0       0.0     1.00000  0.0
0.03000   0.0     0.92520  1*
0.05000   0.00020 0.87643  1*
0.10000   0.00251 0.75842  1*
0.15000   0.00740 0.64624  1*
0.20000   0.01485 0.54021  1*
0.25000   0.02487 0.44071  1*
0.30000   0.03746 0.34821  1*
0.35000   0.05263 0.26327  1*
0.40000   0.07036 0.18664  1*
0.45000   0.09066 0.11936  1*
0.50000   0.11353 0.06295  1*
0.55000   0.13897 0.02016  1*
0.60000   0.16698 0.0      1*
0.65000   0.19756 0.0      1*
0.70000   0.23071 0.0      1*
0.75000   0.26643 0.0      1*
0.79400   0.30000 0.0      0.00 /

--ROCK COMPRESSIBILITY
--REF. PRES.    COMPRESSIBILITY
ROCK
   2803         4.0e-6 /

--SURFACE DENSITIES OF SURFACE OIL ,GAS AND WATER
-- OIL    WATER    GAS
DENSITY
 56.85    65.55    0.04104 /
```

```
--PVT PROPERTIES OF DRY GAS
--PGAS   BGAS      VISGAS
PVDG
14.7     208.974   0.0128
500.0    5.866     0.0132
1000.0   2.810     0.0139
1470.0   1.853     0.0148
1500.0   1.813     0.0149
2000.0   1.334     0.0161
2500.0   1.0640    0.0175
3000.0   0.897     0.0190
3500.0   0.786     0.0205
4000.0   0.7080    0.0220
4500.0   0.652     0.0235
5000.0   0.609     0.0250
/

PVTO
0.0025  14.7  1.0659  18.578 /
0.1229  500.0  1.1135  8.285 /
0.2624  1000.0  1.1686  5.052 /
0.4000  1470.0  1.2229  3.680 /
0.408900  1500.0  1.2265  3.617 /
0.56010  2000.0  1.2862  2.821 /
0.7149  2500.0  1.3474  2.318 /
0.8727  3000.0  1.4097  1.973 /
1.03300  3500.0  1.4730  1.722 /
1.1954  4000.0  1.5372  1.531 /
1.3598  4500.0  1.6021  1.380 /
1.5459  5000.0  1.6678  1.259
        5400.0  1.6634  1.259
        5800.0  1.6590  1.259
        6200.0  1.6546  1.259
        6400.0  1.6524  1.259 / equation used is POIL=-1.1e-5*FVFO + 1.7228
/

PVTW
2803  1.0  3.0e-6  0.50   3.0e-6 /

RPTPROPS
6*0 /

REGIONS ==========================================================
RPTREGS
/
```

```
SOLUTION
=====================================================================
-- DATA FOR INITIALISING FLUIDS TO POTENTIAL EQUILIBRIUM
--DATUM DATUM  OWC   OWC   GOC   GOC   RSVD  RVVD  SOLN
--DEPTH PRESS DEPTH PCOW  DEPTH PCOG  TABLE TABLE METH
EQUIL
6384  2756  6535  0.0  6384  0.0   1   0   -5 /

---RS VS. DPTH
RSVD
6390 0.4000
6420 0.4000 /

AQUFET
--6535 1* 10.5e7 7.0E-6 5.0 1 1 11 1 18 12 12 'K+' /
6535 1* 10.5e11 7.0E-6 5.0 1 1 11 1 18 12 12 'K+' /


-- SWITCH ON OUTPUT OF INITIAL SOLUTION
RPTSOL
5*0 0 0 0 0 38* 6*0 /

SUMMARY
=====================================================================
-------- THIS SECTION SPECIFIES DATA TO BE WRITTEN TO THE SUMMARY FILES
-------- AND WHICH MAY LATER BE USED WITH THE ECLIPSE GRAPHICS PACKAGE
-- FIELD  OIL PRODUCTION
WOPT
'R-101'
/
/
WOGR
'R-101'
/

--BOTTOM HOLE PRESSURE FOR WELL
WBHP
'R-101'
/
WPI
'R-101'
/

RUNSUM
SEPARATE
RPTSMRY
1 /
```

```
SCHEDULE
=================================================================
-------- THE SCHEDULE SECTION DEFINES THE OPERATIONS TO BE SIMULATED
---CONTROLS OF OUTPUT AT EACH REPORT TIME
RPTSCHED
1 1* 1 /

--WELL SPECIFICATION DATA
--WELL  GROUP  LOCATION  BHP  PREF.PHASE
WELSPECS
'R-101' 1*  1  18    6399.3 'OIL'  -1 /
/

WELPI
'R-101' 5.32 /
/


-- COMPLETION SPECIFICATION DATA
--WELLNAME -LOCATION-  OPEN/ SAT CONN WELL
COMPDAT
'R-101'  1  17   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  16   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  15   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  14   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  13   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  12   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  11   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  10   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  9   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  8   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  7   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  6   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  5   3 3 'OPEN'  2*  0.5 3*  'Y' /
'R-101'  1  4   3 3 'OPEN'  2*  0.5 3*  'Y' /
/

--PRODUCTION WELL CONTROLS-OIL RATE IS SET TO 1000 BPD
--WELL  OPEN/  CNTL  OIL  WATER  GAS  LIQU  RES  BHP
--NAME  SHUT  MODE  RATE  RATE  RATE  RATE  RATE
--SPECIFY UPPER LIMIT OF 1 DAY FOR NEXT TIME STEP
TUNING
1 /
/
2* 300 /

WCONPROD
'R-101' 'OPEN' 'ORAT'  500.  4*  500.0/
```

```
/

--AND ADVANCE TO 9953 DAYS    4174 DAYS
TSTEP
1.0 29.0 20.0  169.0  185.0  187.0  199.0 443.0  1857.0  345. 203. 299.0 237.0
395.0 758.0 480.0 318.0  381.0 663.0  593. 730. 730. 731. 731.
/

END
```

APPENDIX B

TILTED RESERVOIR

Critical rate estimation was also carried out for the case of a tilted reservoir with a 5° tilt. All the simulation cases that were carried out for a horizontal reservoir were repeated for a tilted reservoir. The effect of well position, reservoir anisotropy and reservoir geometry on critical rate were studied for vertical as well as horizontal wells of lengths 500', 1000', 2000' and 3000'.

B.1. EFFECT OF WELL POSITION

B.1.1 Horizontal Well

The effect of well position upon the critical rate was studied by determining the critical rate for dimensionless well position, ZD, equal to 1.0, 0.75, 0.5 and 0.25. The reservoir is assumed to be homogeneous and isotropic with an absolute permeability of 45.6 md. The other characteristics related to the PVT properties and reservoir characteristics and geometry are those that are valid for the horizontal reservoir with the exception that the reservoir is not horizontal. The results are shown in Table B.1. These results have been plotted after converting them into appropriate dimensionless form by using the dimensionless numbers defined in Chapter 6. The results are presented in Figure B.1 and Figure B.2. Figure B.1 shows the effect of changing the well length for any given position, while Figure B.2 shows the effect of changing the well position for any given well length upon its' critical rate.

It can be observed from Figure B.1 that as well length is changed for a given position, the critical rate increases from a minimum value for a vertical well to a maximum value for a 3000' well length which is 11 times higher than that for a vertical well. Table B.2 assesses the trend observed as the horizontal well length is increased from 500' to 3000'.

The % increment in critical rate is given in terms of the % drop in critical rate with respect to the critical rate for the longer well. It should be noted that for any given increment in length the % increment in critical rate was found to be the same for all positions. Therefore the values given are representative of this behavior irrespective of the well position.

B.1.2 VERTICAL WELLS

Similar analysis was carried out for the vertical well. The position of the perforated interval was varied and the well was placed in the same positions, ZD, in which the horizontal wells were located. The thickness of the perforated interval remains the same in this study and is taken as 20.0 ft. The result is shown in Table B.3 and in Figure B.1 and Figure B.2 in which the effect of changing the position of the vertical well is illustrated. It can be observed from Figure B.2 that as the well is brought closer to the OWC the critical rate decreases from a maximum value to a minimum value with a 60% drop in the critical rate with respect to that for the ZD=1.0 position.

B.2 EFFECT OF RESERVOIR ANISOTROPY

The effect of reservoir anisotropy was studied by varying the anisotropy ratio, a, for all the well lengths. The analysis was carried out for all the positions, ZD, and the following anisotropy ratios:

1. a = 1.0
2. a = 0.5
3. a = 0.2
4. a = 0.1.

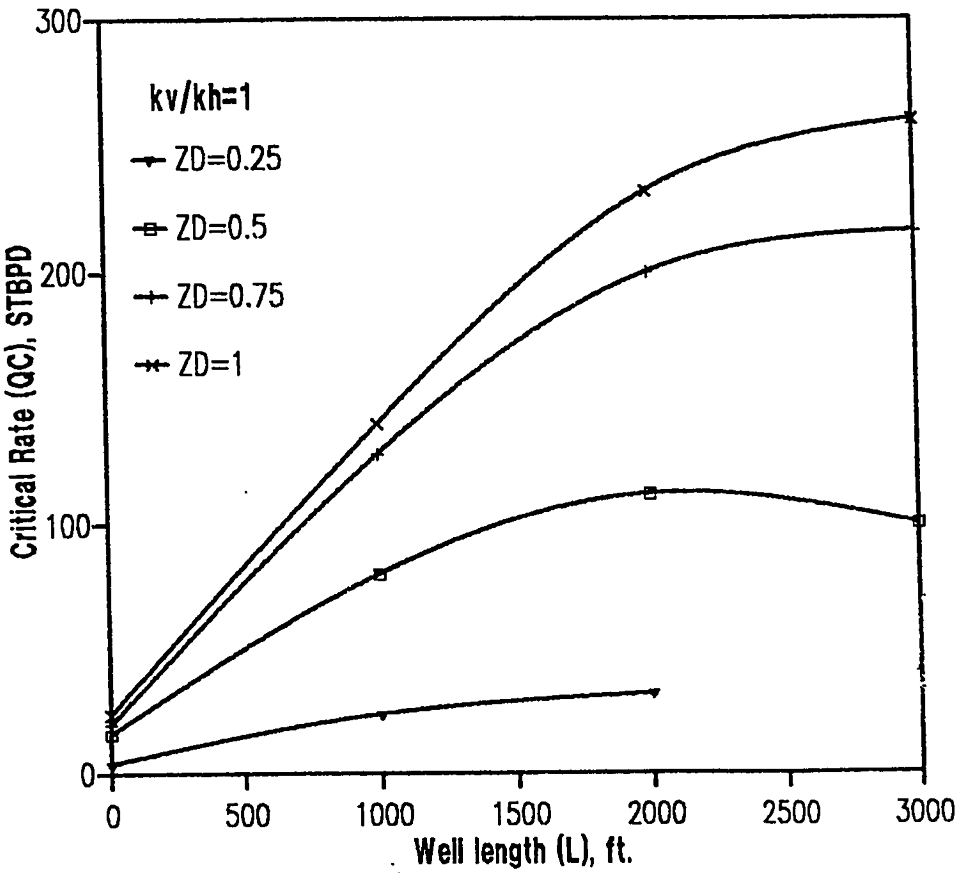


Figure B.1: Variation with length for different well positions.

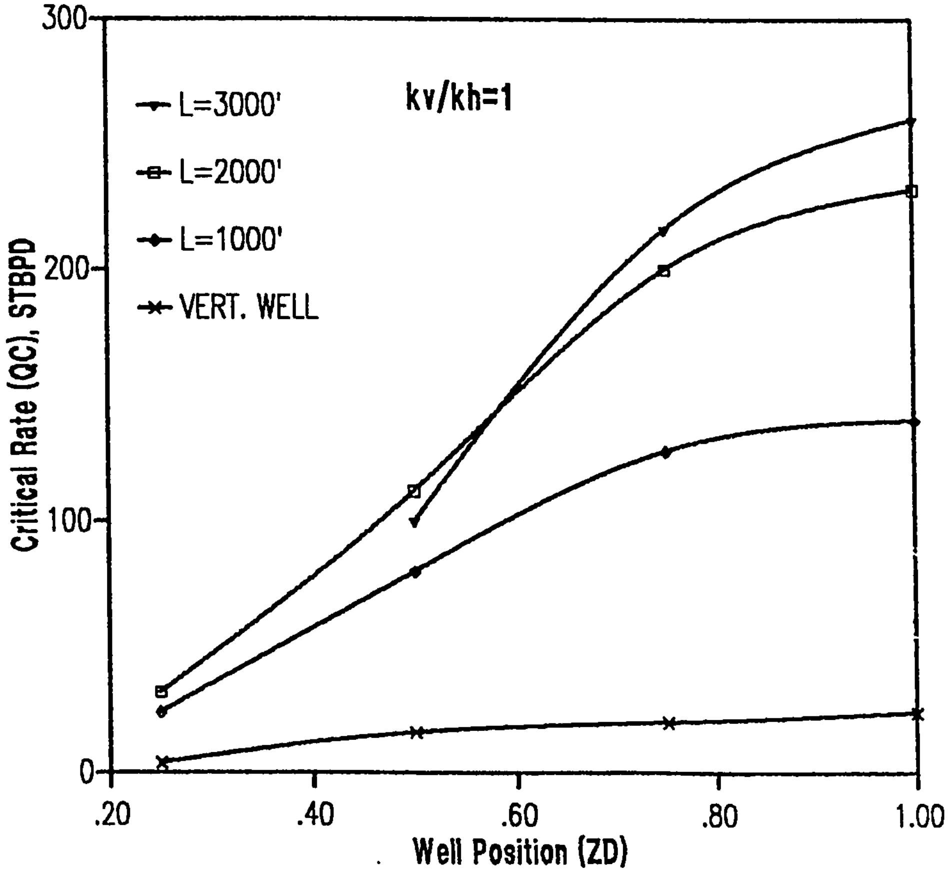


Figure B.2: Variation with position for different well lengths.

Table B.1: Critical rate as a function of well length and it's position.

Tilted	*Reservoir*		a= 1.0	
Length	**Qc, STBPD**	**Qc, STBPD**	**Qc, STBPD**	**Qc, STBPD**
	ZD = 1.0	**ZD =0.75**	**ZD =0.50**	**ZD =0.25**
500'	112	-	-	-
1000'	140	128	80	24
2000'	232	200	112	32
3000'	260	216	100	-

Table B.2: % increment in Qc for increasing Horizontal well length.

Change in well length	**% increment in critical rate**
vertical well - 3000'	91%
vertical well - 500'	79%
500' - 1000'	20%
1000' - 2000'	30%
2000' - 3000'	10%

Table B.3: Critical rate as function of ZD for a vertical well.

Tilted Reservoir	*a=1.0*
ZD	**Qc (STBPD)**
1.0	24
0.75	20
0.50	16
0.25	4

B.2.1 HORIZONTAL WELL

As shown in Table B.4 to B.7, the results show the following trends:

1. As the well position is changed from the top (ZD=1) to the lowest plane (ZD=0.25), it is found that the drop in critical rate increases progressively.
2. It is observed that for the well in the top plane the critical rate increases with length but the % increase itself decreases for each increment in length.

3. For all well positions, as shown in Figure B.3, and presented in Table B.8 to B.11, it is observed that critical rate tends to increase slightly as anisotropy ratio decreases from a maximum value of 1.0 to a minimum value of 0.1. However as the length increases the trend tends to change.

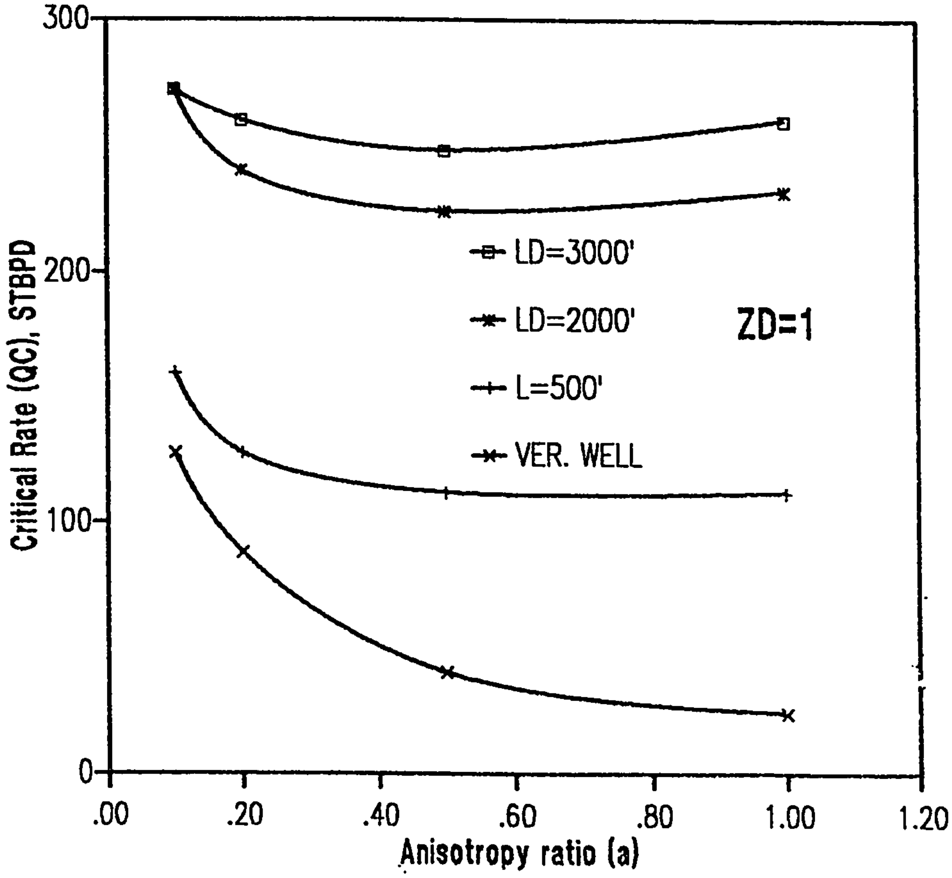


Figure B.3: Effect of anisotropy ratio for a well when ZD=1.

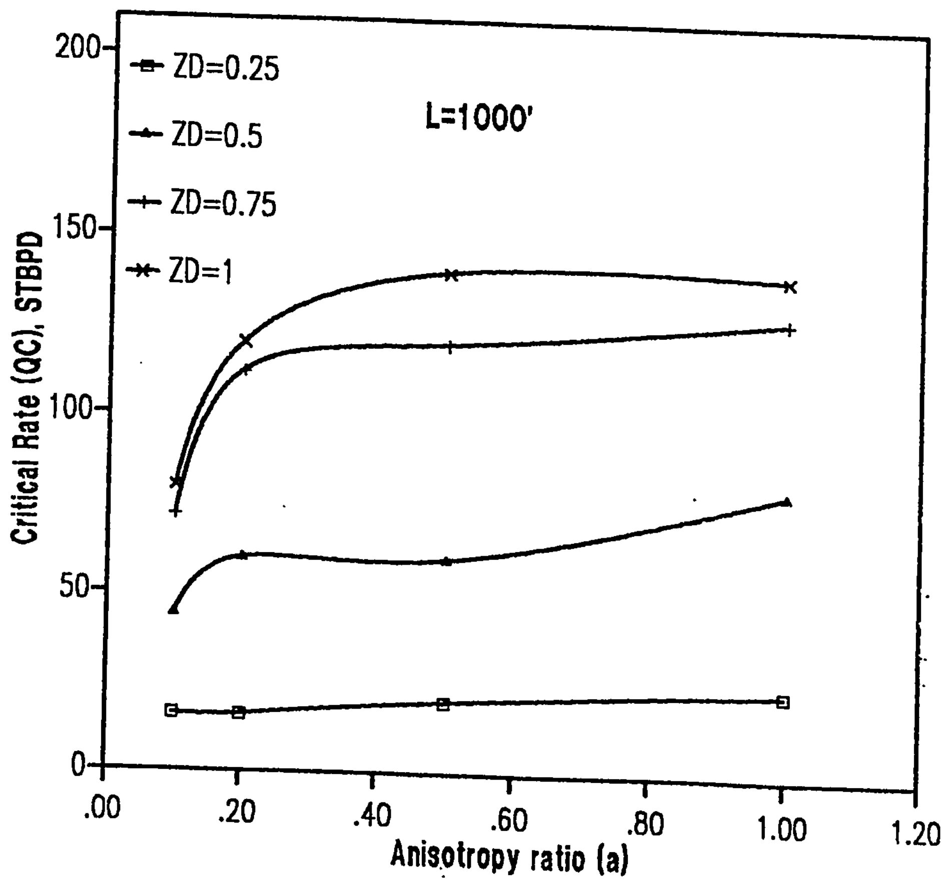


Figure B.4: Effect of anisotropy ratio on L=1000' well for all positions.

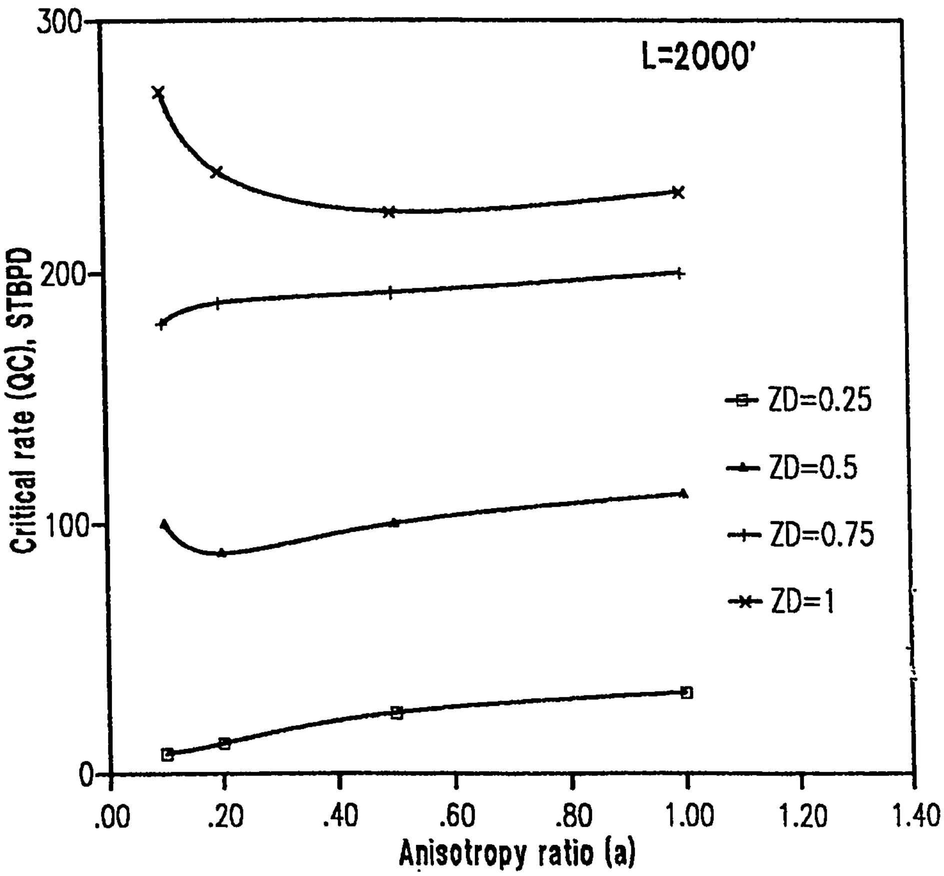


Figure B.5: Effect of anisotropy ratio on L=2000' well for all positions.

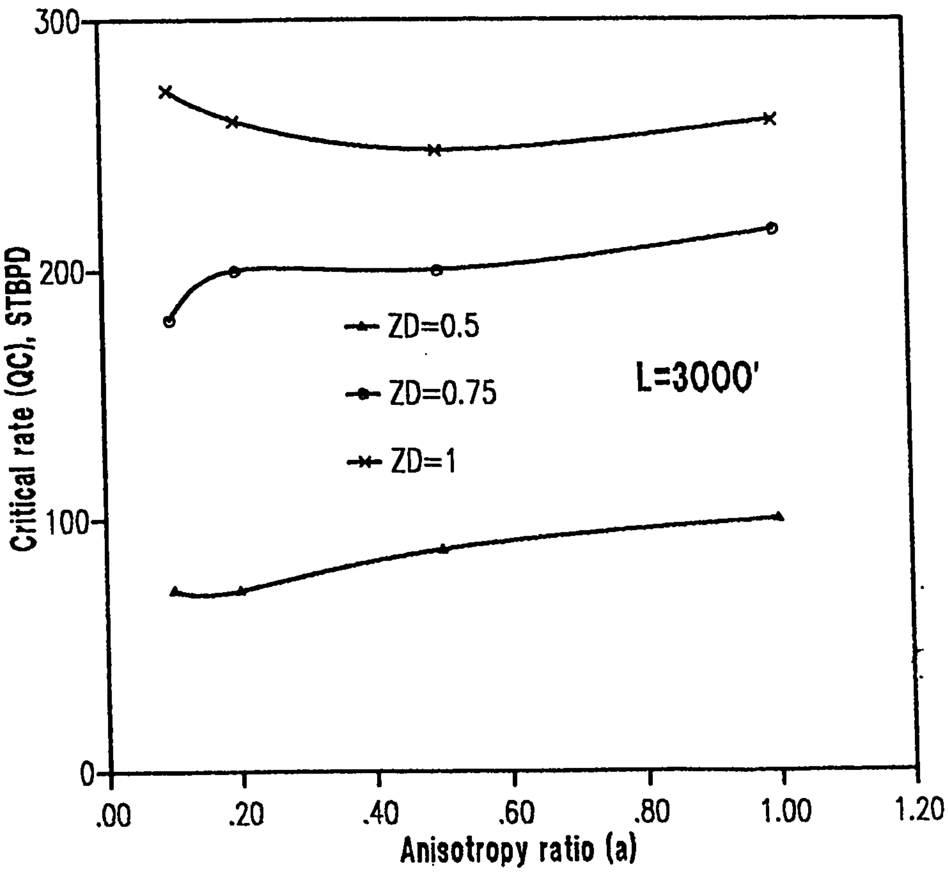


Figure B.6: Effect of Anisotropy ratio on a L=3000' well for all positions.

Table B.4: Effect of Anisotropy ratio on Critical Rates (ZD=1.0)

Tilted reservoir				
	a=1.0	**a=0.5**	**a=0.2**	**a=0.1**
Well Length	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**
500'	112	112	128	160
1000'	140	140	120	80
2000'	232	224	240	272
3000'	260	248	260	272

Table B.5: Effect of Anisotropy ratio on Critical Rates (ZD=0.75)

Tilted reservoir				
	a=1.0	**a=0.5**	**a=0.2**	**a=0.1**
Well Length	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**	**Qc (STBPD)**
500'	-	-	-	-
1000'	128	120	112	72
2000'	200	192	188	180
3000'	216	200	200	180

Table B.6: Effect of Anisotropy ratio on Critical Rates (ZD=0.5)

Tilted	*reservoir*			
	a=1.0	**a=0.5**	**a=0.2**	**a=0.1**
Well Length	**Qc, STBPD**	**Qc, STBPD**	**Qc, STBPD**	**Qc, STBPD**
500'	-	-	-	-
1000'	80	60	60	44
2000'	112	100	88	100
3000'	100	88	72	72

Table B.7: Effect of Anisotropy ratio on Critical Rates (ZD=0.25)

Tilted	*reservoir*			
	a=1.0	**a=0.5**	**a=0.2**	**a=0.1**
Well Length	**Qc, STBPD**	**Qc, STBPD**	**Qc, STBPD**	**Qc, STBPD**
500'	-	-	-	-
1000'	24	20	16	16
2000'	32	24	12	8

Table B.8: Effect of anisotropy ratio on Qc for ZD=1.0

Well Length (ft.)	$\frac{Qc\|_{a=0.1}}{Qc\|_{a=1.0}}$
500'	1.5
1000'	0.6
2000'	1.2
3000'	1.04

Table B.9: Effect of anisotropy ratio on critical rate for ZD=0.75

Well Length (ft.)	$\frac{Qc\|_{a=0.1}}{Qc\|_{a=1.0}}$
7.2	0.6
14.4	0.9
21.6	0.8

Table B.10: Effect of anisotropy ratio on critical rate for ZD=0.5

Well Length (ft.)	$\frac{Qc\|_{a=0.1}}{Qc\|_{a=1.0}}$
7.2	0.6
14.4	0.9
21.6	0.7

Table B.11: Effect of anisotropy ratio on critical rate for ZD=0.25

Well Length (ft.)	$\frac{Q_c\|_{a=0.1}}{Q_c\|_{a=1.0}}$
7.2	0.70
14.4	0.25

B.6 and Table B.12-B.15 show that the drop in critical rate at ZD=0.25 with respect to its' value at ZD=1 increases with decrease in anisotropy ratio. In addition it can also be observed that for a given position the % drop in critical rate remains almost the same regardless of the well length.

Table B.12: Effect of change in well position on well: L=1000'

Anisotropy ratio	% drop in Qc
1.0	83%
0.5	86%
0.2	87%
0.1	80%

Table B.13: Effect of change in well position on well: L=2000'

Anisotropy ratio	% drop in Qc
1.0	86%
0.5	89%
0.2	95%
0.1	97%

B.2.2 VERTICAL WELLS

The effect of anisotropy ratio was also studied for vertical wells in the same manner as for the horizontal wells. Table B.14 gives the results for vertical wells. The results are graphically illustrated in Figure B.7. It can be observed that for a given anisotropy ratio the critical rate drops as the well approaches the OWC from the top plane. This drop expressed as a fraction of the critical rate for the top position of well increases as the value of anisotropy ratio increases. This is presented in Table B.15. Another observation made for horizontal well is related to the behavior of critical rate as the anisotropy ratio changes from 1.0 to 0.1 for different well positions. As shown in Table B.16 the increase in critical rate for vertical well decreases with the position of the well.

B.2.3 DETAILED ANALYSIS OF WELL: L=2000'

The behavior of critical rate with respect to the anisotropy ratio was studied in detail specifically for very small anisotropy ratios by determining the critical rates for additional values of anisotropy ratio and plotting the results to identify its' behavior over a wide range of anisotropy ratio. The analysis was carried out for ZD=1 and ZD=0.5 plane only and for one well length of 2000'. The results shown in Table B.17 and Figure B.8 show that:

1. As anisotropy ratio changes from 1.0 to 0.1 critical rate increases by 17% for ZD=1 and reduces by 40% for ZD=0.5.
2. As anisotropy ratio changes from 1.0 to 0.032 critical rate increases by 42% for the ZD=1 case and by 7% for ZD=0.5 case.

B.3 EFFECT OF RESERVOIR GEOMETRY

For tilted reservoir following reservoir geometries were studied:

1. A square reservoir of dimensions 4500.0*4500.0 sq.ft. **(Case A)**
2. A rectangular reservoir of dimensions 2250.0*4500.0 sq.ft. **(Case B)**
3. The base case reservoir of dimensions 1250.0*4500.0 sq.ft. **(Case C)**

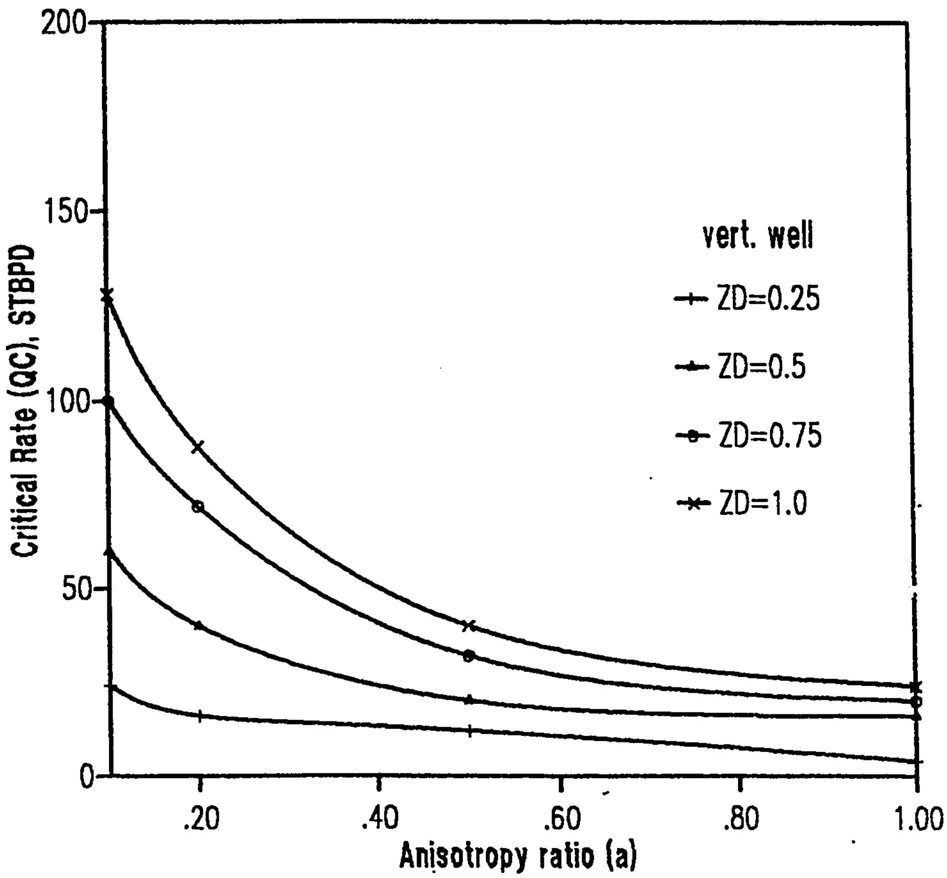


Figure B.7: Effect of anisotropy ratio on vertical well for all positions

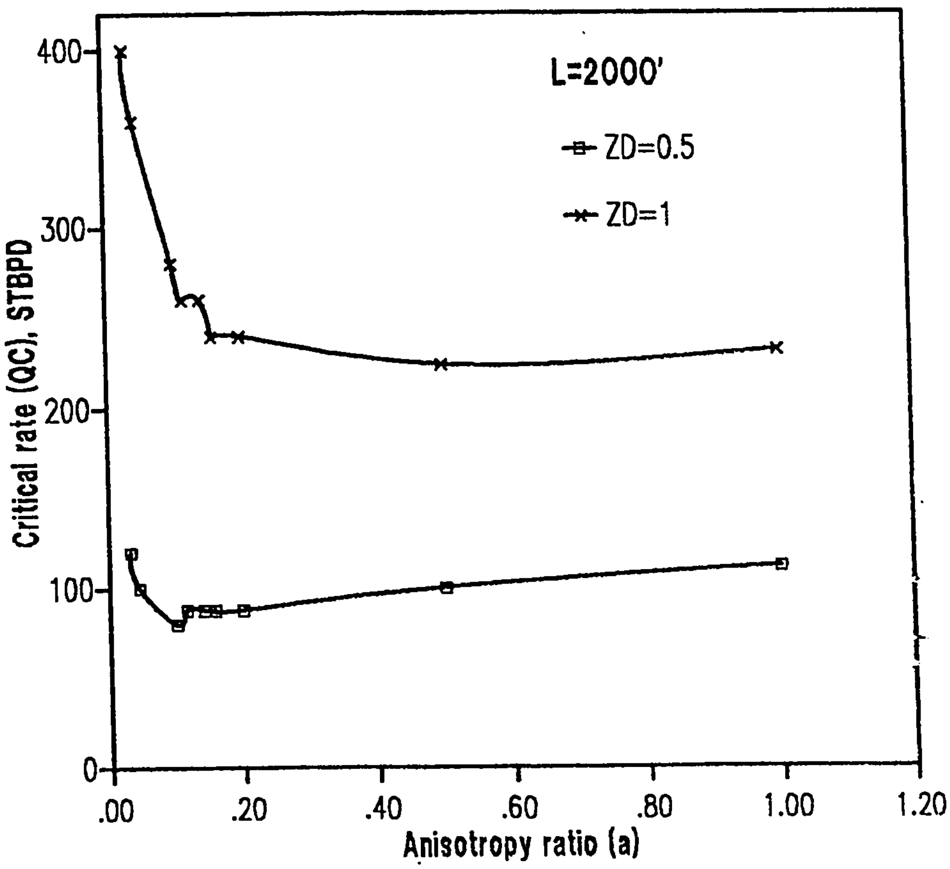


Figure B.8: A detailed analysis of the effect of anisotropy ratio.

Table B.14: Effect of Anisotropy Ratio on Vertical Well for all positions

Tilted Reservoir	
Anisotropy	**ratio = 0.5**
ZD	**Qc (STBPD)**
1.0	40
0.75	32
0.5	20
0.25	12
Anisotropy	**ratio = 0.2**
ZD	**Qc (STBPD)**
1.0	88
0.75	72
0.5	40
0.25	16
Anisotropy	**ratio = 0.1**
ZD	**Qc (STBPD)**
1.0	128
0.75	100
0.5	60
0.25	24

Table B.15: Critical Rate % drop with anisotropy ratios (vert. wells)

Anisotropy ratio	% Drop in Critical rate
1.0	83%
0.5	70%
0.2	82%
0.1	81%

Table B.16: Effect of anisotropy ratio on vert. well Qc for all ZD

ZD	$\frac{Q_c\|_{a=0.1}}{Q_c\|_{a=1.0}}$
1.0	5
0.75	5
0.50	4
0.25	6

The analysis was carried out only for positions ZD=1.0 and ZD=0.5 for the case of homogeneous, isotropic reservoir for well lengths of 1000', 2000', 3000' and for vertical wells.

B.3.1 HORIZONTAL WELL

In case of horizontal wells it was observed that increasing the area of the reservoir resulted in an increase in critical rate. Table B.18 presents the results in terms of the dimensionless as well as the real values. The effect of geometry is presented in Figure B.9 and in Table B.19 to B.21. It is evident that longer the well length shows higher drop in critical rate and this drop is higher if the well position ZD, is closer to the OWC.

B.3.2 VERTICAL WELL

The effect of geometry on vertical well was also studied. Table B.22 and Figure B.9 describe the results obtained for vertical wells. The effect of reservoir geometry is represented in Table B.23 and B.24. It can be observed that reducing the size of reservoir results in a decrease in critical rate and this reduction is more if a well is situated further away from the OWC.

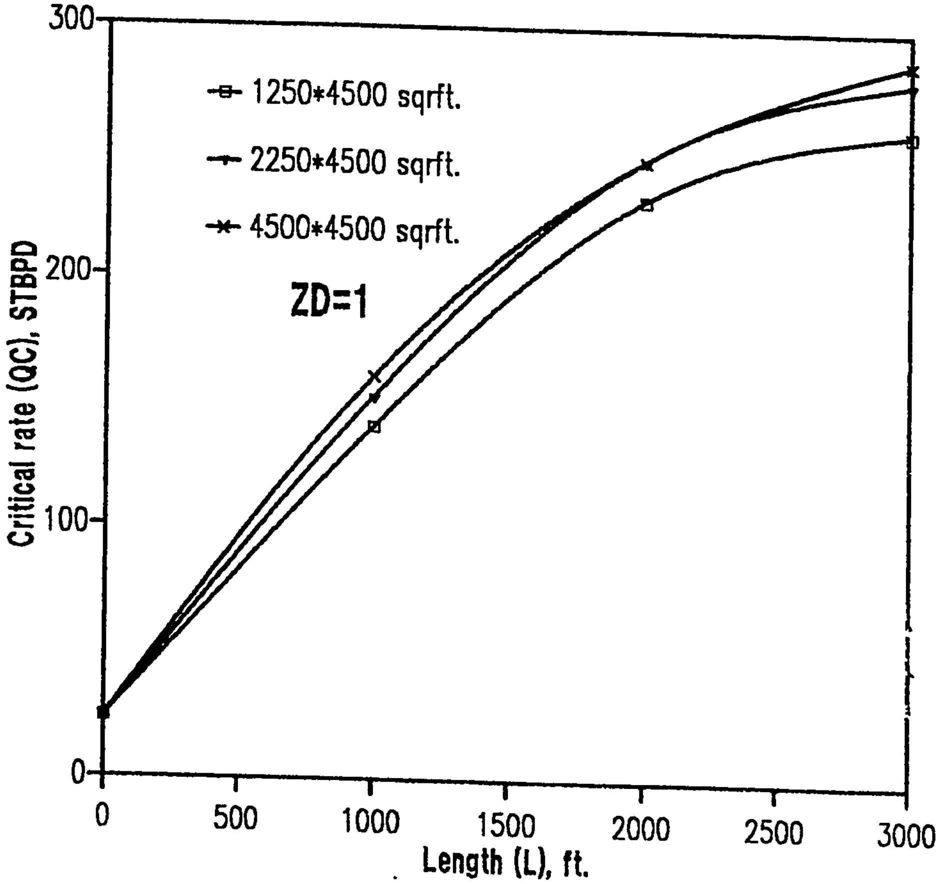


Figure B.9: Effect of reservoir geometry for different well lengths.

Table B.17: Detailed Analysis of Anisotropy Effect for Well: L=2000'

Tilted	*Reservoir*	
L = 2000'	ZD=1	ZD=0.5
Anisotropy ratio	Qc (STBPD)	Qc (STBPD)
1.0000	232	112
0.5000	224	100
0.2000	240	88
0.1580	240	88
0.1414	260	88
0.1155	260	88
0.1000	280	80
0.0450	360	100
0.0316	400	120

Table B.18: Effect of Reservoir Geometry on Critical Rate

Horizontal	*Reservoir*			
	ZD=1		ZD=0.5	
	4500'*4500'	2250'*4500'	4500'*4500'	2250'*4500'
Well length	Qc (STBPD)	Qc (STBPD)	Qc (STBPD)	Qc (STBPD)
1000'	160	152	140	80
2000'	248	248	152	120
3000'	288	280	160	112

Table B.19: Critical Rate % drop with reservoir geometry:

L=1000'

Reservoir Geometry	% Drop in Qc	Reservoir Geometry	% Drop in Qc
ZD=1		ZD=0.5	
A-C	13%	A-C	43%
A-B	5%	A-B	43%
B-C	8%	B-C	no change

Table B.20: Critical Rate % drop with reservoir geometry: L=2000'

Reservoir Geometry	% Drop in Qc	Reservoir Geometry	% Drop in Qc
ZD=1		ZD=0.5	
A-C	6%	A-C	26%
A-B	no change	A-B	21%
B-C	6%	B-C	7%

Table B.21: Critical Rate % drop with reservoir geometry: L=3000'

Reservoir Geometry	% Drop in Qc	Reservoir Geometry	% Drop in Qc
ZD=1		ZD=0.5	
A-C	10%	A-C	38%
A-B	3%	A-B	30%
B-C	7%	B-C	11%

Table B.22: Effect of Geometry on Vertical Well

Tilted Reservoir	
ZD=1	
Geometry (ft^2)	**Qc (STBPD)**
4500*4500	24
2250*4500	24
ZD=0.5	
4500*4500	12
2250*4500	12

Table B.23: Critical Rate % drop with reservoir geometry for vertical wells (ZD=1)

Reservoir Geometry	% Drop in Critical rate
A-C	no change
A-B	no change
B-C	no change

Table B.24: Critical Rate % drop with reservoir geometry for vertical wells (ZD=0.5)

Reservoir Geometry	% Drop in Critical rate
A-C	25%
A-B	no change
B-C	25%

VITA

Ali Abbas Hakim
Candidate for the degree of
Master of Science

Thesis: A PARAMETRIC STUDY OF WATER CRESTING IN HORIZONTAL WELL

Major Field: Petroleum Engineering

Biographical:

Personal Data: Born in Karachi, Pakistan, November 12, 1966, the son of Mr. and Mrs. Mansoor Ali Hakim.

Education: Obtained Bachelor of Engineering degree in Mechanical Engineering from N.E.D. University of Engineering and Technology, Karachi, 1991; recieved the Master of Science degree from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, in January 1995.

Professional Experience: Research Assistant in Petroleum Engineering at King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, 1992-1994.

Professional Membership: Pakistan Engineering Council, Society of Petroleum Engineers.