CHAPTER V

EFFECTS OF PRODUCTION RATE ON ULTIMATE RECOVERY

It has been doubtful whether ultimate oil recovery is affected by oil production rate. Several studies' results[3,4,5] have been published but no unanimous conclusions have been made. In addition, those studies were performed during or before 1970s when efficiency of computers was incomparable to that of the computers being used at present.

Oil production rate is considered the most probable factor that has effects on ultimate recovery of oil from natural depletion process. To investigate the effects of oil production rate on ultimate oil recovery, a reservoir model described in chapter IV has been used. It was decided to investigate the effects that has occurred at the sand face and in the reservoir. The benefit of having investigation at the sand face is to ensure that the ultimate oil recovery and behavior of the reservoir producing under the depletion drive mechanism have been closely investigated without the effect of the production operation setup.

To investigate the effects of oil production rate on ultimate recovery, a series of maximum allowable oil production rates have been set as an upper limit when running the numerical reservoir model. The well is then allowed to produce at its capacity but not greater than the maximum allowable oil rate until its oil production rate has reached the economic limit which is set to 50 STB/D. Then, the well will be shut in. In term of gas production rate, no limitation is used. The reason of having no limitation of gas production rate is due to the fact that the limitation of gas production rate is one of the factors that control ultimate recovery of oil. Producing oil from a solution gas drive reservoir requires that gas be produced. Therefore, if the gas production rate is limited, oil rate will be controlled accordingly. Limitation of water production rate is also excluded from this work since there is no active aquifer. However, water production which is from within the reservoir is insignificant. The results of the study confirm this assumption. At initial condition, the reservoir has volume of oil initially in place of 9.77 million stock tank barrels (MMSTB). Its solution gas volume is 4.89 billion standard cubic feet (MMMSCF). Initial reservoir pressure is 3,000 psia.

Table 5.1 presents a series of maximum allowable oil production rates and the resulting of ultimate oil recovery. The time to reach the ultimate oil recovery of each case, and average reservoir pressure at abandonment are also tabulated. A comparison of oil production rates from each case as a function of time is shown in Figure 5.1. Figure 5.2 is a comparison of producing gas oil ratio, which will be referred to as GOR throughout this work, obtained from each case.

It could be seen from the above table that ultimate oil recovery values obtained for all cases are close to 10.9%. The maximum magnitude of differences is only 1% and is found between the case of 500 STB/D and the case of 300 STB/D. As the magnitude of differences of ultimate recovery are relatively small, it is considered that these differences are negligible.

In term of time to reach ultimate recovery of each case, it can be seen that there are three figures of producing days to reach ultimate recovery of oil. For the cases which have maximum allowable oil production rates of 800 STB/D or greater the number of days to reach ultimate recovery is 3,441. In the case which has maximum

Table 5.1. Effects of oil production rate on ultimate oil recovery for the base cases

Case	Maximum allowable rate (STB/D)	Ultimate Oil Recovery (%)	Time to reach ultimate recovery (days)	Avg. reservoir pressure at abandonment (psia)
1001	3392	10.93	3441	612
1002	3000	10.94	3441	612
1003	2500	10.93	3441	612
1004	2000	10.91	3441	623
1005	1500	10.92	3441	616
1006	1000	10.89	3441	622
1007	800	10.88	3441	625
1008	500	10.84	3653	656
1009	300	10.99	4553	685

allowable oil production rate of 300 STB/D, the well has to produce for 4,553 days. In the latter case, it requires 1,112 days longer than the former cases to reach ultimate oil recovery of the same magnitude. The case with 500 STB/D has to produce for 3,653 days prior to abandonment.

It is found that for the cases which maximum allowable oil rates are set to 1,000 STB/D or greater, oil flow rate of each case becomes similar after the well has been producing for a certain period (Figure 5.1). Oil flow rates of the cases which

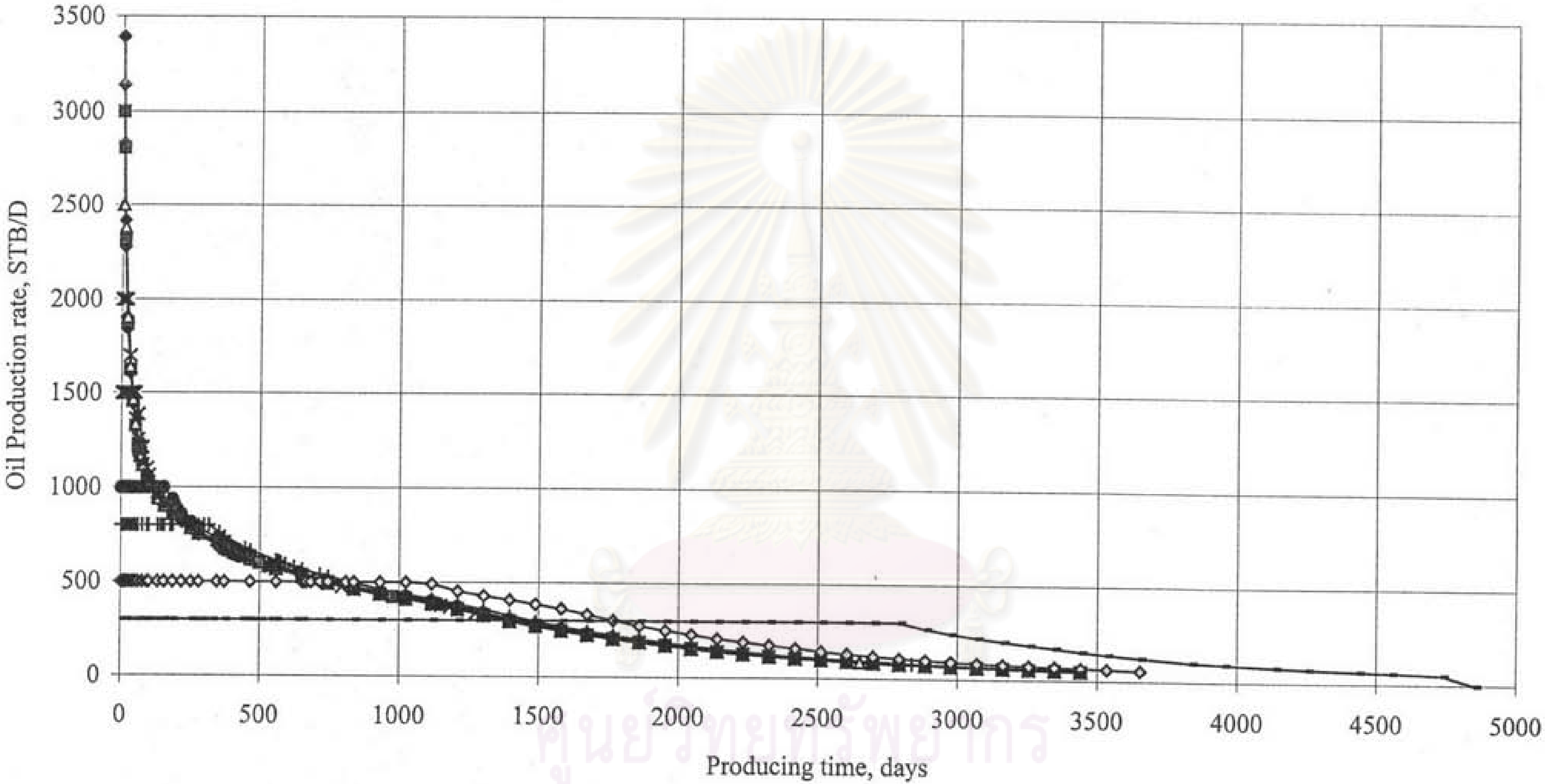

Figure 5.1 Oil production rates at various producing time

Maximum allowable oil rate

Qo = 3391 STB/D, Qo = 3000 STB/D, Qo = 2500 STB/D, Qo = 2000 STB/D, Qo = 1500 STB/D, Qo = 1000 STB/D, Qo = 800 STB/D, Qo = 500 STB/D, Qo = 300 STB/D

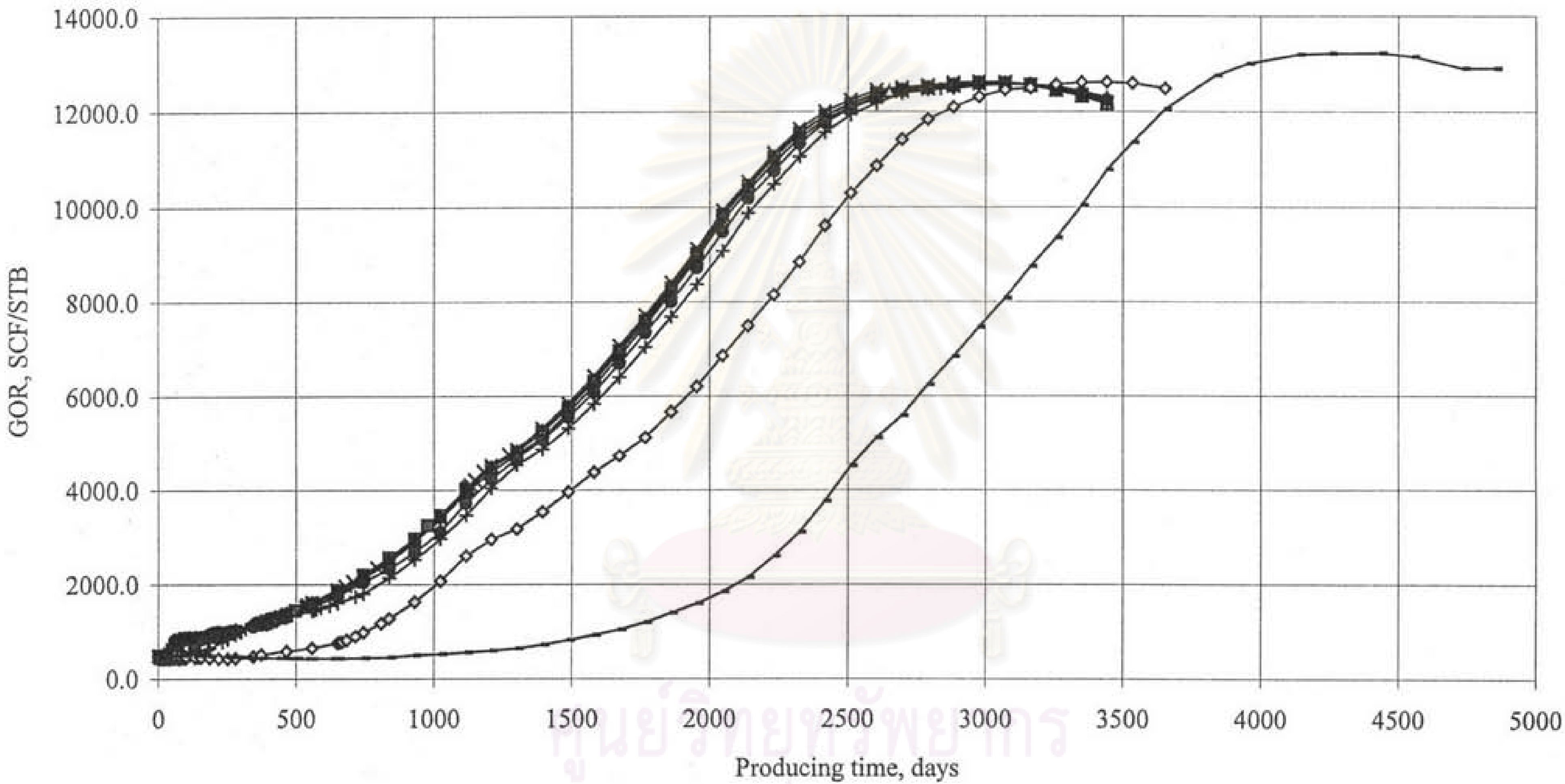

Figure 5.2 Producing Gas Oil Ratios, GOR, at various producing time

Maximum allowable oil rate

Qo = 3391 STB/D, Qo = 3000 STB/D, Qo = 2500 STB/D, Qo = 2000 STB/D, Qo = 1500 STB/D, Qo = 1000 STB/D, Qo = 800 STB/D, Qo = 500 STB/D, Qo = 300 STB/D

have maximum allowable oil production rates of 1,000, 1,500, 2,000, 2,500, 3,000 and 3,392 STB/D become close to that of one another as the well has produced for 400 days. The case with 800 STB/D has to produce for 1,000 days prior to having oil production rate similar to that of the group with 1,000 STB/D or greater. This does not apply to the case where maximum allowable oil production rate is set to less than 500 STB/D. On the other hand, oil production rates of the cases with 500 STB/D or smaller do not follow oil production rate of the cases with 800 STB/D or greater.

Figure 5.1 shows that in the cases where maximum allowable oil rates are high, the well could not sustain that high rate for a long time. This could be found from the cases which have maximum allowable oil rates of 2,500, 3,000 and 3,392 STB/D. Oil production rates of the cases of 3,392 and 3,000 STB/D drop drastically after the well starts to produce. This is believed to be the result of having the rate higher than the capacity of the reservoir. The well in the case of 2,500 STB/D could sustain this oil rate for 20 days prior to declining. Figure 5.2 shows that GOR of these three cases are approximately similar although the maximum allowable oil rates are different.

Oil production rates of the cases of 2,500, 3,000 and 3,392 STB/D become close to that of the cases of 1,500 and 2,000 STB/D as the well has produced for 160 days. Oil production rates of these five cases keep close to that of each other until the abandonment. Oil production rate of the case of 1,000 STB/D can be sustained for 150 days before declining and its oil rate is very close to those of the first five cases after the well has produced for 400 days. The case with 800 STB/D has plateau rate for 350 days prior to declining to reach the trend of the cases with 1,000 STB/D or greater after 1,000 days of production.

Figure 5.3 is a plot of pressure difference between average reservoir pressure and bottom hole pressure. This figure is used to explain the above phenomena. Consider the cases which have maximum allowable oil production rates equal 1,500 STB/D or greater. As the well starts to produce, pressure differences for each case are not similar. Therefore, oil production rates at the beginning for each case are different. Pressure difference for each case becomes identical as the well has produced for 160 days. This is consistent with the investigation made from a comparison of oil production rates as well as a comparison of GOR. Pressure difference for the case with 1,000 STB/D becomes similar to that of the group of 1,500 STB/D or greater after the well has produced for 400 days. At this time, its oil production rate falls into the same trend of the group with 1,500 STB/D or greater. Furthermore, GOR becomes very close as well.

Average reservoir pressure as a function of producing time of each case is plotted in Figure 5.4. It could be seen from this figure that average reservoir pressure of each case is similar for the cases which have maximum allowable oil rates equal to or greater than 1,000 STB/D. The case which has maximum allowable oil rate of 500 STB/D has higher average reservoir pressure. In addition to average reservoir pressure at various time points, it could be concluded that for the cases with maximum allowable oil rate less than 1,000 STB/D, average reservoir pressure relates inversely to maximum allowable oil rate. The higher maximum allowable oil rate results in more rapid drop in average reservoir pressure. The cases with maximum allowable oil rate of 1,000 STB/D or greater have similar average reservoir pressure.

It is further found that the average reservoir pressure at abandonment of each case varies between 612 and 685 psia. Considering the cases which have time to reach recovery of 3,341 days indicates that average reservoir pressure at abandonment varies

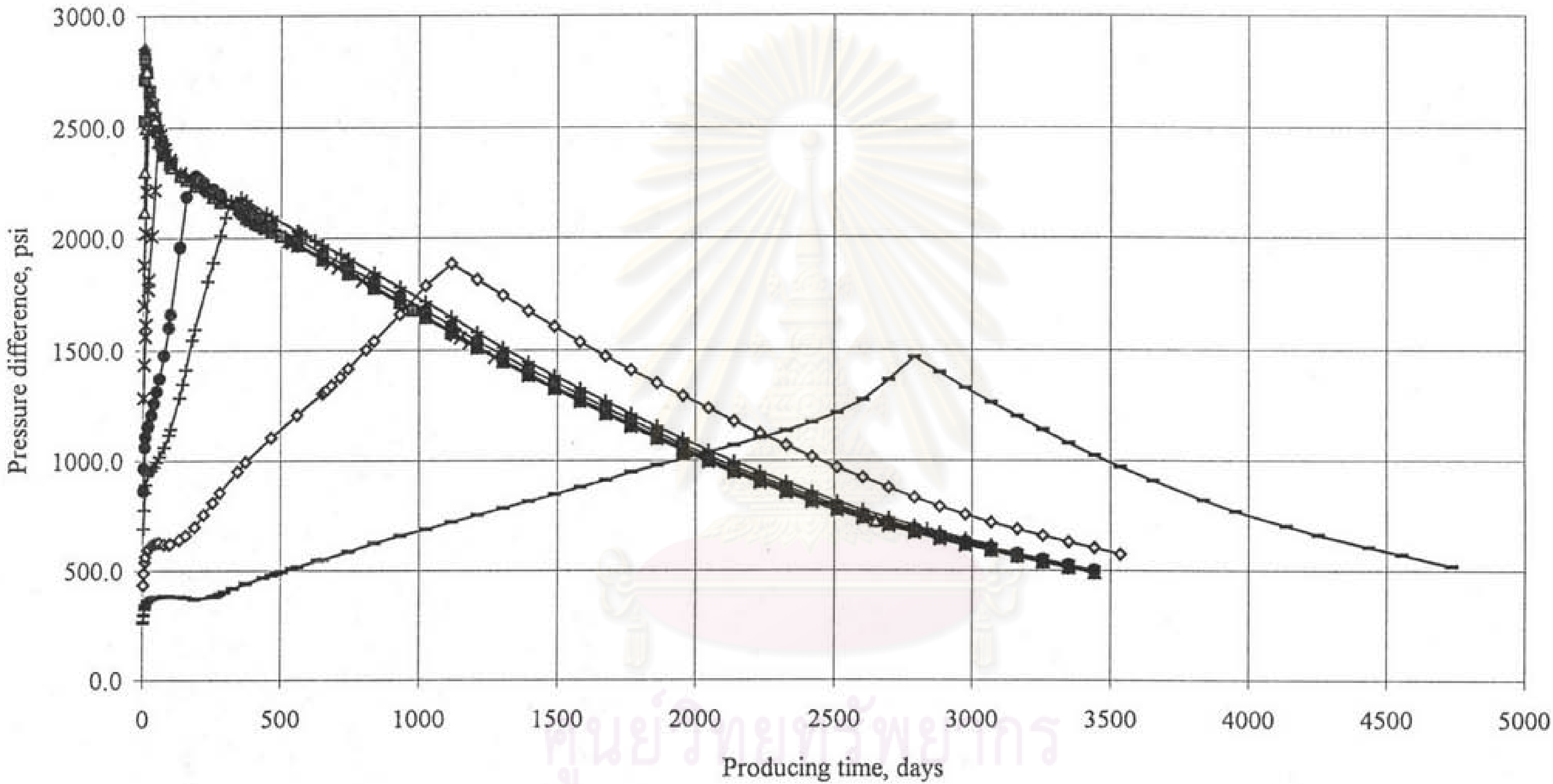

Figure 5.3 Pressure difference between average reservoir pressure and flowing bottom hole pressure

Maximum allowable oil rate

Qo = 3391 STB/D, Qo = 3000 STB/D, Qo = 2500 STB/D, Qo = 2000 STB/D, Qo = 1500 STB/D, Qo = 1000 STB/D, Qo = 800 STB/D, Qo = 500 STB/D, Qo = 300 STB/D

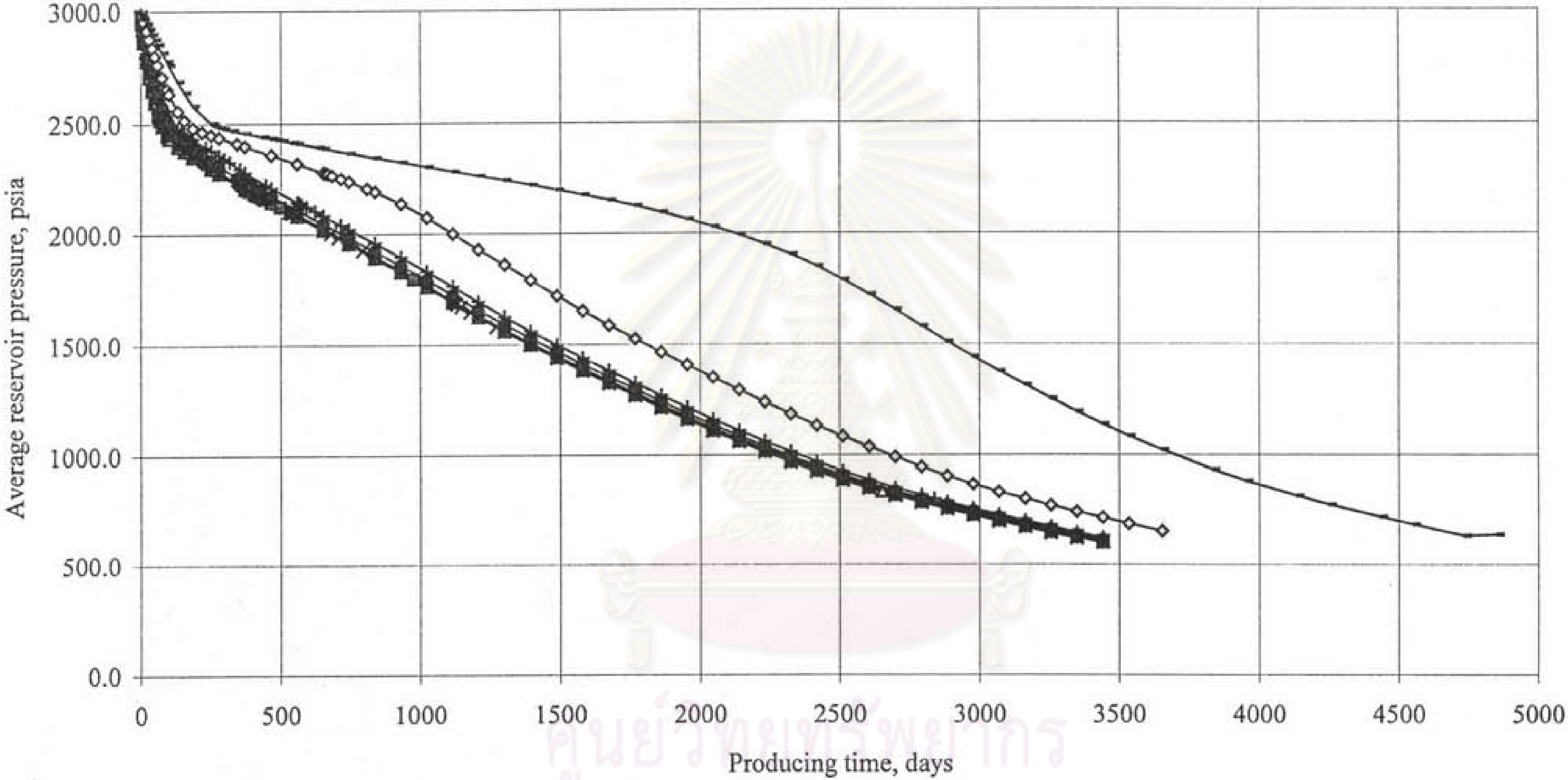

Figure 5.4 Average reservior pressure at various producing time

Maximum allowable oil rate

Qo = 3391 STB/D, Qo = 3000 STB/D, Qo = 2500 STB/D, Qo = 2000 STB/D, Qo = 1500 STB/D, Qo = 1000 STB/D, Qo = 800 STB/D, Qo = 500 STB/D, Qo = 300 STB/D

between 612 to 625 psia. This variation is considered negligible. Only the case with maximum allowable oil production rate of 500 STB/D has average reservoir pressure at abandonment of 656 psia. The highest average reservoir pressure at abandonment is of the case with 300 STB/D.

Average reservoir pressure is an indicator that determines energy of the reservoir. Difference between initial average reservoir pressure and average reservoir pressure at abandonment indirectly refers to energy that has been used to produce fluid from the reservoir during the production process. It can be noticed from table 5.1 that at the end of natural depletion process, reservoir which has been produced at maximum allowable oil production rate limited to 300 STB/D has higher level of energy than the cases that let the reservoir produce at higher maximum allowable rate. This is consistent to the result on the ultimate recovery. That is, more oil is left in the reservoir for the case of 300 STB/D.

Figure 5.5 is a comparison of oil recovery fraction as a function of producing time. It can be seen that oil recovery fraction of the cases with maximum allowable oil rate of 1,000 STB/D or greater are almost identical. In the early and middle life of the production, the cases with maximum allowable oil rate of 500 STB/D and 300 STB/D have lower oil recovery fractions than that of the cases of 800 STB/D or greater. However, ultimate oil recovery fraction of the former case becomes very close to that of the cases with maximum allowable oil rate of 800 STB/D or greater at the end of the natural depletion process.

From the above observations it can be concluded that ultimate oil recovery of a closed reservoir having homogenous properties and solution gas drive mechanism is independent on rate. It should be emphasized that the ultimate oil recovery mentioned in this study is measured at the abandonment. Although the magnitude of the ultimate

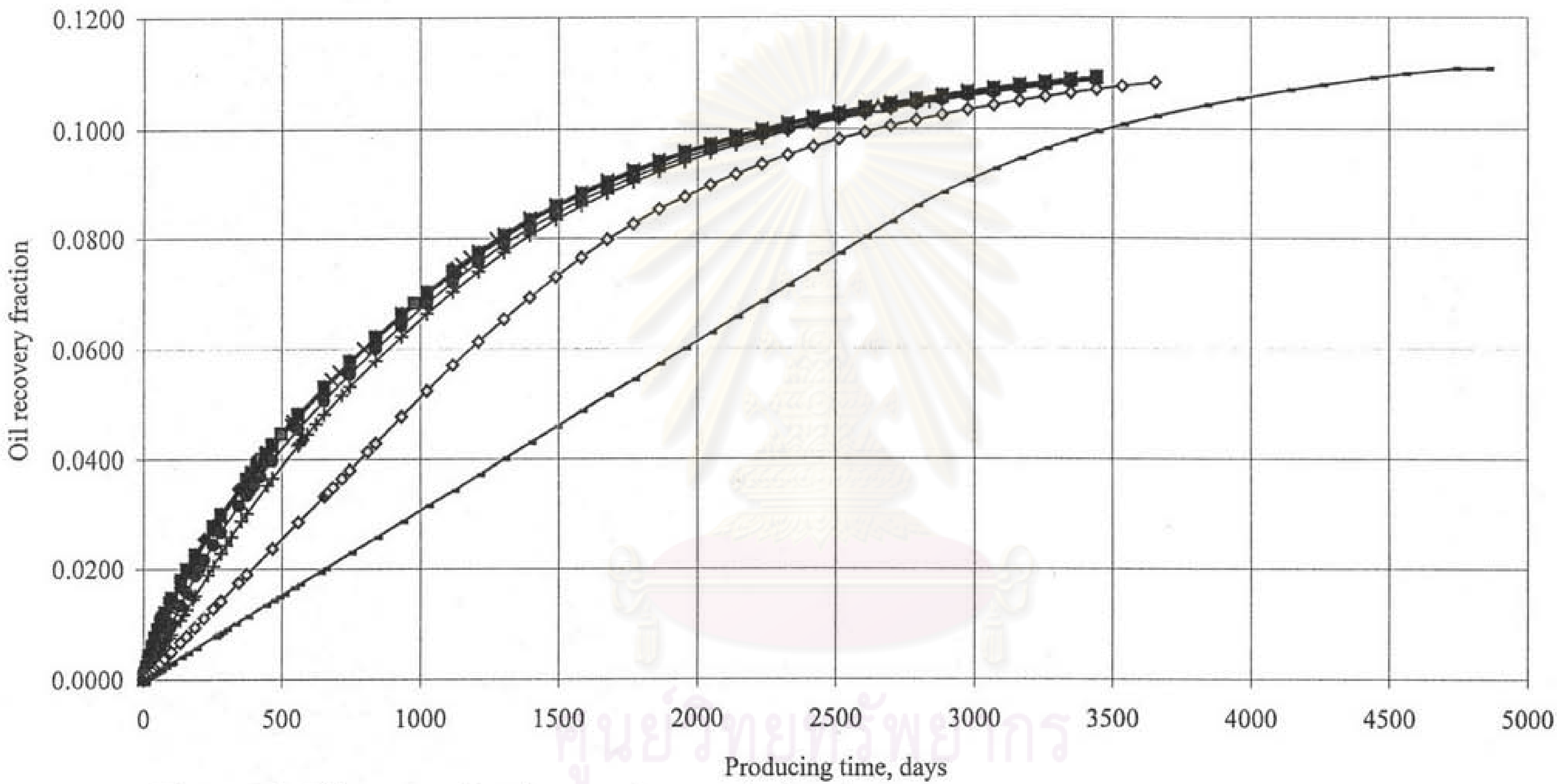

Figure 5.5 Oil recovery fraction at various producing time

Maximum allowable oil rate

Qo = 3391 STB/D, Qo = 3000 STB/D, Qo = 2500 STB/D, Qo = 2000 STB/D, Qo = 1500 STB/D, Qo = 1000 STB/D, Qo = 800 STB/D, Qo = 500 STB/D, Qo = 300 STB/D

oil recovery of the cases which have different maximum allowable oil rates are approximately equal, recovery of oil at the same time of all cases are not equal. The case which has the lowest maximum allowable production rate has the longest time to reach ultimate recovery. It could be further noticed from Figure 5.5 that as maximum allowable oil rate is greater or equal to a certain value, recovery of oil at various producing time is approximately equal. In this case it is found that the cases with 800 STB/D or greater have almost the same recovery at various producing time.

Observation of Formation of Gas

Plots of pressure and fluid saturation distributions in the reservoir as a function of time and distance from the well bore of each case are available. These plots are used as tools for investigating behavior of the reservoir as the well has been producing.

Consider Figure 5.2 which represents the comparison of GOR obtained from each case. It is found that the cases with maximum allowable oil rates of 1,000 STB/D or greater have similar GOR behavior. Those GOR curves follow typical GOR behavior of the solution gas drive reservoir. The case with 500 STB/D has a more gentle increasing of GOR but still follows typical GOR behavior of the solution gas drive reservoir. Figure 5.6 is a plot of GOR for the first year of production. It is found from this figure that the increment of GOR of the cases with 2,000 STB/D or greater are similar since the beginning of production. The case with 1,500 STB/D has slightly lower GOR at the first 100 days, prior to becoming similar to that of the first group. Furthermore, the case with 1,000 STB/D has similar GOR behavior to that of this group after the well has produced for approximately 250 days while GOR of the case with 800 STB/D become similar to that of the first group after 300 days. The case with 500 STB/D has almost constant GOR of approximately 500 SCF/STB

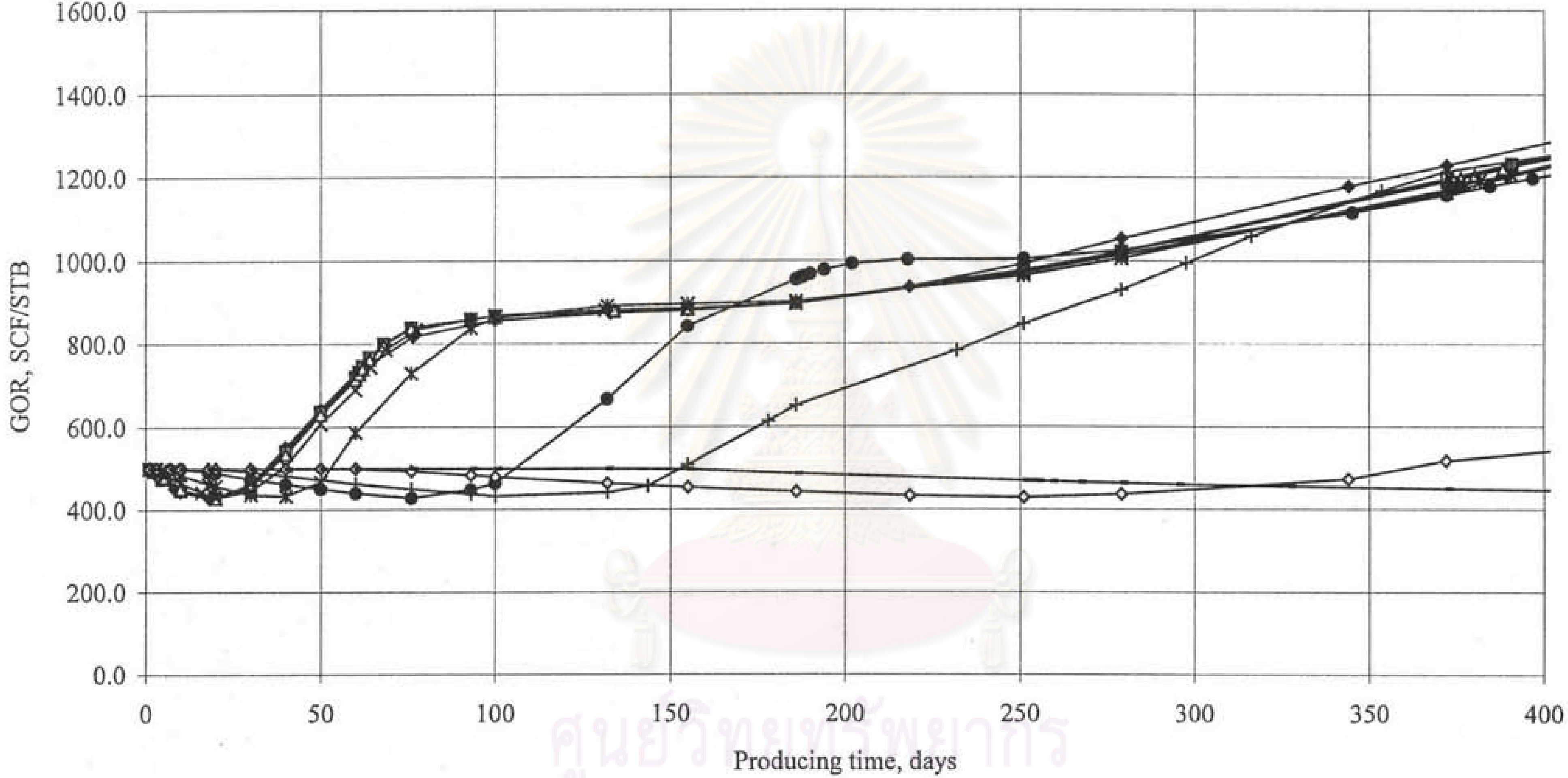

Figure 5.6 GOR in the first year of production

Maximum allowable oil rate

Qo = 3391 STB/D, Qo = 3000 STB/D, Qo = 2500 STB/D, Qo = 2000 STB/D, Qo = 1500 STB/D, Qo = 1000 STB/D, Qo = 800 STB/D, Qo = 500 STB/D, Qo = 300 STB/D

during the first year and GOR of the case with 300 STB/D remains at 500 SCF/STB for the first year.

According to the behavior of the formation of gas in the reservoir, during the first period of production, GOR will be constant and equal to initial solution gas oil ratio (R_{si}). After the well has produced for a certain period, GOR becomes lower than initial solution gas oil ratio. The reduction in GOR is because of immobility of liberated gas in the reservoir. Gas liberates from oil when the pressure in the reservoir becomes lower than the bubble point pressure. This results in reservoir oil having lower gas content. However, since gas saturation is still less than the critical gas saturation, this free gas does not move. Therefore, volume of gas measured at the surface is less than initial solution gas oil ratio. Once the gas saturation is greater than the critical gas saturation, GOR becomes increasing and will be finally greater than initial solution gas oil ratio.

Shape of GOR plot indicates that average gas saturation in the reservoir of each case becomes greater than critical gas saturation at different times. In this study, critical gas saturation is set to 5%. Figure 5.7 presents saturation of gas at each block in layer 1, which is located at top of the model, of the case with maximum allowable oil rate of 1,000 STB/D. The abscissa of this plot represents the distance away from the well bore to the reservoir. The ordinate represents saturation values. Each set of data points represents gas saturation values at a particular producing time. Figure 5.8 to 5.12 are plot of saturation of gas at each block of layer 2 to 6 respectively. Figure 5.13 is a plot of pressure distribution in the reservoir as the well has been producing for 100 days. Figure 5.14 is a plot of oil saturation distribution in the reservoir as the well has been producing for 100 days. It is shown in Figure 5.14 that the oil saturation of each layer at the first 100 days of production is not equal. Note that the initial oil saturation of each layer is different due to the capillary effect. Therefore, oil volume in each layer is different. It is seen from Figure 5.13 that pressure distribution of each layer is very close. This implies that gas is liberated from oil of each layer at almost the same time. Since oil saturation of each layer is not equal, therefore the volume of gas liberated from the oil is different. The difference in the volume of liberated gas results in the difference in gas saturation since the pore volume of each layer is identical. This could be seen from Figure 5.7 to 5.12. The gas saturation at 100 days of production of layer 4 to 6 are less than critical gas saturation, i.e., 5%. In contrast, the gas saturations at 100 days of production of layer 1 to 3 are greater than critical gas saturation. The liberated gas will not move until its saturation becomes at least equal to critical gas saturation. Gas saturation of layer 1 of the case with maximum allowable oil rate of 1,000 STB/D becomes greater than critical gas saturation as the well has produced for 100 days, represented by the lowest curve in Figure 5.7. During this time, the gas is present in the region within the radius of 1 feet around well bore. Although it occurs only in this region, GOR becomes increasing and greater than initial solution gas oil ratio as the well has produced for 100 days. After that, GOR increasing rate becomes slower. As the well has been producing for 270 days, GOR of the reservoir increases drastically. This is because the accumulation of gas saturation in the outer cells become greater than critical gas saturation. Thus gas liberating from oil in the reservoir flows directly to the well bore.

Formation of gas in layer 2 starts at almost the same time as that of layer 1, as shown in Figure 5.8 in comparison to Figure 5.7. Gas starts to flow from layer 2 when the well has produced for 100 days. At that time, the formation of gas with saturation greater than 5% occurs at approximately 0.5 feet from the well bore. The increasing rate of gas saturation is not fast compared to that of the first layer.

It is seen in Figure 5.9 that the gas from layer 3 starts to flow as the well has produced for 100 days. But the region which have gas saturation higher than critical gas saturation is approximately 0.5 feet at that time. Gas from blocks away from the well of layer 3 starts to flow as the well has produced for 279 days.

It could be seen from Figure 5.10 to 5.12 that gas from the lower layers of this reservoir does not increase GOR much in the early life of the reservoir. Although the gas saturation of these lower layers become greater than critical gas saturation at approximately 465 days after production has commenced, it is considered that the volume of the mobile gas liberated from these layers are small compared to that of the upper three layers. This is because the oil saturations of the upper three layers are higher than that of the lower three layers, as seen in Figure 5.15. Therefore, the volume of free gas from the lower three layers is considered small. Hence, it does not have significant impact on the increasing of GOR compared to that of the upper three layers.

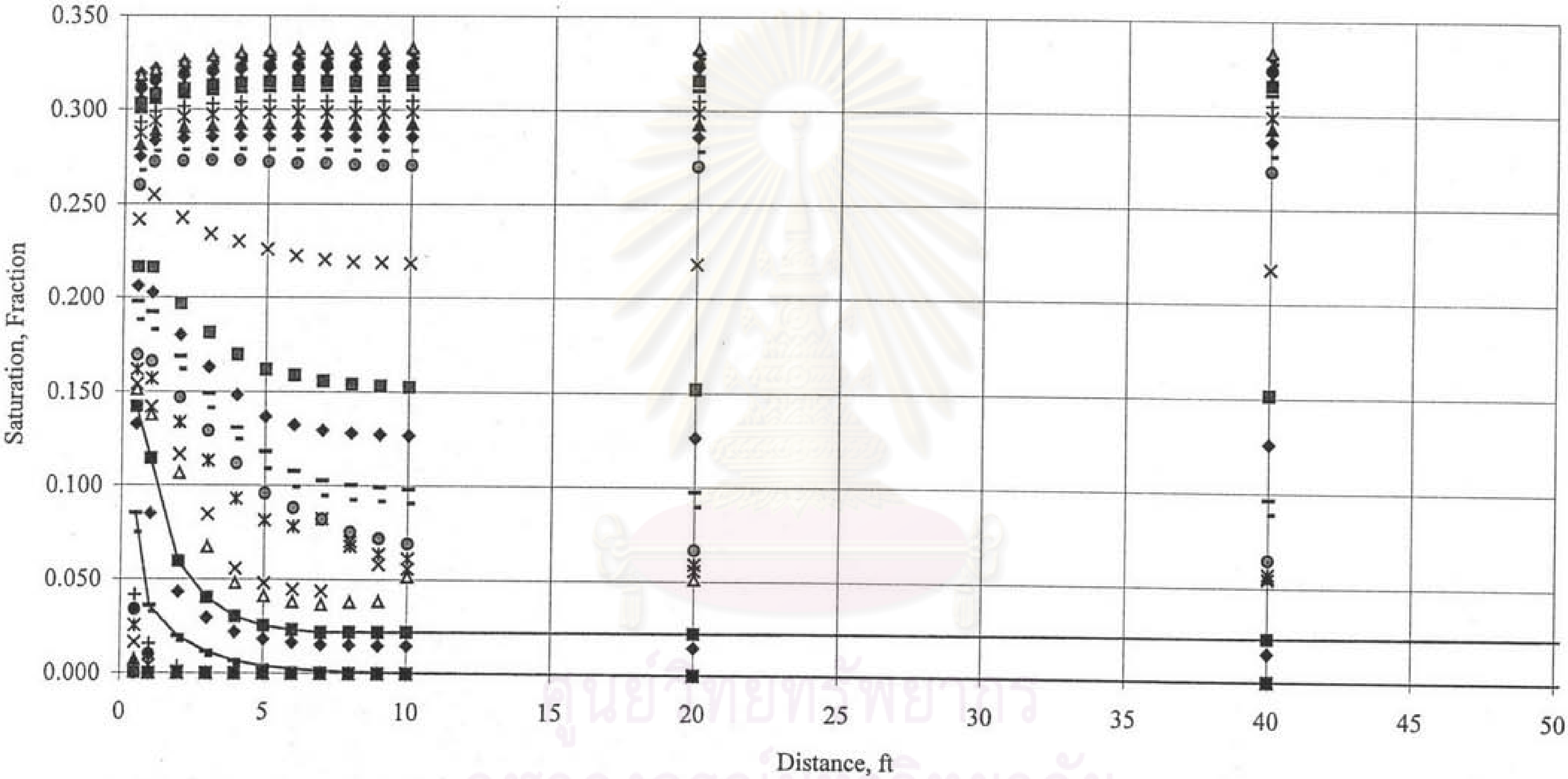

Figure 5.7 Gas saturation in layer 1of the case with maximum allowable oil production rate of 1,000 STB/D

Producing time, days

◆ 1 ■ 10 ▲ 20 × 30 ✱ 40 ● 50 + 60 - 93 — 100 ◆ 155 —■— 186 △ 251 × 279 ✱ 372 ◎ 465 - 651 — 744
◆ 837 ■ 930 × 1116 ◎ 1302 - 1488 ◆ 1674 ▲ 1860 ✱ 2046 + 2232 — 2418 ■ 2604 × 2790 ● 2976 - 3162 ◆ 3348 ▲ 3534

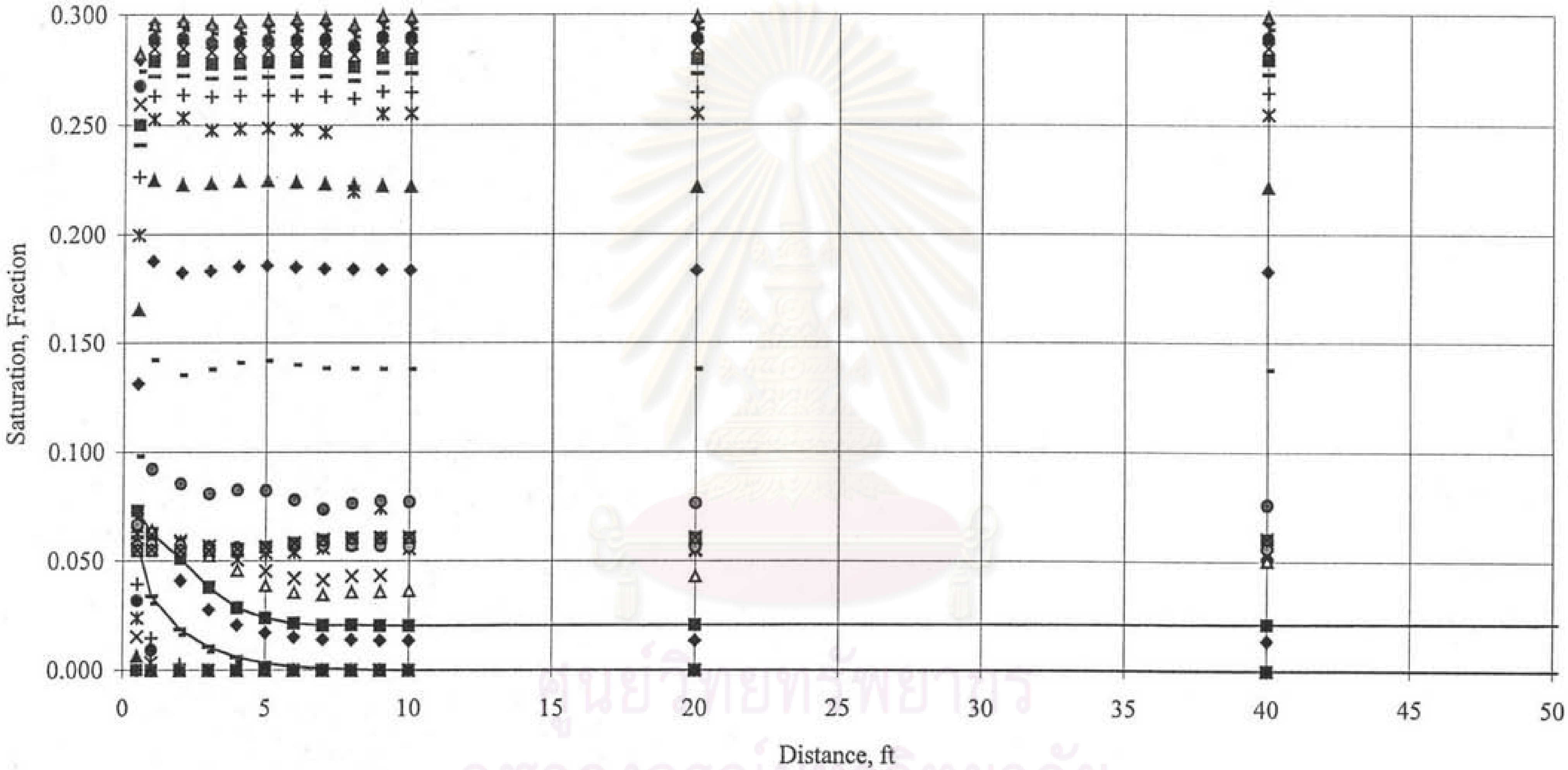

Figure 5.8 Gas saturation in layer 2 of the case with maximum allowable oil production rate of 1,000 STB/D

Producing time, days

1, 10, 20, 30, 40, 50, 60, 93, 100, 155, 186, 251, 279, 372, 465, 651, 744, 837, 930, 1116, 1302, 1488, 1674, 1860, 2046, 2232, 2418, 2604, 2790, 2976, 3162, 3348, 3534

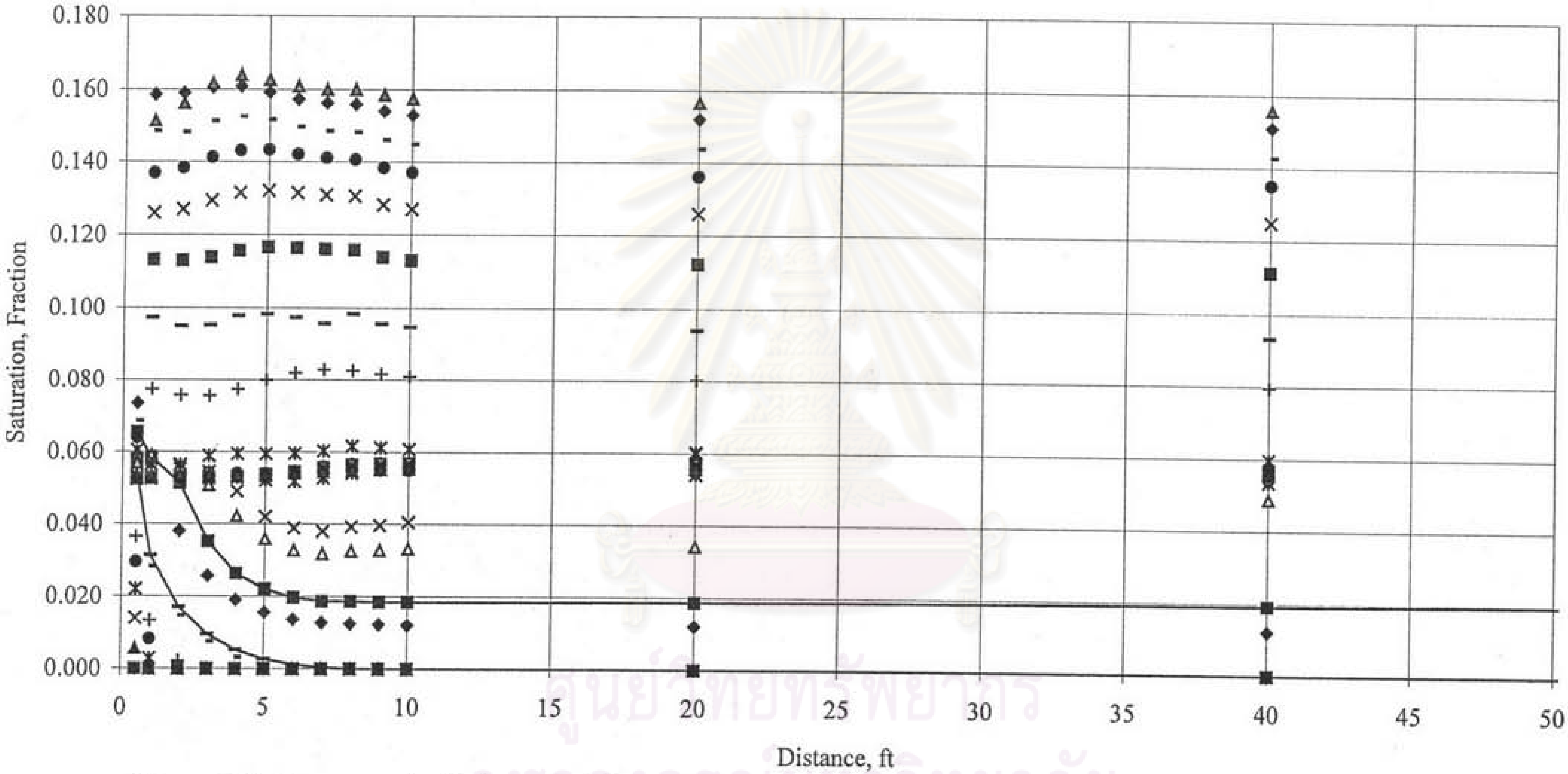

Figure 5.9 Gas saturation in layer 3 of the case with maximum allowable oil production rate of 1,000 STB/D

Producing time, days

1, 10, 20, 30, 40, 50, 60, 93, 100, 155, 186, 251, 279, 372, 465, 651, 744, 837, 930, 1116, 1302, 1488, 1674, 1860, 2046, 2232, 2418, 2604, 2790, 2976, 3162, 3348, 3534

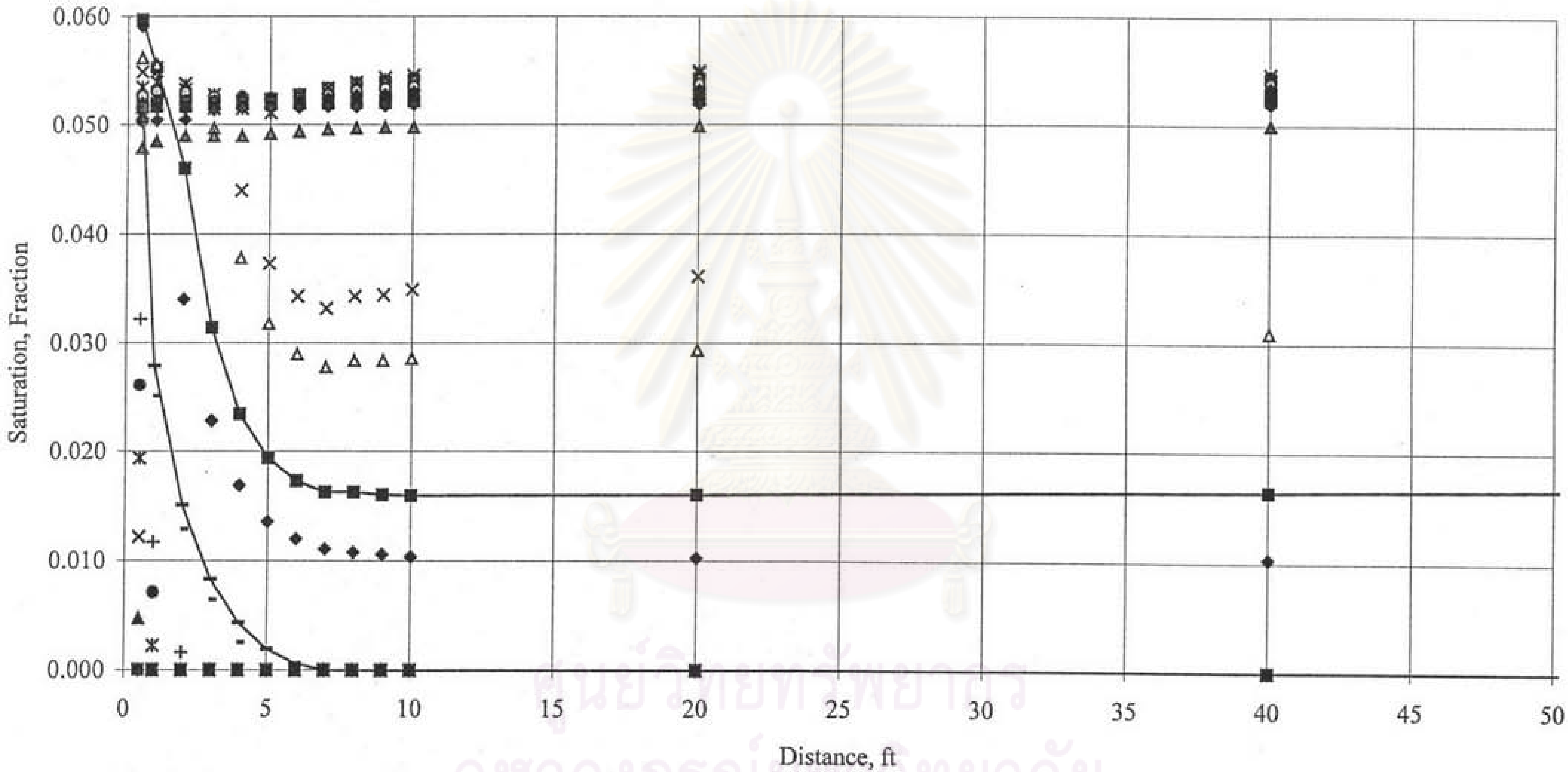

Figure 5.10 Gas saturation in layer 4 of the case with maximum allowable oil production rate of 1,000 STB/D

Producing time, days

1, 10, 20, 30, 40, 50, 60, 93, 100, 155, 186, 251, 279, 372, 465, 651, 744, 837, 930, 1116, 1302, 1488, 1674, 1860, 2046, 2232, 2418, 2604, 2790, 2976, 3162, 3348, 3534

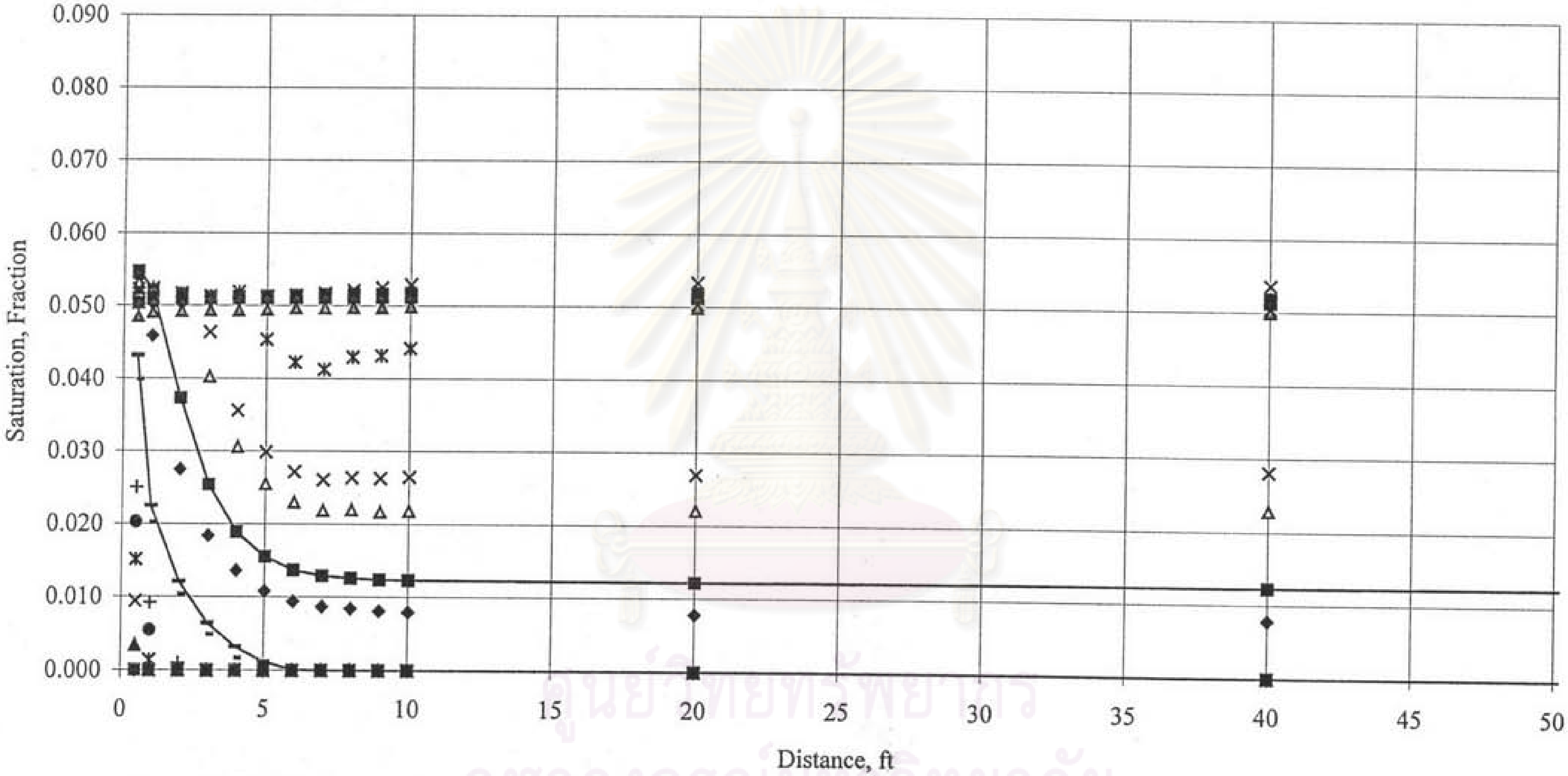

Figure 5.11 Gas saturation in layer 5 of the case with maximum allowable oil production rate of 1,000 STB/D

Producing time, days

◆ 1 ■ 10 ▲ 20 × 30 ✳ 40 ● 50 + 60 - 93 —100 ◆ 155 —■—186 △ 251 × 279 ✳ 372 ● 465 - 651 — 744
◆ 837 ■ 930 × 1116 ● 1302 - 1488 ◆ 1674 ▲ 1860 ✳ 2046 + 2232 — 2418 ■ 2604 × 2790 ● 2976 - 3162 ◆ 3348 ▲ 3534

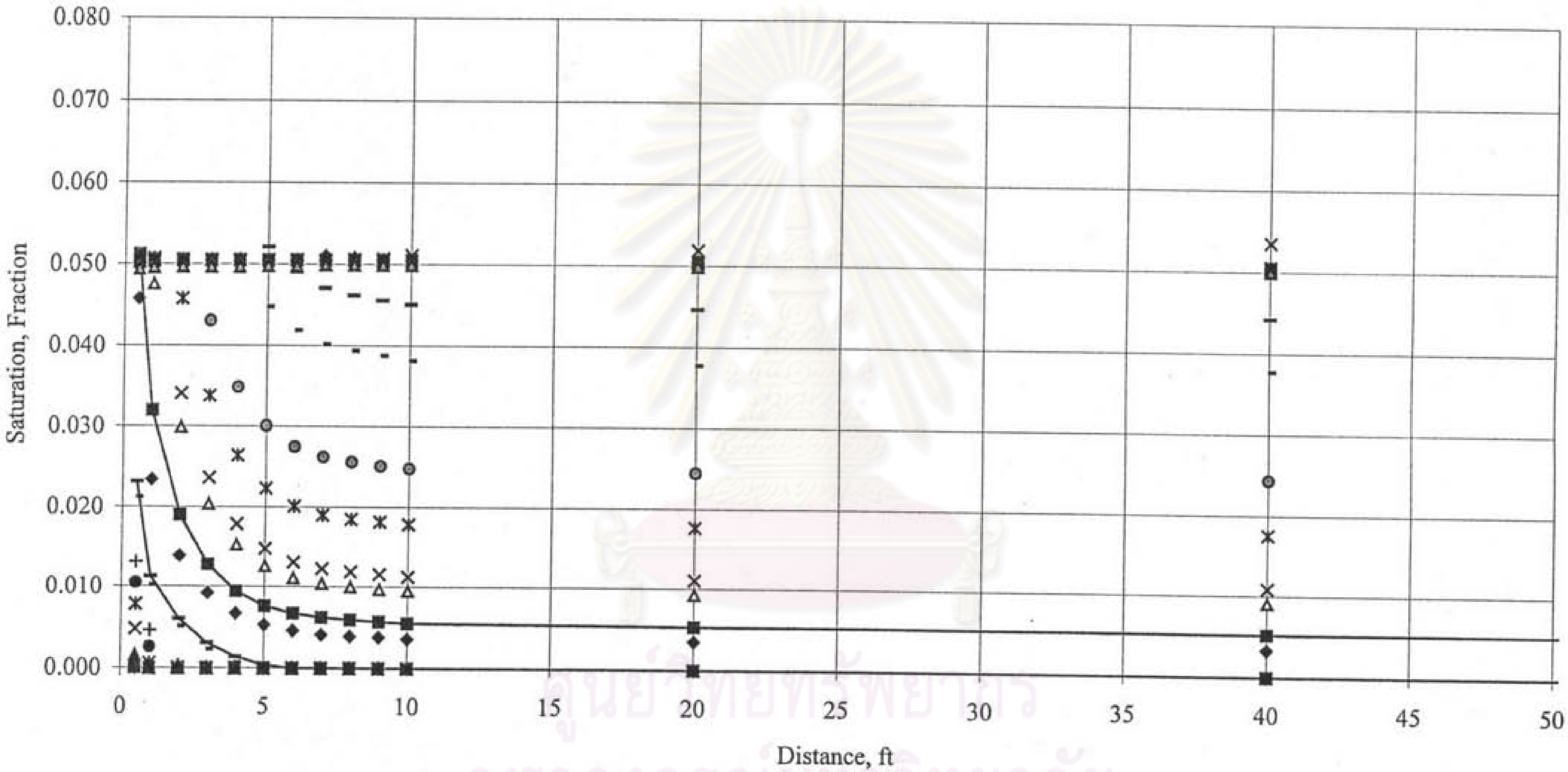

Figure 5.12 Gas saturation in layer 6 of the case with maximum allowable oil production rate of 1,000 STB/D

Producing time, days

1 10 20 30 40 50 60 93 100 155 186 251 279 372 465 651 744
837 930 1116 1302 1488 1674 1860 2046 2232 2418 2604 2790 2976 3162 3348 3534

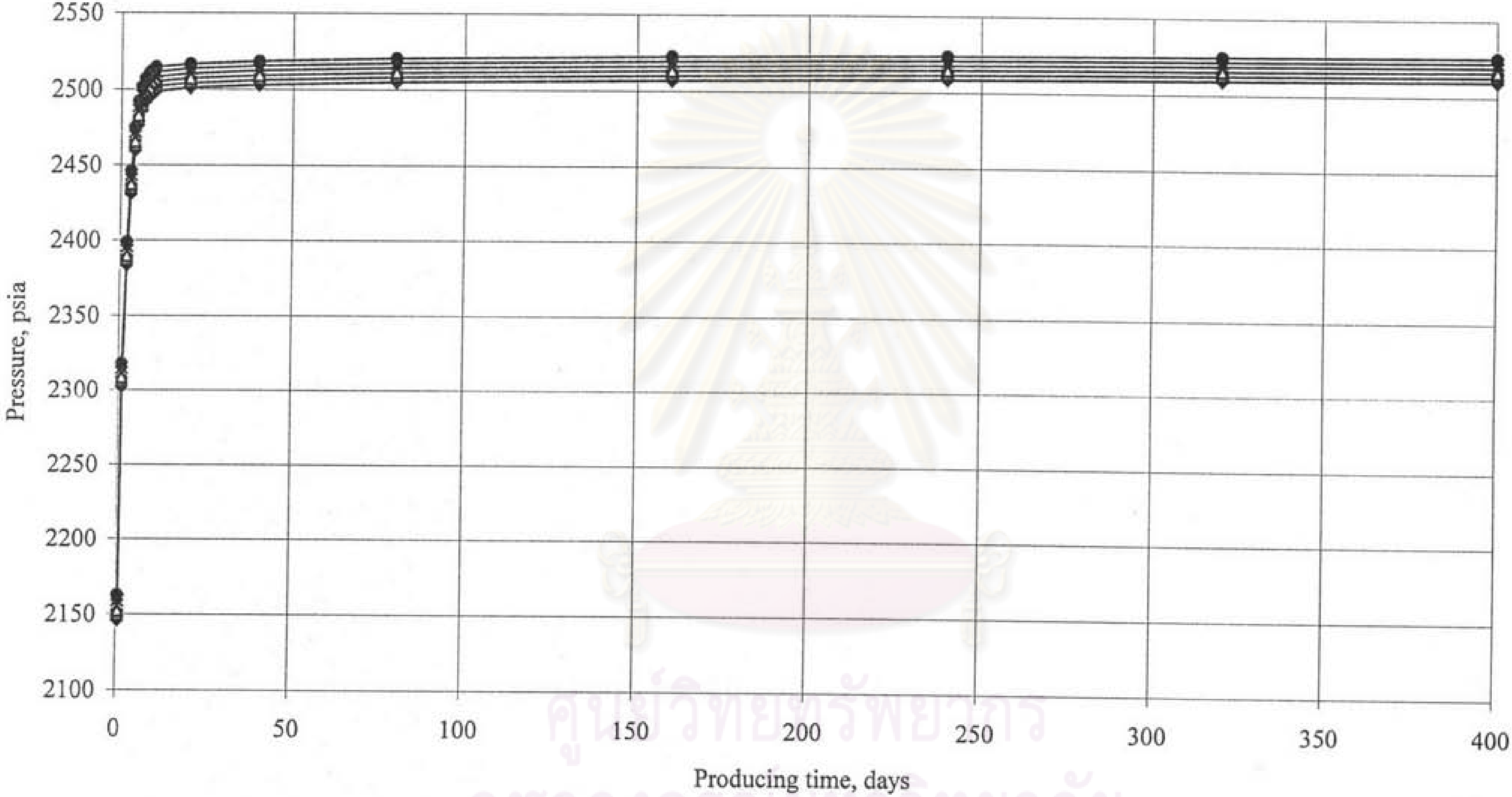

Figure 5.13 Pressure distribution in all layers at 100 days of production of the case with maximum allowable oil production rate of 1,000 STB/D

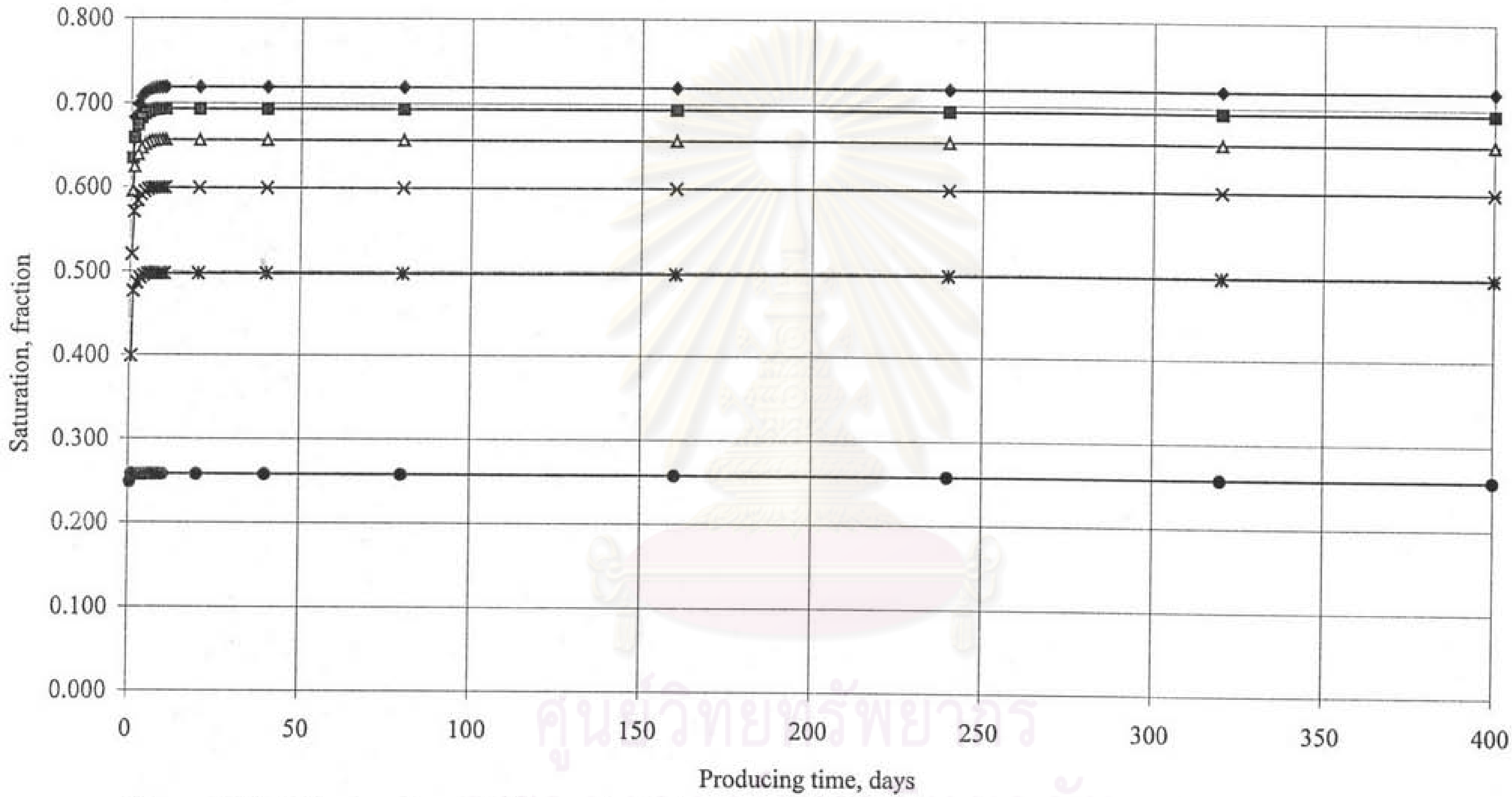

Figure 5.14 Oil saturation distribution in all layers at 100 days of production of the case with maximum allowable oil production rate of 1,000 STB/D

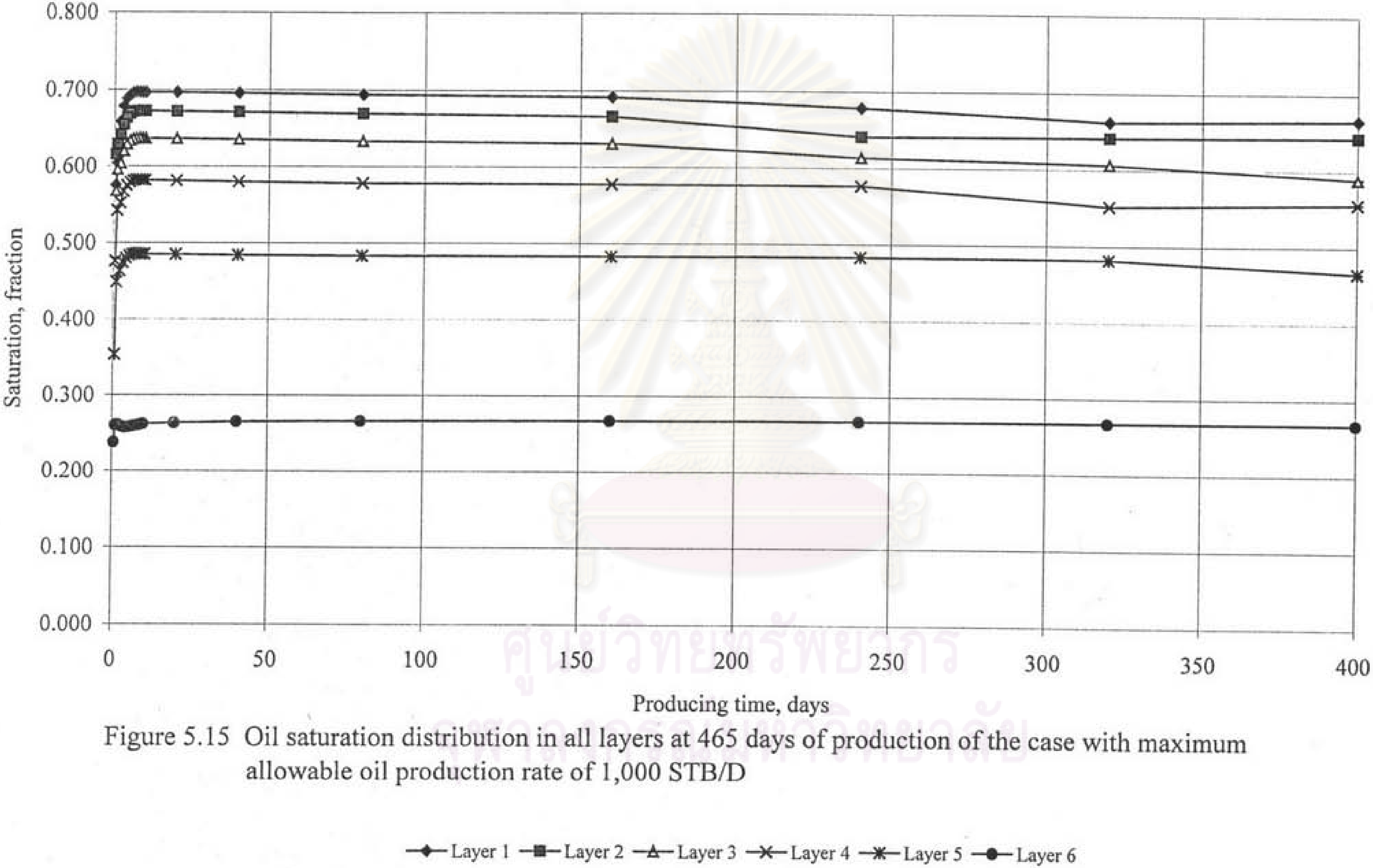

Figure 5.15 Oil saturation distribution in all layers at 465 days of production of the case with maximum allowable oil production rate of 1,000 STB/D