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FLOW CONTRIBUTION OF MULTILAYER OIL SYSTEM

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การศึกษานี้ได้ศึกษาภาวะที่ความจุของการไหล (kh) สามารถประยุกต์ใช้ได้กับสัดส่วนการไหลของระบบน้ำมันหลายชั้น มีการศึกษาปัจจัยที่ควบคุมสัดส่วนการไหลในกรณีความจุของการไหลไม่สามารถประยุกต์ใช้ได้ การศึกษาใช้แบบจำลองแหล่งกักเก็บ ประมวลผลสัดส่วนการไหลในหลายๆกรณี ระบบของแหล่งกักเก็บที่มีการศึกษามีสองระบบคือ ระบบแบบสองชั้น และระบบแบบสามชั้น ระบบที่ใช้เป็นหลักในการศึกษาคือระบบแบบสองชั้น ขณะที่ระบบแบบสามชั้นใช้ในการแสดงและยืนยันข้อสรุปจากระบบแบบสองชั้น งานวิจัยนี้เน้นปัจจัยควบคุมของ ความจุของการไหล และ ปริมาตรรูพรุน (ΦAh) นอกจากนี้ อิทธิพลของคุณสมบัติของของไหลได้ถูกศึกษาในการวิจัยนี้ด้วย

ผลการศึกษาพบว่าสัดส่วนการไหลถูกควบคุมด้วยความจุของการไหลหรือปริมาตรรูพรุน มิใช่ตัวแปรตัวใดตัวหนึ่งของความจุของการไหลหรือปริมาตรรูพรุน สัดส่วนการไหลจะปฏิบัติตามกฎของความจุของการไหลเมื่อการไหลจากระบบเต็มความจุของการไหลและ เกิดเฉพาะในช่วงแรกๆของการผลิต สัดส่วนการไหลจะปฏิบัติตามกฎของปริมาตรรูพรุนเมื่อการไหลจากระบบน้อยกว่าความจุของการไหลและมีผลกระทบจากการขยายตัวของน้ำมัน นอกจากนี้ยังมีปัจจัยควบคุมอื่นๆ ได้แก่ การมีแก๊สอิสระ การลดลงของความดัน และ การขยายตัวของของไหล ปัจจัยควบคุมเกือบทั้งหมดเกี่ยวข้องกับพลังงานในแหล่งกักเก็บ ยกเว้นความจุของการไหล คุณสมบัติของของไหลมีผลต่อสัดส่วนการไหลในระบบแต่ยังคงอยู่ภายใต้อิทธิพลของความจุของการไหลหรือปริมาตรรูพรุน

ภาควิชา......วิศวกรรมเหมืองแร่และปิโตรเลียม... ลายมือชื่อนิสิต Kittisak

สาขาวิชา....วิศวกรรมปิโตรเลียม........................ ลายมือชื่ออาจารย์ที่ปรึกษา...............................

ปีการศึกษา..................... 2550.......................... ลายมือชื่ออาจารย์ที่ปรึกษาร่วม...............................

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KITTISAK WUTTINANSANTIKUL: FLOW CONTRIBUTION OF MULTILAYER OIL SYSTEM. THESIS ADVISOR: JIRAWAT CHEWAROUNGROAJ, Ph.D., THESIS CO-ADVISOR: YOTHIN TONGPENYAI, Ph.D., 93 pp.

The study is intended to investigate the condition that kh rule can be applied for flow contribution of multilayer oil system. The controlling factor in case that flow contribution does not obey kh rule is investigated. The investigation used reservoir simulation generation the flow contribution on various cases. The systems for this study are two-layer system and three-layer system. The main system for study is two-layer system while three-layer system used to demonstrate or confirm conclusions for two-layer system to apply for more layer system. The controlling factors that are emphasized for this thesis are flow capacity (kh) and pore volume (ϕAh). In addition, the effect of fluid properties is investigated.

From the study flow contributions are controlled by kh rule or ϕAh rule and not controlled by individual parameters in these groups. Flow contribution obeys kh rule when the flow from the system is at fully flow capacity (kh) and only at starting period of production time. Flow contribution obeys pore volume when the flow from the system is lower than flow capacity and is affected by pore volume due to oil expansion. There are other controlling factors affecting flow contribution, i.e. presence of free gas, pressure depletion, and expandable fluid. Most controlling factors affecting flow contribution are related to energy in the reservoir except kh. There exists effect of fluid properties to flow contribution in the system, but flow contribution is still under influence of flow capacity and pore volume

Department: Mining and Petroleum Engineering Student's signature....Kittisak............
Field of study: Petroleum Engineering Advisor's signature...................
Academic year 2007 Co-advisor's signature...................

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Nomenclatures

q_T	=	Total flow rate, (STB/D)
q_1	=	Flow rate of layer 1, (STB/D)
q_2	=	Flow rate of layer 2, (STB/D)
q_3	=	Flow rate of layer 3, (STB/D)
k_1	=	Permeability of layer 1, (md)
k_2	=	Permeability of layer 2, (md)
k_3	=	Permeability of layer 3, (md)
h_1	=	Thickness of layer 1, (ft)
h_2	=	Thickness of layer 2, (ft)
h_3	=	Thickness of layer 3, (ft)
$ø_1$	=	Porosity of layer 1
$ø_2$	=	Porosity of layer 2
$ø_3$	=	Porosity of layer 3
A_1	=	Drainage area of layer 1, (sq.ft)
A_2	=	Drainage area of layer 2, (sq.ft)
A_3	=	Drainage area of layer 3, (sq.ft)
OOIP	=	Original Oil in Place, (MMSTB)
S_w	=	Water saturation
Bo	=	Formation Volume Factor, (rb/STB)
k_1h_1	=	Flow capacity of layer 1, (md-ft)
k_2h_2	=	Flow capacity of layer 2, (md-ft)
k_3h_3	=	Flow capacity of layer 3, (md-ft)
$(øAh)_1$	=	Pore volume of layer 1, (MMcu.ft)
$(øAh)_2$	=	Pore volume of layer 2, (MMcu.ft)
$(øAh)_3$	=	Pore volume of layer 3, (MMcu.ft)

Nomenclatures (cont'd)

(From simulation)

FOPR	=	Field Oil Production Rate, (STB/D)
ROPR: (1)	=	Region 1 Oil Production Rate, (STB/D)
ROPR: (2)	=	Region 2 Oil Production Rate, (STB/D)
FPR	=	Field Pressure, (psia)
RPR: (1)	=	Region 1 Pressure, (psia)
RPR: (2)	=	Region 2 Pressure, (psia)

CHAPTER I

INTRODUCTION

Many reservoirs are composed of two or more layers called multilayered reservoirs. The production system for the reservoirs having two or more permeable layer of sands and impermeable shales between sands is the multilayer system. There is connection of layers only in the well without inter-connection between layers in the reservoir. Normally the total flow rate is controlled by a choke at the surface, so the total flow rate is kept constant as long as the reservoir can maintain the rate. The estimation of flow contribution of each layer is commonly used parallel rule based on kh rule. The flow contribution of each layer is the fraction of kh values of each layer. Although, the total flow rate is kept constant the flow from each layer is not constant because of the difference of rock and fluid properties. The condition that flow contribution obey kh rule is interesting to investigate. In addition, in case that kh rule cannot be applied other controlling factors need to be known.

There are many studies regarding multilayered reservoir using several methods such as well testing analysis, pressure transient data analysis, and flow rate transient type curve analysis to determine the reservoir characteristics of each layer. In addition to flow capacity (kh) and storativity ($\Phi c_t h$), the effects of some properties affect flow contribution have been studied also. However, the conclusion of properties of the reservoirs affecting the flow contribution has not demonstrated obviously. They have not emphasized to study the condition that kh rule can or cannot be applied. Moreover, the controlling factors in case that flow contribution does not obey kh rule have not illustrated. There are many authors studying fluid phase change in heavy oil reservoirs, but no study about multilayer oil system.

The thesis will study the flow contribution of multilayer oil system using reservoir simulation because it is the best to investigate the complexity of flow, either one or two phase flow, in porous media of several layers system. In addition, the reservoir simulation is independence to change several parameters. This makes investigation more easily. The systems that are investigated for this study are two-layer and three-layer system. The variation of parameters that are emphasized is rock properties. These are permeability (k), thickness (h), area (A), porosity (Φ). The fluid properties are kept constant for each layer. Because the reservoir for this study is solution gas reservoir, so the flow contribution will change from single phase into two phase when the reservoir pressure decline below the bubble point. Therefore, the effect of this behavior will be observed.

The controlling factors that will be emphasized for this study are kh and ΦAh because many investigators have studied some effects and conditions of them. However, the certain conditions, that flow contribution is controlled by either kh or ΦAh or both, have not demonstrated. The conditions that flow contribution obeys kh rule or obeys ΦAh rule are demonstrated in this study.

CHAPTER II

LITERATURE REVIEWS

Many authors have studied multilayered reservoirs with cross-flow and commingled system to determine reservoir characteristics using several methods such as well testing, pressure transient data analysis, and flow rate transient type curve analysis. The reservoir characteristics have been studied namely: layered skin factors, flow capacity, storativity, permeabilities, vertical permeabilities, and relative permeabilities. The comparison of methods to estimate reservoir properties of each layer has been studied also.

Larsen[(1)] studied multilayered commingled systems. He used pressure transient data to estimate reservoir parameters. He found that bottom-hole pressure transients from the infinite acting period prior to production can be used to estimate reservoir parameters. If the initial pressures in two layer systems are sufficiently different, and in addition known, the analysis can be used to determine the flow capacity fraction of each layer. If skin factors are different in the systems, the semi-log analysis can lead to estimate of total flow capacities below the actual value. If the second rise in buildup data shows a definite trend, the flow capacity of each layer can be estimated by matching actual and computed data.

Kucuk[(2)] studied multilayered reservoirs using well testing and analysis technique to estimate individual layer of permeability and skin factor. They recommended a procedure to conduct a multilayered test (MLT) for the reservoirs consisting of simultaneous pressure and flow rate measurements on layered reservoir. They gave two analysis techniques logarithmic deconvolution method and non-linear least square estimation.

Ehlig-Economides[(3)] studied flow rate transient type curve analysis to determine individual layer properties in multilayered reservoir. She compared the general characteristics of two different multilayered reservoir models. The first model consists of two commingled zones. Each zone was divided into several inter-communicating layers. The second model was a five-layer commingled reservoir. The zonal properties were determined using commingled reservoir type curves, while the individual layer properties in each zone were calculated from cross flow type curves.

She found that the combination of wellbore pressure and layered flow rates provides sufficient information of the complete layered reservoir description consisting of layered permeabilities, skins, and effective interlayer vertical permeabilities.

Park and Horne[4] studied multilayered reservoir with cross-flow using well test analysis to determine the parameters of the reservoir. They observed the multilayered system responds to production in three stages. It behaves like a commingled system at early time and equivalent homogeneous system at late time. Transition occurs in the intermediate stage.

Jatmiko[5] studied multilayered commingled reservoirs containing multi-phase fluid using well testing to determine the relative permeability curves of each layer. They concluded that in the multi-phase well testing the pressure squared method can be used to determine effective oil permeability even if the layered gas rate is considerably high. However, Perrine method is valid as long as the gas rate is negligible. Superposition principles have been applied successfully in multi-phase multilayered reservoir to handle variable problem. Chebychev's polynomial function can be utilized to fit the flowing pressure data, and smooth monotonically decreasing relative permeability curves can be obtained.

Lakovlev[6] studied multiphase flow in several layers regarding limitation of applicability of conventional buildup analysis in two layers of multilayered commingled reservoir. He used commercial black oil simulator with variable bubble point to generate pressure and production data. He stated that the higher the contrast in layered absolute permeabilities, thicknesses, pore volumes, and skin factors, the less accurate results he should expect. The error in average oil permeability and skin estimation depends on the combined contrast of effect in layered properties and production characteristics.

Al-Ajmi[7] studied the estimation of storativity ratio on multilayered reservoir with cross-flow using pressure transient data. They stated that the method uses an analytically derived formula for the storativity ratio in terms of the separation between the two semi-log straight lines on pressure versus log-time plot. Knowing the storativity ratio from the well test, individual layered properties may be estimated if the layered flow rates are available from production logs.

The study of layered flow rate has been studied by several authors. The total flow rate will be constant, while layered flow will be estimated based on function of time, flow capacity (transmissibility) or storativity depending on the period of production.

Lefkovits[8] studied the behavior of bounded multilayered reservoirs with commingled system. They showed that in early time the layered flow rate fractions approached the layered flow capacity fraction. In late time on the pseudo steady state the fraction of layered flow rate was equal to the ratio of layered storativity.

Raghavan[9] studied multilayered commingled and cross-flow systems using pressure and flow rate data to determine the flow capacity, skin factor and average pressure. He examined that the production rate of each layer will be a function of time despite the total production rate is constant. If the layered skin factors are zero and the well is produced at a constant rate, the layered flow rate will be calculated in the equation given by Lefkovits et al.

Cabrera *et al*.[10] studied the cross-flow multilayered reservoir evaluation. They used the equation of Eligh-Economides to develop the computer program called Multicap. They compared the results including pressure and flow rate transient of each layer with effect of skin value generated by among real, simulation and Multicap. They found that the in layer with similar skin the flow rate will take place according to flow capacity of each layer. In case of skin difference the production will be lower at early times. At later time the production will be recovered by layered ability according to flow capacity and storativity.

Osman and Mohammed[11] studied the Pulse Testing Data to predict the characteristics of multilayered reservoirs with cross-flow. They found that the apparent storativity calculated by Pulse Testing Data is always less than or equal to the actual storativity of the reservoir and the apparent transmissibility is always greater than or equal to the actual transmissibility. For short cycle intervals, the flow rate form the certain layer is not proportional to its transmissibility fraction, while the effect of storativity on the layered flow rate is negligible. Wellbore damaged affects both apparent transmissibility and storativity.

In the solution gas drive mechanism when the pressure falls below the bubble point, gas will be generated from the oil, so the fluid phase will be changed at the period. There are many authors studying behavior of this period.

Yortsos and Parlar[12] studied liquid-to-vapor phase change in porous media by pressure decline. The representative example for their study is solution gas drive system. The issues for the study are nucleation, critical supersaturation, and vapor phase growth. They found that at low supersaturation a percolation approach is proposed that allows for the estimation of critical gas saturation and relative permeabilities from nucleation and pore structure characteristics.

Kumar *et al*.[13] studied heavy oil reservoirs with solution gas drive mechanism using comparison between real pressure decline rate and that expected. They found anomalous behavior that the pressure falls below the bubble point some of wells have shown much higher oil rates than that expected from a conventional oil reservoir.

Kamp *et al.*[14] studied heavy oil solution gas drive reservoir. They found different kinds of explanation that when bubble were generated, asphaltenes would absorb on their interfaces, which would cause the crude oil to be less viscosity and more easy to produce, mixture of gas bubble and oil resulting in particular viscosity behavior, or some particular oil would be able to trap gas bubbles modifying the compressibility of oil. They stated that in light oil a few gas clusters grow because of molecular diffusion of dissolved gas.

CHAPTER III

CONCEPTS AND METHODOLOGY

As mentioned before, it should be emphasized that the system investigated in this study is a system of two or three layers of sands which are separated from one another by impermeable shale. This means that these layers are separated from regions which are communicated at the production well only as shown figure 3-1

The mentioned system is known in general as a parallel from system into a well with no cross-flow. For this kind of system, it is generally understood that the flow from each layer can be estimated by the parallel rule based on kh rule as follows:

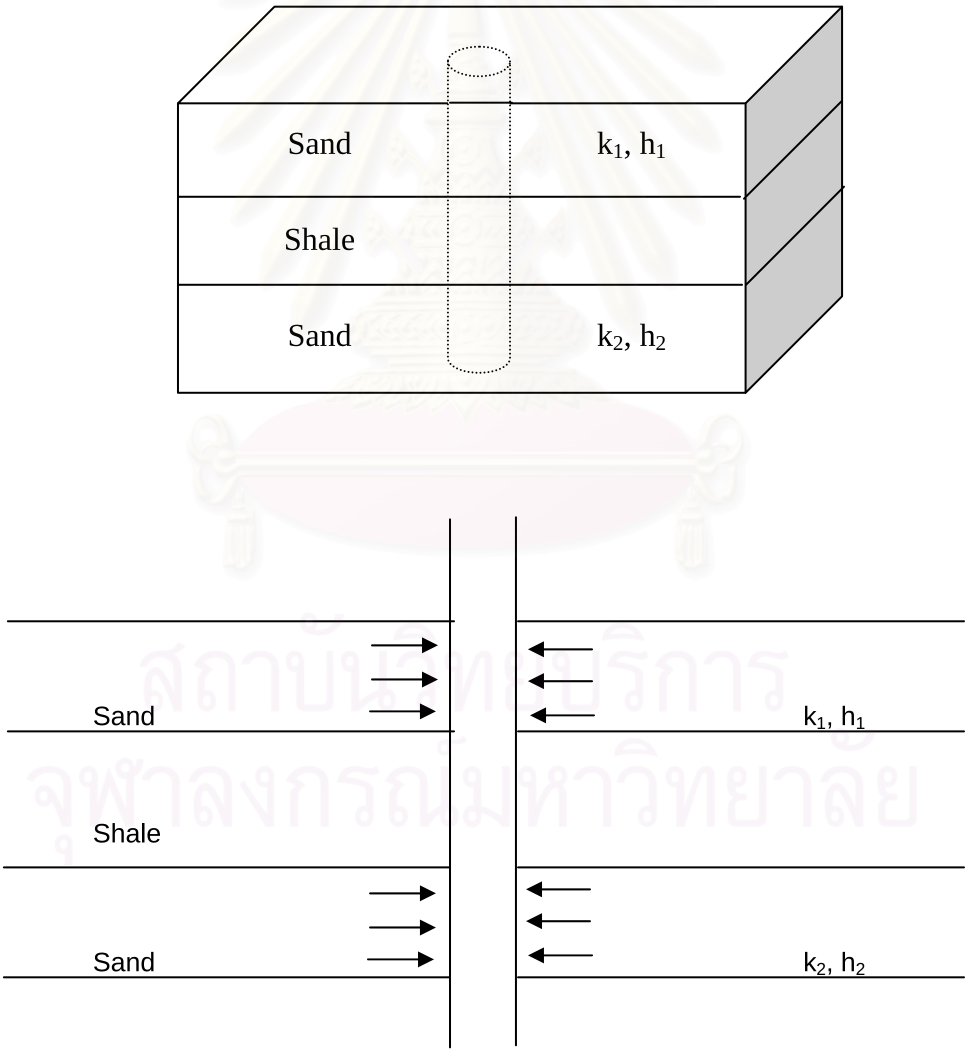


Figure 3-1 Two-layer flow system

$$q_1 / q_T = \frac{k_1 h_1}{(k_1 h_1 + k_2 h_2)} \tag{3-1}$$

and

$$q_2 / q_T = \frac{k_2 h_2}{(k_1 h_1 + k_2 h_2)} \tag{3-2}$$

where q_1 = flow rate of layer 1

q_2 = flow rate of layer 2

q_T = total flow rate = $q_1 + q_2$

k_1 = permeability of layer 1

k_2 = permeability of layer 2

h_1 = thickness of layer 1

h_2 = thickness of layer 2

The two equal equations are applicable with the additional assumption that other factors or other rock and fluid properties such as viscosity, porosity, area, etc. are the same for both layers.

However, several investigators have demonstrated that the kh rule is not the only rule that govern the flow fraction from each layer. Nevertheless, it has not been pointed out clearly how flow from each layer is controlled.

In this study, a simplified model will be used to investigate the controlling factors for the multilayer system. Two-layer models will be mainly used while a three-layer model will be used to illustrate and confirm some common observations.

<u>Flow Regime</u>

The system used in this study is a form of oil in a two-layer and three-layer system. Each layer has uniform thickness with close boundary. Fluids in all layers have the same properties. The flow starts from unsteady state flow when the flow is investigated to pseudo-steady state flow when all boundaries have full effect on flow in the system. The investigation will also cover flow from undersaturated condition or reservoir pressure above bubble point pressure to saturated condition or reservoir pressure below bubble point pressure. Flow above bubble point pressure involve only one phase while flow below bubble point pressure involve two phases, oil and gas.

That is, the system represent flow in two or three layers which contain undersaturated oil at the beginning and with pressure depletion below bubble point pressure, the flow is later influenced by free gas liberated from the oil.

Behavior of oil flowing from each layer under these periods (above bubble point and below bubble point) will be investigated. Various controlling factors will be identified.

The Model

The simplified square model is used in this study. This model is, in fact, a representative of a drainage area around a will in a regular, uniform well spacing system (Figure 3-2). However, as it is known from previous studied that flow from each layer is mainly governed by either kh or pore volume (AhΦ) or both, assuming the compressibility (c_t) and fluid properties are the same for all layers, it is also investigated that theses two groups of parameters are really the main controlling factor, and not each individual parameter. Hence, at the beginning of the investigation, effect of individual parameters, k, h, A, and Φ on the flow of each layer will be analyzed.

Controlling Factors

The conclusion is applicable for only the case of one phase flow or the case with reservoir pressure is higher than bubble point pressure. In addition to identify the condition of which each or both of these controlling factors have their influence, the reason behind these behaviors will also be analyzed and discussed.

For the condition which reservoir pressure is lower than bubble point pressure, (free) gas expansion (exercising through total compressibility, c_t) will obviously have strong influence on flow of each layer. In addition, other parameters such as oil and gas viscosity and oil and gas relative permeability will also have impact on flow of each layer. Though influence of these parameters on flow of each layer during the below bubble point pressure condition will be considered quantitatively they will be analyzed quantitatively in this study.

In order to be able to identify if the conclusions can be used for various ranges of fluid properties, variation of fluid properties for various cases will also be investigated.

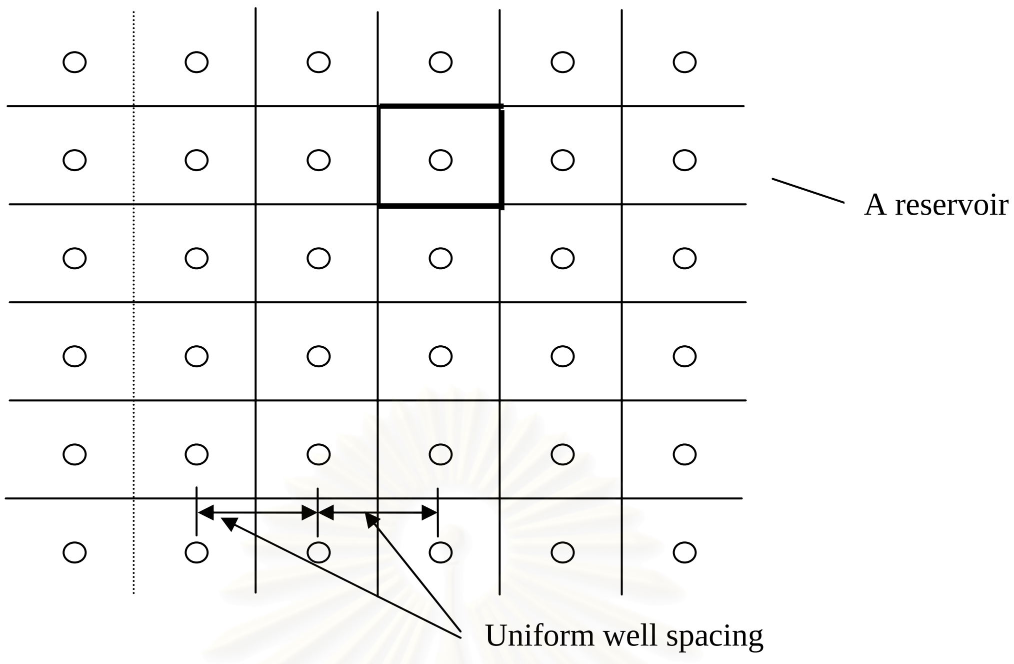


Figure 3-2 Regular, uniform well spacing system with square drainage area

CHAPTER IV
MODEL FORMULATION

Because of complexity of flow, either one or two phase flow, in porous media of several layers system, it is best to investigate this kind of problem by using reservoir simulation. In addition, reservoir simulation provides the freedom in changing various parameters. This makes the investigation much more easier. Two main systems are used for investigation in this study, a two-layer system and a three-layer system. Investigation is mainly conducted using the two-layer system while the three-layer system is used only to demonstrate or confirm that the conclusion for the two-layer system can be extended to larger number of layers.

4.1 Model for two-layer system

The model for two-layer system is shown in Figure 4-1. The two porous layers are separated by impermeable shale. Each layer has uniform thickness and uniform rock properties. Both layers have fluid with the same properties. The thickness of the impermeable shale is only 50 ft. Therefore, the initial pressures of the two layers are not much different.

Each layer is assumed to have closed boundaries (volumetric reservoir). Hence, flow behavior of both layers will be unsteady state at early period and become pseudo-steady state after all boundaries fully affect the flow.

In order to be able to identify the controlling factor and to investigate their impact on flow from each layer, various values of each parameter are used. Table 4-1 shows values of parameters that are fixed for all runs while table 4-2 shows various values of parameters that are varied for various runs. The fluids for both layers have the same properties.

Under flowing condition the total rate from the well is kept to be not higher than some specific value. This is to simulate flow limit of any tubing system. However, it is not to say that various well flow rates used in this study is equal to flow limit of some tubing system. They are nominal values for the purpose of this study. After the well is allowed to flow for some time, the well flow rate may be lower than the set flow limit. This represent depletion in the reservoir, i.e. there is not sufficient energy to maintain the well flow rate at the set flow limit.

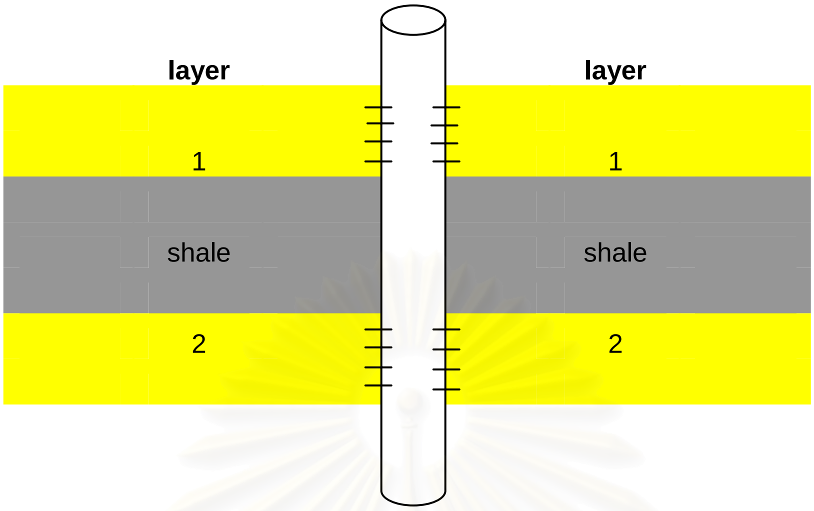
In terms of flowing from each layer into the well, it is assumed that each layer is fully opened for flow. This eliminates the possibility of having skin due to partial open sand section.

Table 4-1 Fixed parameter values for all runs

Properties and Conditions	**Values**
Initial Oil Saturation, Soi	0.8
Initial Water Saturation, Swi	0.2
Initial Gas Saturation, Sgi	0
Critical Gas Saturation, Sgcr	0.037
Connate Water Saturation, Swc	0.2
Irreducible Water Saturation, Swirr	0.2
Water Compressibility, (psi^{-1})	3.254E-6
Rock Compressibility, (psi^{-1})	1.530E-6
Water Viscosity at standard condition, (cp)	0.268
Water Formation Volume Factor at Pi, (RB/STB)	1.030
Oil Formation Volume Factor at Pi, (RB/STB)	1.259
Top structure (top of the reservoir), (ft)	5,800
Reference Elevation, (ft)	5,800
Pressure at reference elevation, (psia)	2,610
Reservoir Temperature, (^{o}F)	220
Wellbore ID, (ft)	0.583
Oil density at surface conditions, (lb/cuft)	53.00
Water density at surface conditions, (lb/cuft)	62.43
Gas density at surface conditions, (lb/cuft)	0.05

Table 4-2 Variable parameter values for various runs in two-layer system

Properties and Conditions	**Values**
Permeability, k (md)	1, 2, 2.5, 3.125, 5, 6.25, 7.5, 10, 12.5, 15, 20, 25, 30, 50, 62.5, 75, 100, 125, 150, 250, 312.5, 500, 625, 1000
Total flow rate, q_T (STB/D)	50, 100, 500, 600, 1000
Porosity, ø (fraction)	0.125, 0.2, 0.25, 0.3
Thickness, h (ft)	25, 40, 50, 60, 75
Pressure at top of layer 2, (psia)	2655, 2659.5, 2666.3



Side view

Top view

Figure 4-1 Location of production well for two-layer system

4.2 Model for three-layer system

Figure 4-2 shows model for three-layer system. There are three permeable layers or sands and two impermeable shales. The general criteria used in the two-layer system are also applicable here. Table 4-3 shows the variable value parameters used for this model.

The three-layer system is used to test various conclusions from the two-layer cases to check if the same conclusions can be applied to the three-layer system.

Table 4-3 Variable parameter values for various runs for three-layer system

Properties and Conditions	Values
Permeability, k (md)	2.2, 3.1, 5, 220, 310, 500
Total flow rate, q_T (STB/D)	100, 1000
Porosity, Φ (fraction)	0.25
Thickness, h (ft)	25, 30, 45
Pressure at top of layer 2, (psia)	2641.5
Pressure at top of layer 3 , (psia)	2664

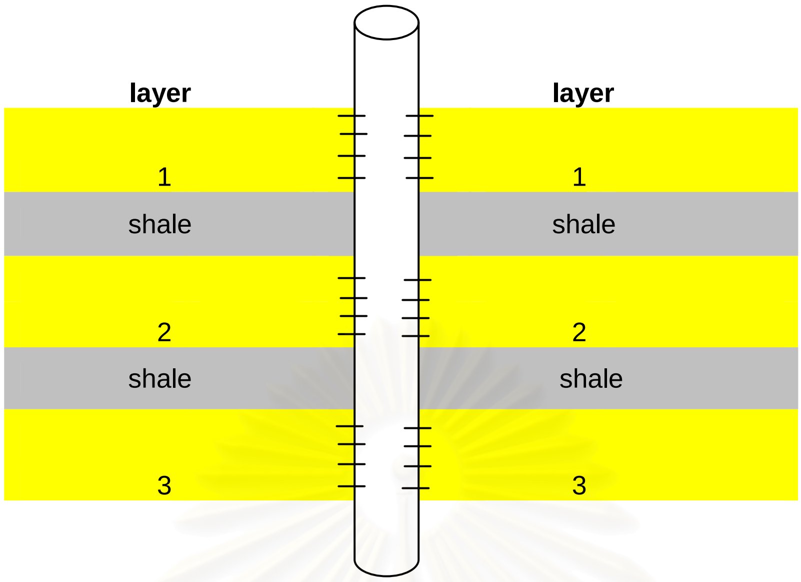
4.3 Effect of fluid properties

The model for this study is the same as the two-layer system but some fluid properties are different. The different fluid properties in the system are API gravity and bubble point pressure. Both layers have fluid with the same properties though there are different fluid properties in the system. Table 4-4 shows the variable parameters used for this case.

The different fluid property cases are used to test several conclusions from two-layer cases to check the same conclusions can be applied to the different fluid properties in the two-layer system.

Table 4-4 Variable parameter values for studying effect of fluid property

Properties and conditions	Values
Bubble point pressure, Pbub (psia)	1600, 1800
Oil gravity, API	30, 35



Side view

Top view

Figure 4-2   Location of production well for three-layer system

CHAPTER V

CONTROLLING FACTORS FOR FLOW FROM MULTILAYER OIL SYSTEM

In this chapter, the flowing investigations will be conducted:

1. Investigate that with some specific sets of two-layer system, kh or ΦAh will be the controlling factor, not each individual parameters, k, h, Φ, or A.
2. Identify approximate conditions of the two-layer system of which kh or ΦAh has full influence on flow from each layer.
3. Test the influence of kh and ΦAh for the three-layer system.
4. Test the influence of kh and ΦAh for different fluid properties.

5.1 The Controlling Factors

5.1.1 kh as a controlling factor

During the course of the study, it has been observed that kh factor is likely to have influence for the system with low value of kh. Therefore, in order to investigate that kh is the controlling factor and k or h alone do not have any effect, the systems with properties shown in Table 5-1 are used.

Figure 5-1 to 5-3 show flow rate of each layer and the ratio of layer flow rate to total flow rate of two systems which have the same kh value for each layer but different k or h values for each layer.

Figure 5-1 shows that with various values of k and h while kh value of each layer is kept constant flow rate from each layer are the same especially at early time when no free gas in the reservoir. Figure 5-2 confirms the mentioned conclusions as the ratios q_1/q_T and q_2/q_T for each system are the same for early time period (less than 1200 days).

Figure 5-3 further confirms the conclusion. The Figure shows the behavior of layer flow rate at very early time. In fact, with $(kh)_1$ / $(kh)_T$ and $(kh)_2$ / $(kh)_T$ of 0.75 and 0.25 for both systems, the kh rule is not really obeyed because q_1/q_T is less than 0.75 while q_2/q_T is more than 0.25. This may be because the total flow rate (50 STB/D) used is not high enough for this range of kh value. This point will be discussed more later.

Figures 5-4 to 5-6 show the case that kh as controlling factor on the flow rate of 1000 STB/D. More cases that the flow rates are 100 and 600 STB/D for this section are shown in Appendix A.

In conclusion, it is shown by Figure 5-1, 5-2, and 5-3 that kh is a controlling factor, not individual k or h.

Table 5-1 Rock and fluid properties for system under influence of kh

Properties	**Layer 1**	**Layer 2**
k, md	6.25, 7.5	2.5, 3.125
h, ft	50, 60	40, 50
Φ	0.125, 0.3	0.2, 0.25
A, (MMsq.ft)	1.49, 2.38	1.49, 2.24
kh, (md-ft)	375	125
ΦAh, (MMcuft)	22.36	22.36
Pi, (psia)	2610	2655, 2666.3
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	2.5	2.5
q_T, (STB/D)	50, 100, 600, 1000	50, 100, 600, 1000
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.5	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.5

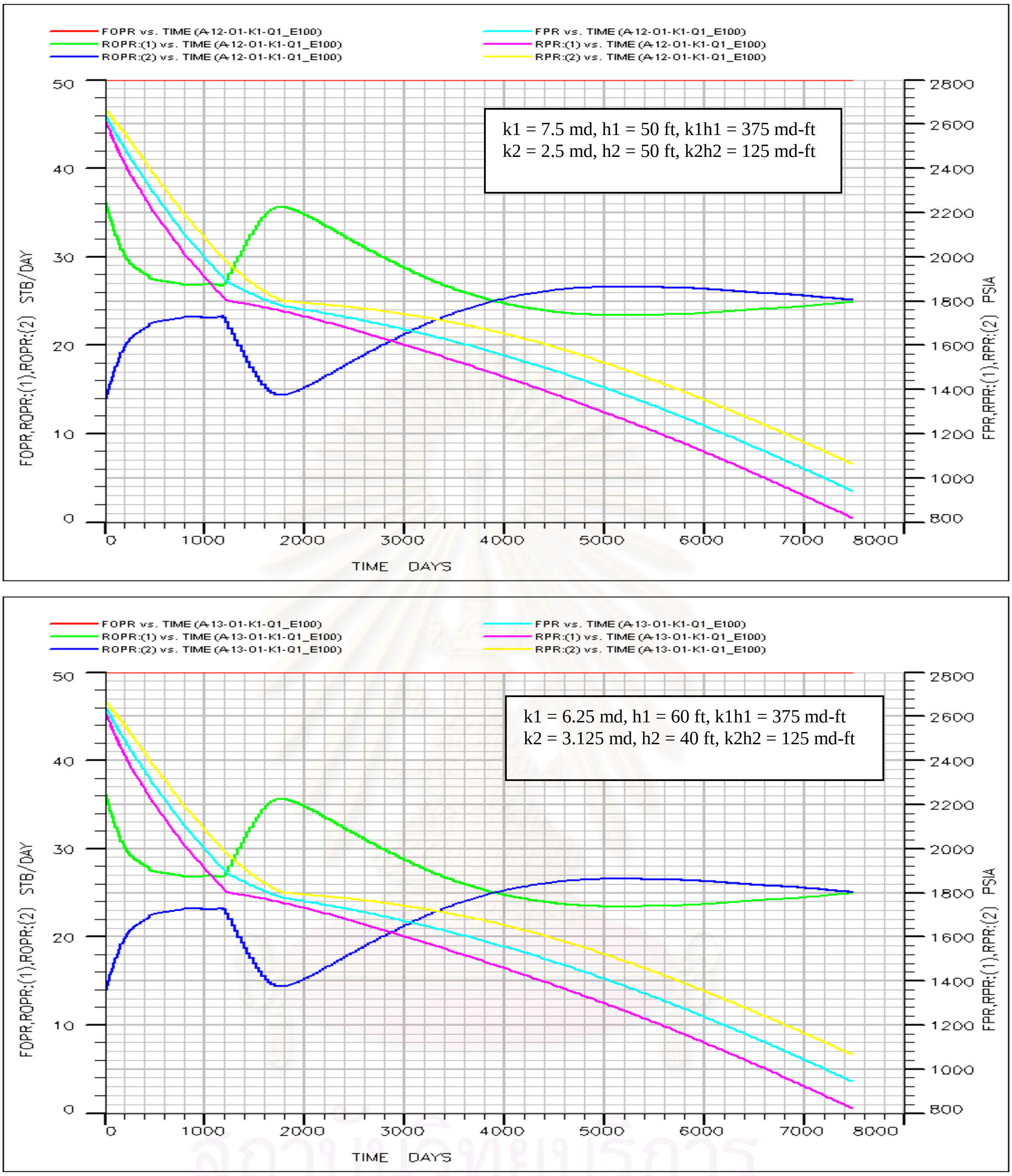


Figure 5-1 Layer flow rates (green and blue) obeying kh rule and not affected by individual value of k or h (q_T = 50 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

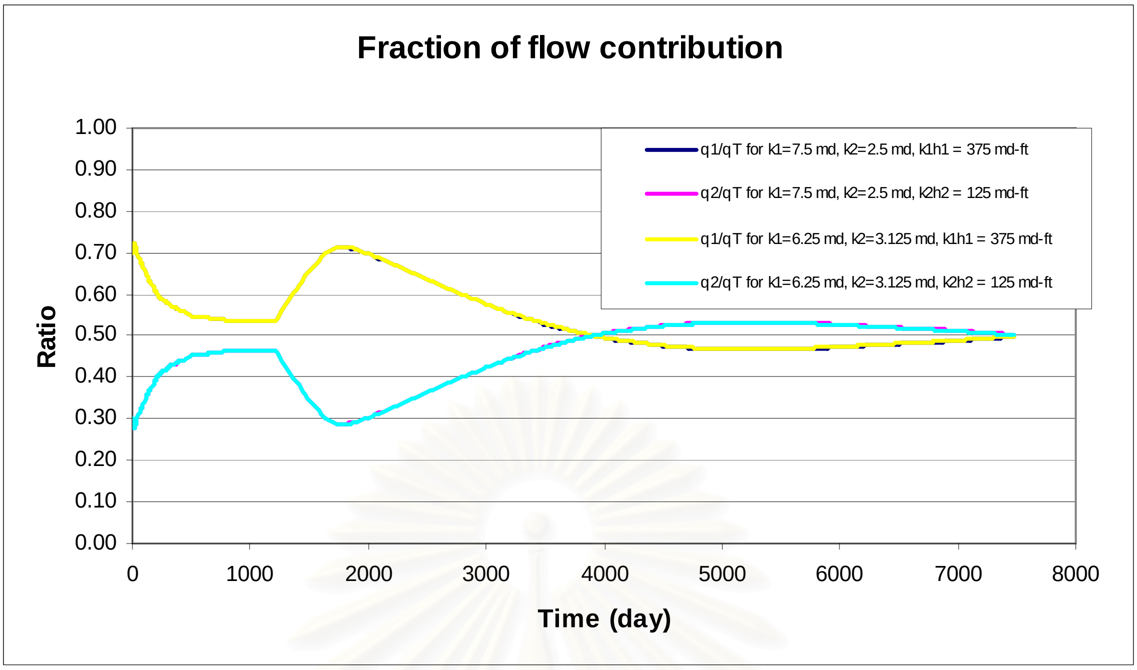


Figure 5-2 q_1/q_T and q_2/q_T ratios obeying kh rule and not affected by individual value of k or h (q_T = 50 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

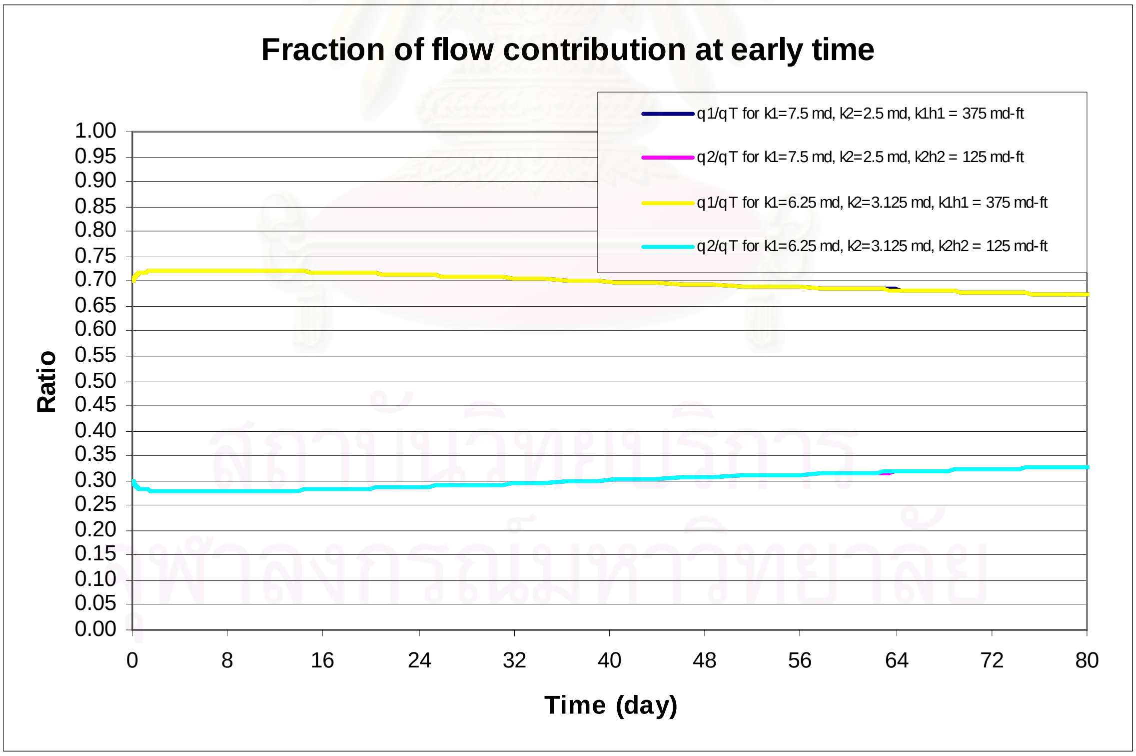
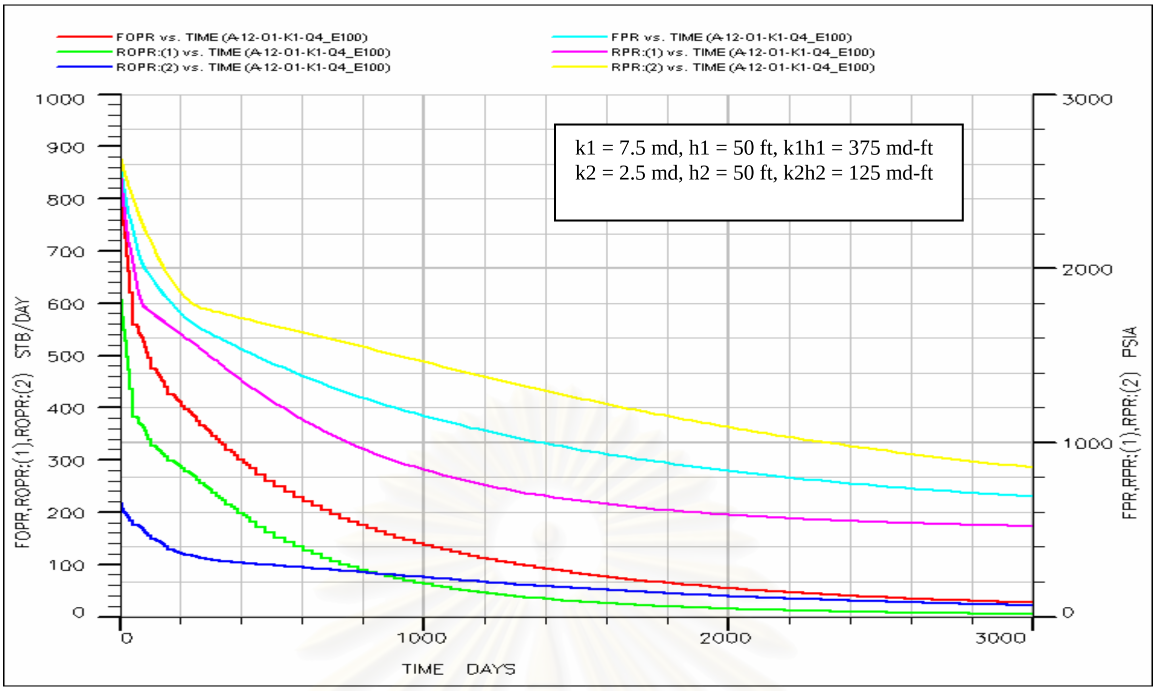


Figure 5-3 q_1/q_T and q_2/q_T ratios at early time (q_T = 50 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)



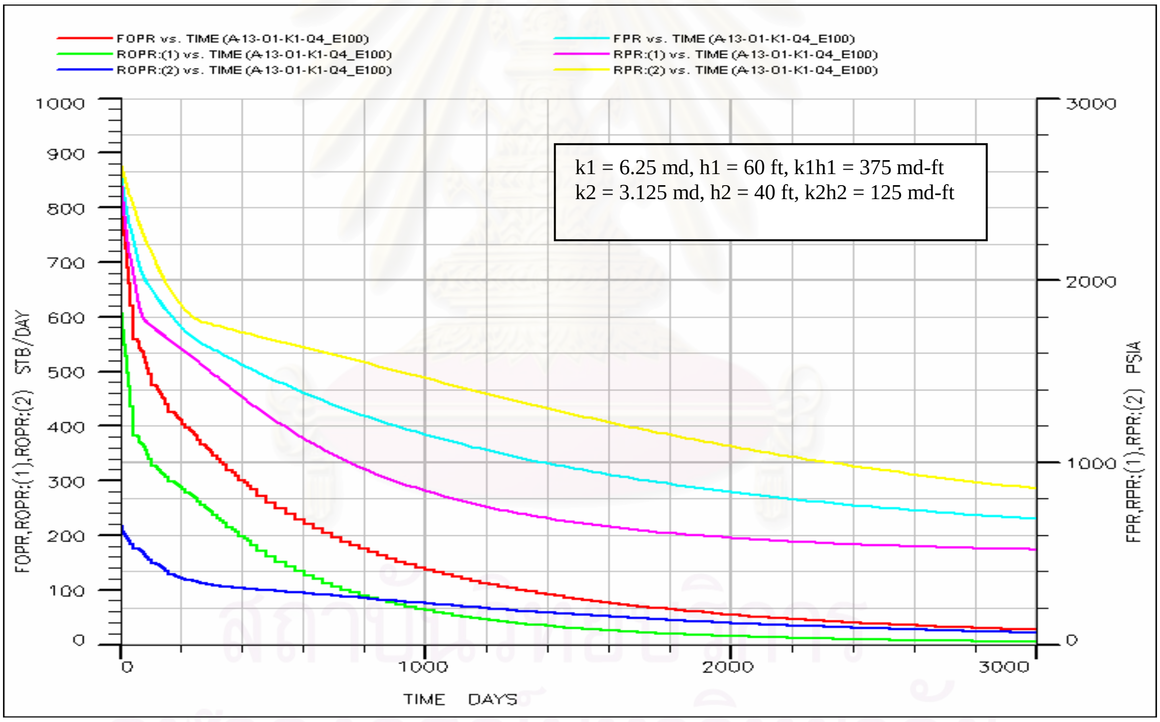


Figure 5-4 Layer flow rates (green and blue) obeying kh rule and not affected by individual value of k or h (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

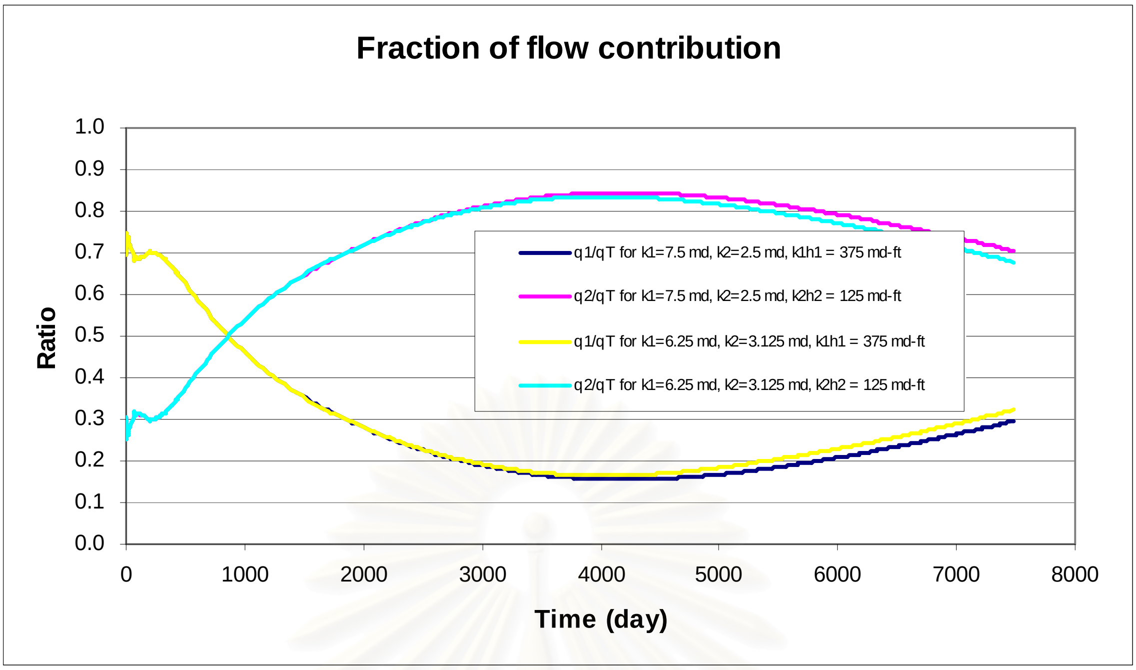


Figure 5-5 q_1/q_T and q_2/q_T ratios obeying kh rule and not affected by individual value of k or h (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

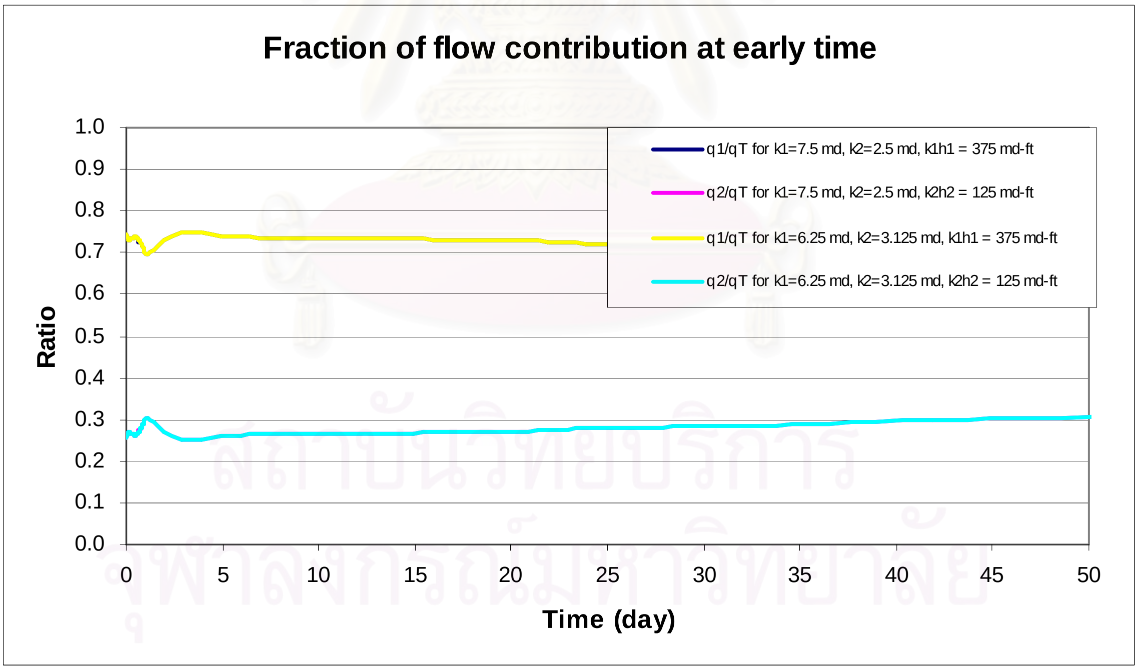


Figure 5-6 q_1/q_T and q_2/q_T ratios at early time (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

5.1.2 ΦAh as a controlling factor

Now let's back at the system with high value of permeability and not too high value of total flow rate. It is expected that flow rate from each layer will obey the ΦAh rule (to be demonstrated later) for this kind of systems. Similarly, it will be shown here that ΦAh is the controlling factor and not each individual parameters, Φ, A, or h. Table 5-2 shows rock and fluid properties for this case.

Figure 5-7 shows flow rate of each layer and total flow rate. It can be seen that whichever values of Φ, A, or k, the corresponding layer flow rate of each system is the same as long as ΦAh of each layer is the same. There are many observes discrepancy in layer flow rates in Figure 5-4 in the regions of ripple shape. In the regions of ripple shape it is believed that some peculiar behavior occurs and fractional flow (ratio of layer flow rate to total flow rate) does not obey the ΦAh rule. Therefore, in order to investigate the effect of individual parameters, Φ, A, and h, only in the regions outside the regions of ripple shape are considered.

Figure 5-8 shows q_1/q_T and q_2/q_T ratios of both systems. q_1/q_T and q_2/q_T ratios obey the ΦAh rule in the period before presence of free gas (less than 650 days), neglecting the ripple shape regions and the very early region where another peculiarity in observes. These peculiar phenomena will be discussed in detail later.

Figure 5-10 to 5-12 show the case of ΦAh as controlling factor at total flow rate of 1000 STB/D. Other cases for total flow rate of 50 and 600 STB/D will be showed in Appendix B

In conclusion, it is shown here that when the fractional flow of each region obeys the ΦAh rule, it will not be affected by individual values of Φ, A, or h. Hence, the controlling factor is ΦAh, not individual Φ, A, or h.

Table 5-2 Rock and fluid properties for system under influence of ΦAh

Properties	Layer 1	Layer 2
k, md	625, 750	250, 312.5
h, ft	50, 60	40, 50
Φ	0.125, 0.3	0.2, 0.25
A, (MMsq.ft)	1.49, 2.38	1.49, 2.24
kh, (md-ft)	37500	12500
ΦAh, (MMcuft)	22.36	22.36
Pi, (psia)	2610	2655, 2666.3
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	2.5	2.5
q_T, (STB/D)	50, 100, 600, 1000	50, 100, 600, 1000
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.5	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.5

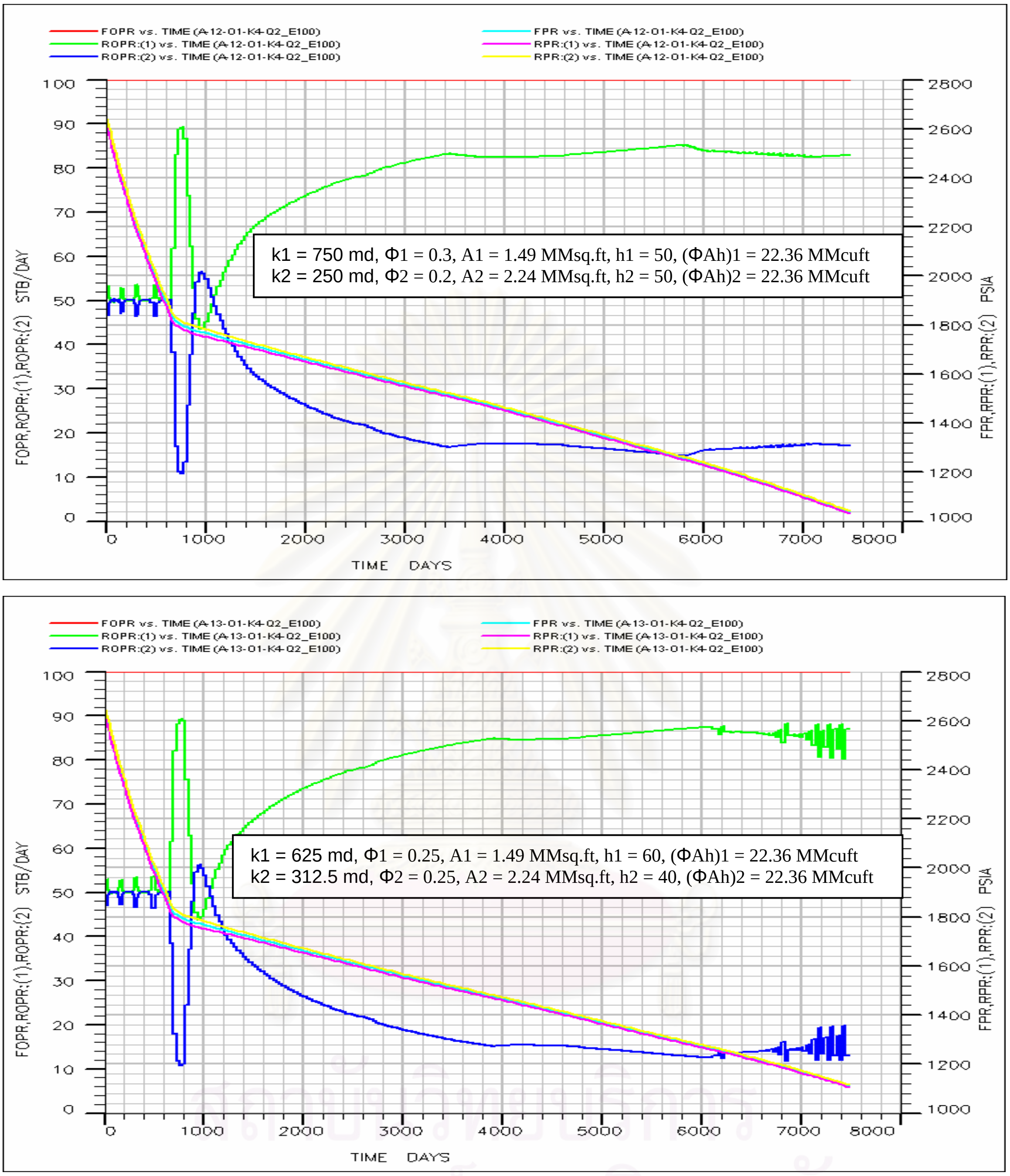


Figure 5-7 Layer flow rate (green and blue) obeying ΦAh rule and not affected by individual value of Φ, A, or h (q_T = 100 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

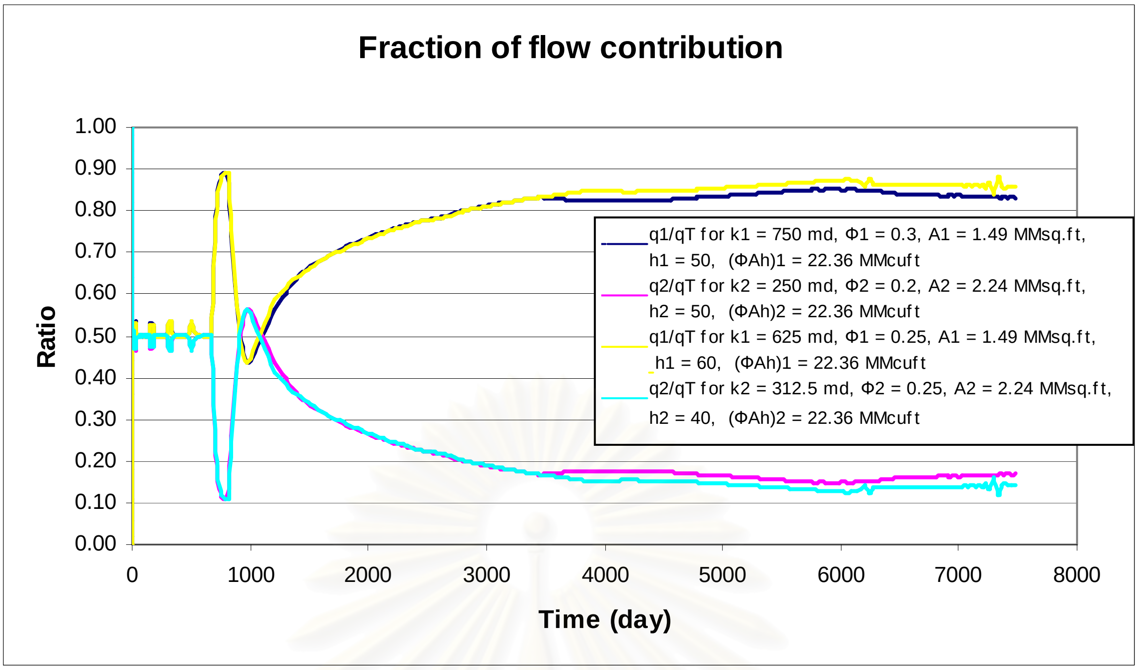


Figure 5-8 q_1/q_T and q_2/q_T ratios obeying ΦAh rule and not affected by individual value of Φ, A, or h (q_T = 100 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

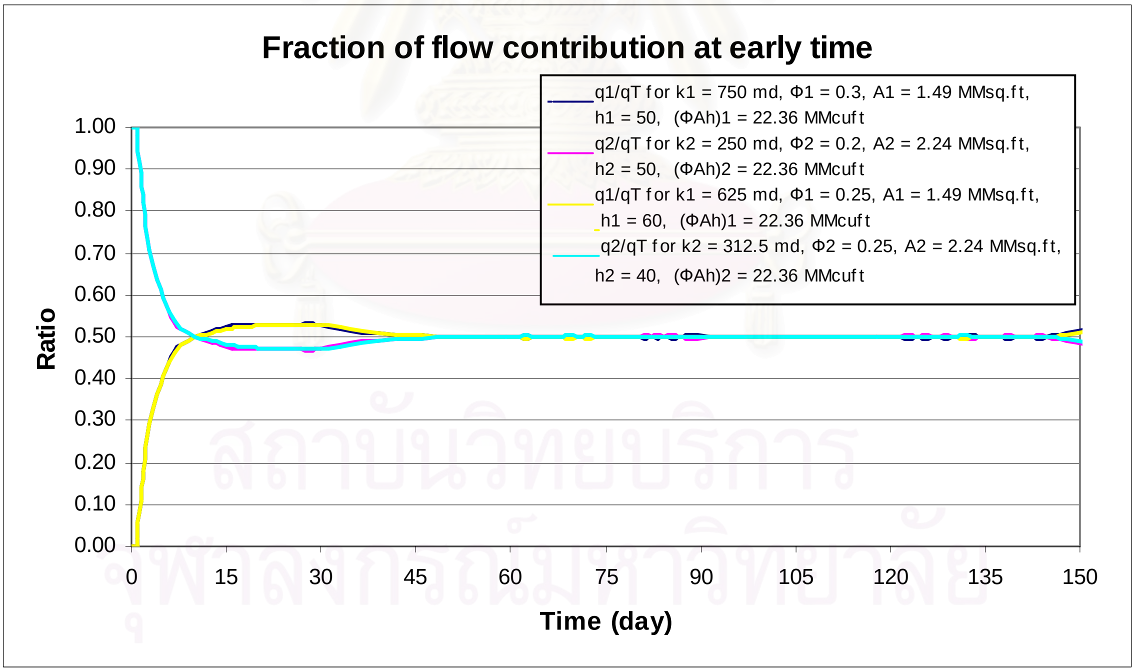


Figure 5-9 q_1/q_T and q_2/q_T ratios at early time (q_T = 100 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

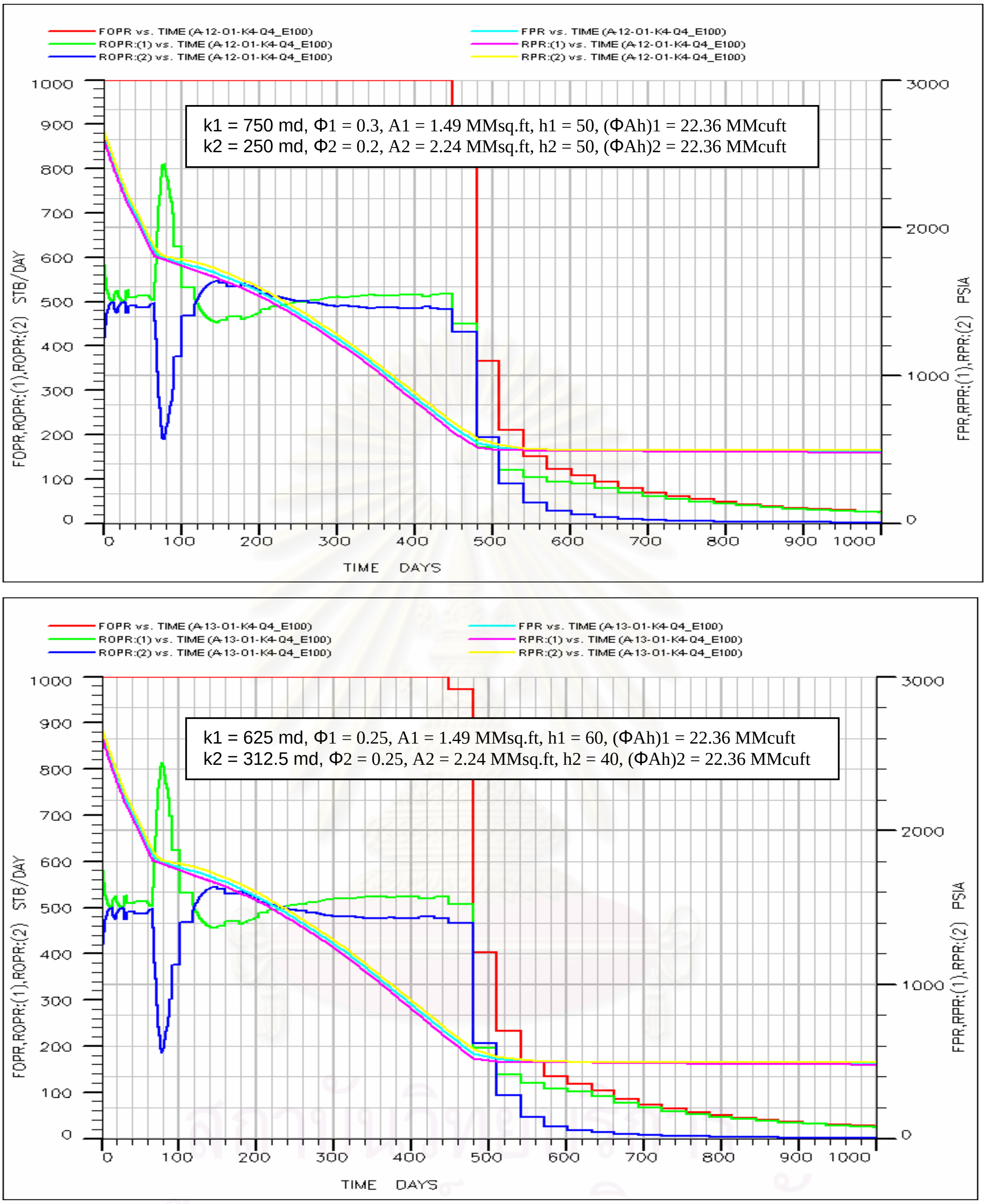


Figure 5-10 Layer flow rate (green and blue) obeying ΦAh rule and not affected by individual value of Φ, A, or h (q_T = 1000 STB/D, k_1h_1= 37500 md-ft., k_2h_2= 12500 md-ft)

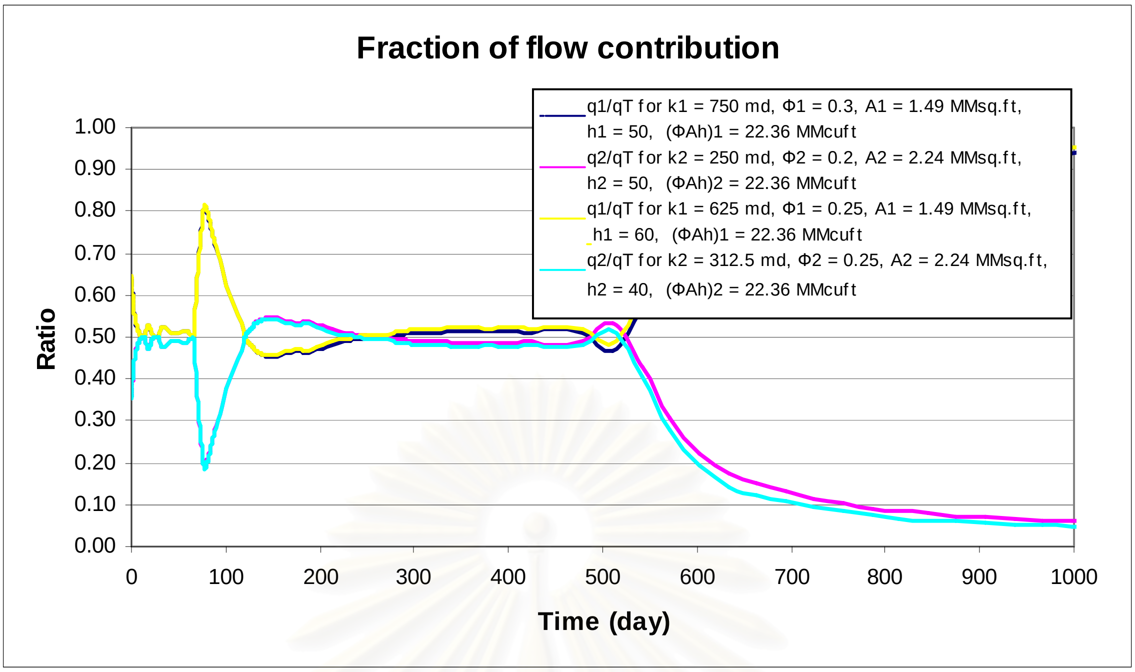


Figure 5-11 q_1/q_T and q_2/q_T ratios obeying ΦAh rule and not affected by individual value of Φ, A, or h (q_T = 1000 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

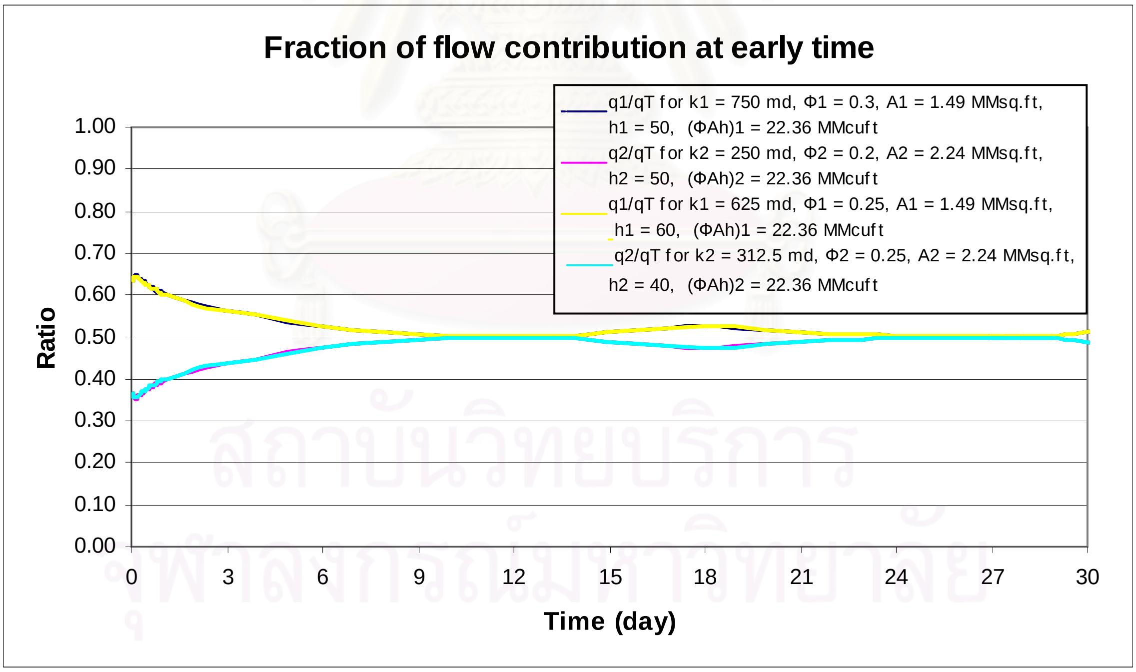


Figure 5-12 q_1/q_T and q_2/q_T ratios at early time (q_T = 1000 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

5.2 kh as Controlling Factor

As it is well-known that flow from the parallel layers (two-layer system in this study is a subset of this) obey the kh rule, it is interesting to investigate how robust this rule is and when it can be applied.

The question on robustness of the kh rule is a reasonable one, considering that the kh rule is derived based on the assumption that pressure gradient in each layer is the same and also equal to the system pressure gradient. This condition has never existed in reality, especially for the volumetric oil reservoirs.

From a member of cases run in this study, it has been noticed that the kh rule is likely to be applicable in the system with low kh and sizable flow rate from each layer. It is further hypothesized that the kh rule should govern when flow rate in each layer is at the level that allow by the flow capacity or kh of the layer. This can be approximately compared with flowing from a well through a choke. If well flow capacity is high, the choke will limit the flow rate of the well. For this case, various choke sizes are equivalent to various kh values. Smaller choke sizes or low kh will allow oil to flow at lower rate. Oppositely, larger choke size or high kh will allow oil to flow at higher rate. Hence, choke size or kh is the controlling factor for oil rate.

Therefore, if there are two layers with low kh values, flow rate from each layer will be controlled by its kh. Here the ratio of layer flow rate to the total flow rate from the multilayer system of which each layer has limited volume is more complicate than the flow rate vs. choke concept. In addition to kh, flow from each layer is also controlled by drawdown or pressure gradient in that layer. Only in the case that pressure drop in each layer is in the condition that combination of effect of kh and pressure gradient of each layer is maintained such that the ratio of layer flow rate to total flow rate is maintained for all layers, flow from the multilayer system will obey the kh rule.

Figure 5-13 shows oil flow rates and pressure for each layer and for the system. The rock and fluid properties use for this are shown in table 5-3. In this case, kh are low (k_1h_1 = 120 md-ft and k_2h_2 = 40 md-ft) which total flow rate is set at 1000 STB/D. However, the set total flow rate of 1000 STB/D is too high for this system as can be seen from Figure 5-13 that the initial total flow rate from the system is only approximately 260 STB/D (q_1 = 190 STB/D and q_2 = 70 STB/D). This implies that flow rate from each layer is limited by its kh. (it is known that the volume of oil originally in the system can yield total flow rate more than 1000 STB/D if the rock properties allow.) Hence, flow from this system is controlled by kh. Figure 5-13 also shows that q_1 and q_2 continuously decrease with time. This implies pressure in each layer is also decreasing.

The ratio of layer flow rate to total flow rate, q_1/q_T and q_2/q_T, are shown in Figures 5-14 and 5-15. It can be seen from Figure 5-15 which shows the ratios at early time that q_1/q_T are close to 0.75 and q_2/q_T are close to 0.25 for same time, approximately less than 100 days. There are some erratic shapes of q_1/q_T and q_2/q_T during this period. The erratic behavior is considered to be due to inability of reservoir simulator to simulate the real behavior and will be neglected. Hence, it can be said that during the period of 100 days, q_1/q_T and q_2/q_T obey the kh rule. However, after 100 days, q_1/q_T and q_2/q_T deviate from the kh rule probably due to pressure depletions in each layer are not uniform. If this is the case, the pseudo-steady state is one of the factors that cause flow from multilayer system not to obey kh rule.

At even later time, more than 1000 days, q_1/q_T and q_2/q_T has never followed the kh rule again as shown in Figure 5-14. Here in addition to pressure depletion, presence of free gas in the reservoir is also one of the factors that cause flow from a multilayer system to deviate from the kh rule. Figure 5-13 shows that layer 1 has pressure lower than the bubble point pressure at around 1000 days. This allows flow from layer 1 to drop more slower compared with layer 2, hence causing q_1/q_T to increase while q_2/q_T to decrease (≈ 1000-3000 days period). During these later periods, it is believed that the controlling factor would be pressure depletion, presence of gas and it size, and volume of remaining oil. In fact, all these factors are related to the energy available in the reservoir to push oil out of the reservoir or each layer. To understand the influence of this available energy, further study is required. The more cases for this section will be shown in Appendix C

In addition, flow from each layer will be controlled by kh though high kh values in case that total flow rate is very high because flows from each layer are fully flow capacity. The rock and fluid properties are shown in table 5-4. In this case, kh are high (k_1h_1 = 37500 md-ft and k_2h_2 = 12500 md-ft) which total flow rate is set at 60000 STB/D. However, the set total flow rate of 60000 STB/D is too high for this system as can be seen from Figure 5-16 that the initial total flow rate from the system is approximately 58500 STB/D (q_1 = 42000 STB/D and q_2 = 16500 STB/D). This implies that flow rate from each layer is limited by its kh. Hence, flow from the system is controlled by kh. Figure 5-16 also shows that q_1 and q_2 continuously decrease with time. This implies pressure in each layer is also decreasing.

The ratio of layer flow rate to total flow rate, q_1/q_T and q_2/q_T, are shown in Figures 5-17 and 5-18. It can be seen from Figure 5-18 which shows the ratios at very early time that q_1/q_T are close to 0.75 and q_2/q_T are close to 0.25 for same time, approximately less than a day. After a day q_1/q_T and q_2/q_T deviate from the kh rule probably due to pressure depletions in each layer are not uniform. If this is the case, the pseudo-steady state is one of the factors that cause flow from multilayer system not to obey kh rule.

At this point, it can be concluded as follows:

1. kh is a controlling factor for flow from the multilayer system only when flow from each layer is at the level of its (layer's) flow capacity or kh.
2. For a volumetric system (closed boundary reservoir), kh is a controlling factor for a start period of time, compared to reservoir life, and other controlling factor will come into play.
3. Presence of free gas has significant influence on flow from the multilayer system.
4. Other controlling factors include pressure depletion and presence of other expandable fluid.
5. In fact, all controlling factors mentioned, except kh, are related to the available energy to push oil out of the reservoir.
6. Further study is required to really understand the influence of the available energy on flow from a multilayer system.

Table 5-3 Rock and fluid properties for system under influence of kh (k_1h_1 = 120 md-ft, k_2h_2 = 40 md-ft, and q_T = 1000 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	2	1
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	120	40
ΦAh, (MMcuft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	1000	1000
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

Table 5-4 Rock and fluid properties for system under influence of kh (k_1h_1 = 37500 md-ft, k_2h_2 = 12500 md-ft, and q_T = 60000 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	625	312.5
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	37500	12500
ΦAh, (MMcuft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	60000	60000
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

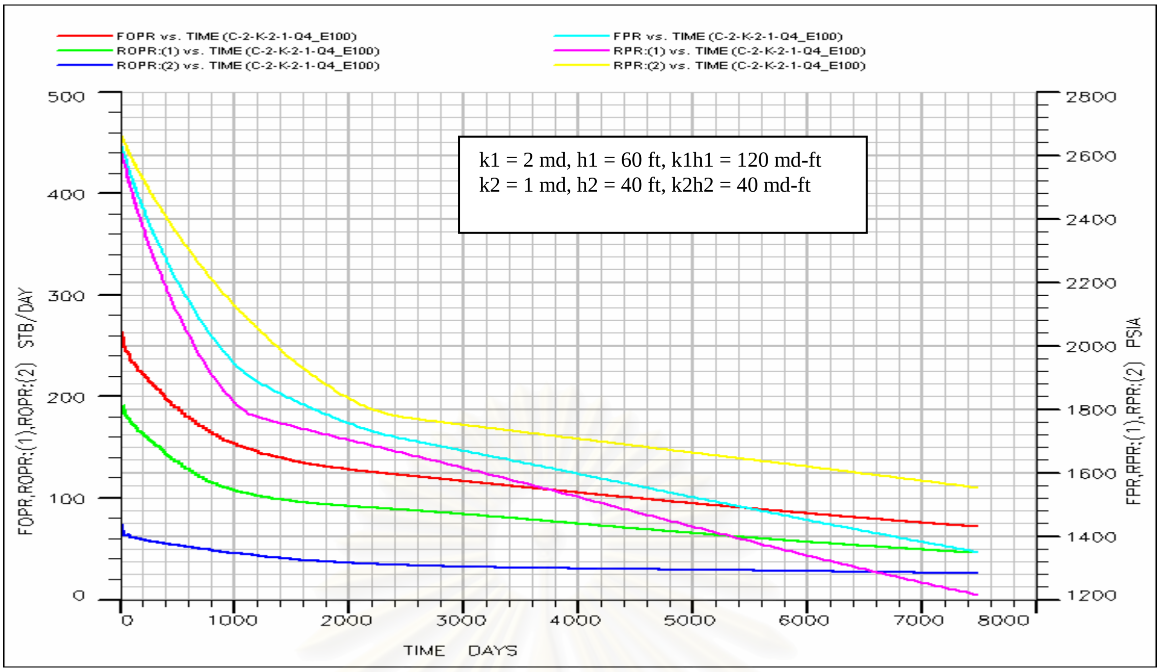


Figure 5-13 Flow from multilayer system partially under influence of kh (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

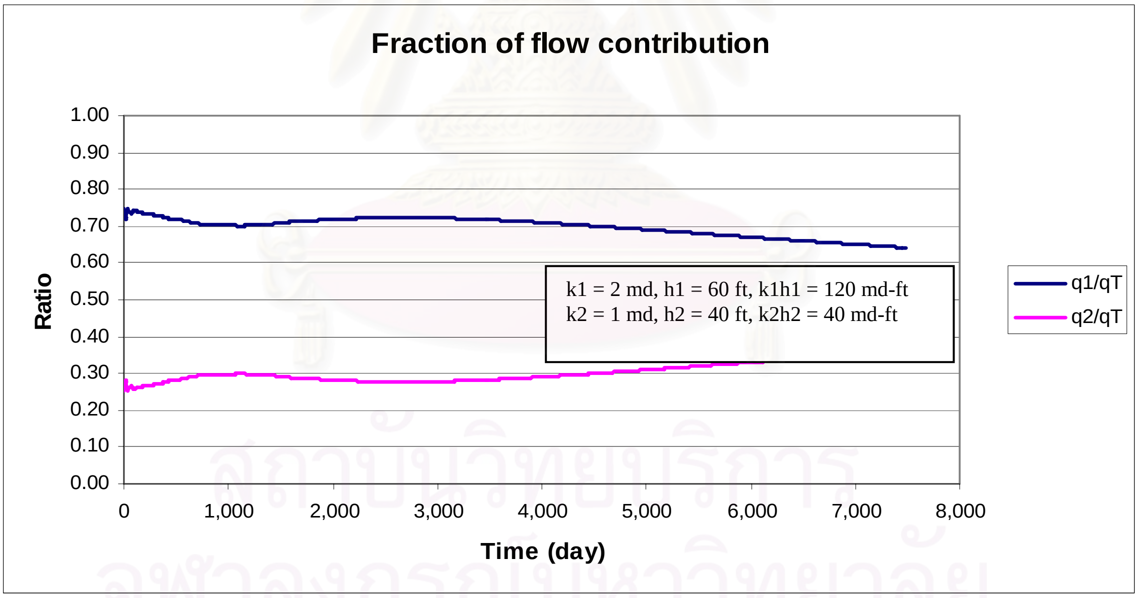


Figure 5-14 q_1/q_T and q_2/q_T ratios at various times (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

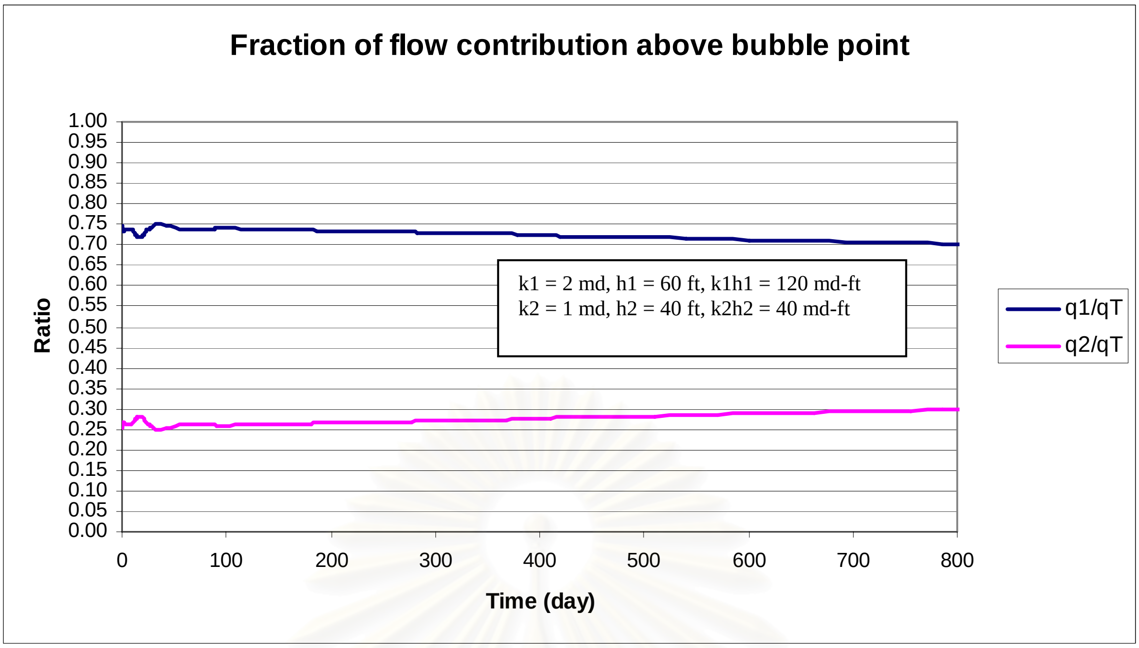


Figure 5-15 q_1/q_T and q_2/q_T ratios at early time (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

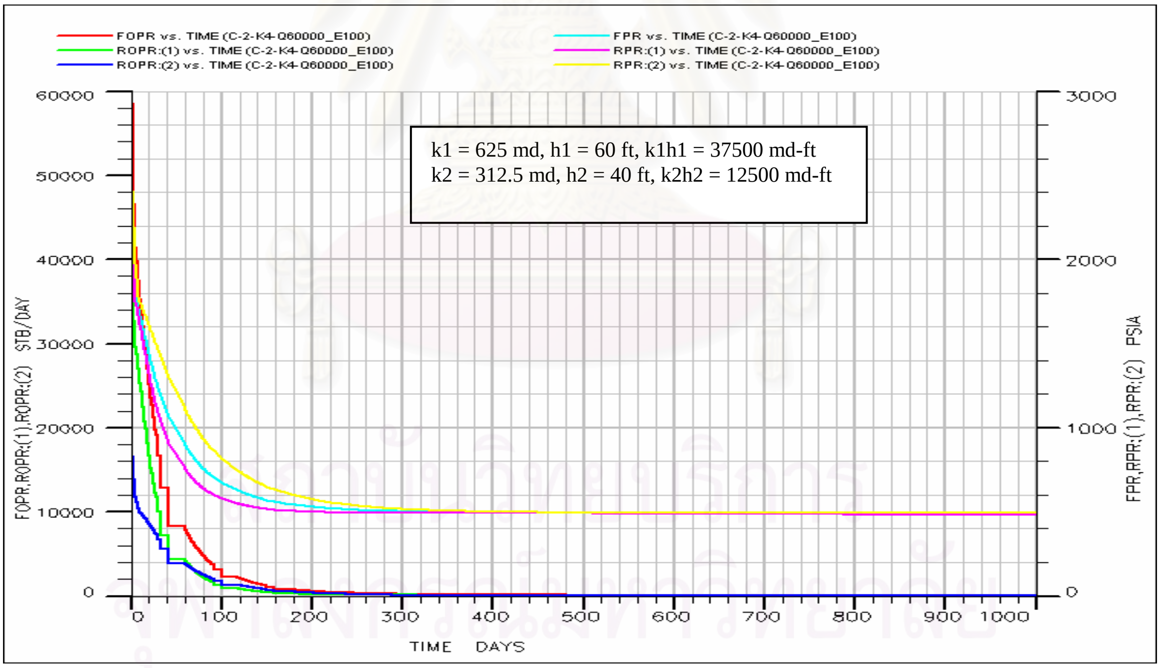


Figure 5-16 Flow from multilayer system partially under influence of kh

(q_T = 60000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

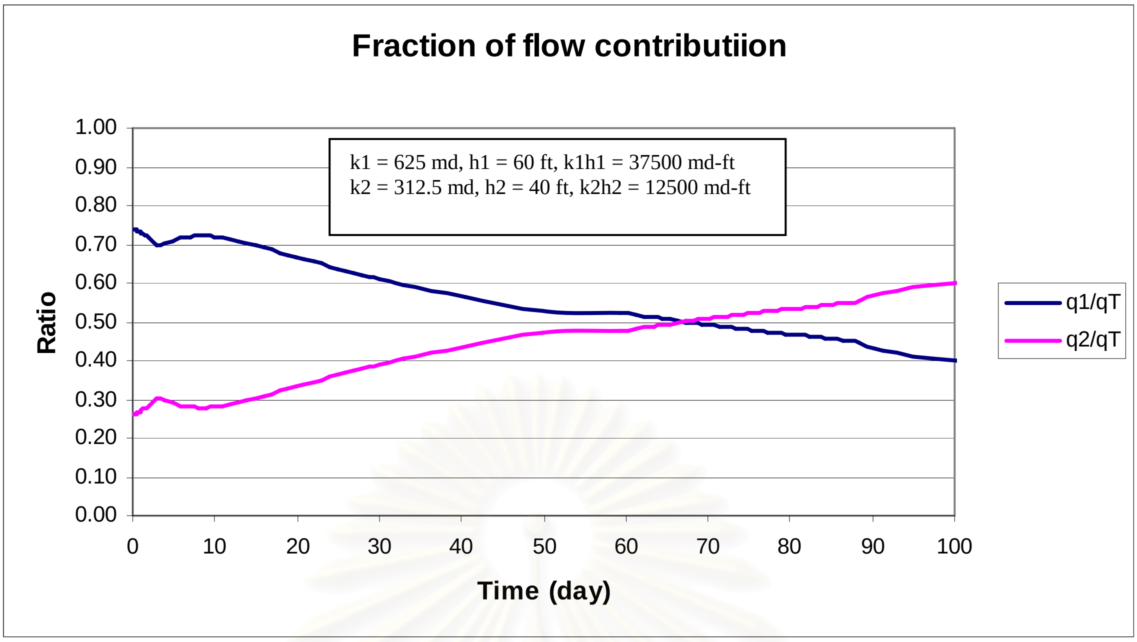


Figure 5-17 q_1/q_T and q_2/q_T ratios at various times (q_T = 60000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

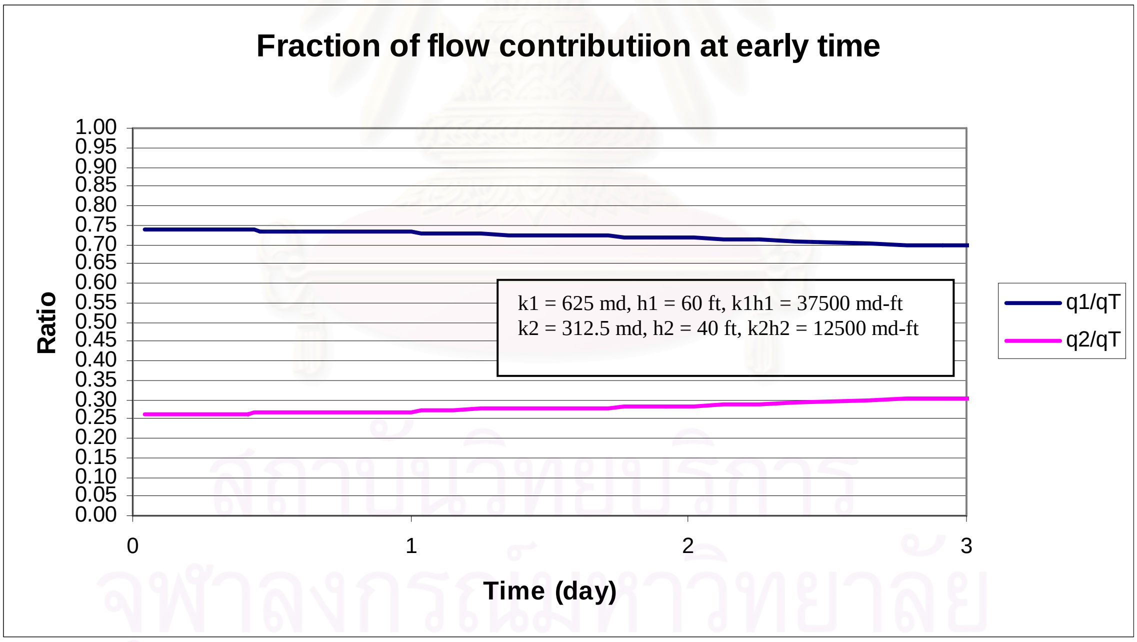


Figure 5-18 q_1/q_T and q_2/q_T ratios at early time (q_T = 60000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

5.3 ΦAh as a controlling Factor

Similarly, observation from a number of simulation runs in this study leads to a conclusion that the kh rule is not applicable for the systems which here high value of kh and total flow rate is not high. This, in turn, leads to a conclusion that when fluid flow from the reservoir is not at the level that the reservoir allows the fluid to flow, kh is not a controlling factor at all.

This can also analyze to the case of flow from a well with choke control. Even the reservoir is highly depleted and flowing from the well is too low such that even at the minimum choke size (let's assume it exists, i.e. neglecting shutting-in the well) flow rate from the well is not control by choke. This means that choke size has no influence on flow from the well. The controlling factor on flow from the well is the capacity of the reservoir to yield fluids. Similarly, when flow from a multilayer system at rates lower than the flow capacity or kh of each layer, kh will have no influence on flow from each layer. This condition is equivalent to the real system that the well flow capacity is low and the reservoir flow capacity cannot be fully utilized. This condition is normally net existent for oil well-reservoir system, except for the exceptional good rock properties. However, this condition is usually existent for gas well-reservoir system where flow capacity of gas well is usually limited and, in several occasions, less that the reservoir flow capacity.

When kh is not a controlling factor for this condition, what the controlling factor should be. Figures 5-19 to 5-21 show clearly that ΦAh is the controlling factor during the period before solution liberated from the oil. Rock and fluid properties of the system being described are shown in Table 5-5. It should be noted that fluid properties for both layers are the same, hence effect of oil expansion is cancelled out and only ΦAh remaining.

Figures 5-22 to 5-24 show that before the presence of free gas in the reservoir, q_1/q_T = 0.6 and q_2/q_T = 0.4 which are exactly equal to $(\Phi Ah)_1/(\Phi Ah)_T$ = 0.6 and $(\Phi Ah)_2/(\Phi Ah)_T$ = 0.4, respectively. In all these Figures, there are several short periods within the period that ΦAh is the controlling factor (up to approximately 2400 days) that the q_1/q_T and q_2/q_T do not obey the ΦAh rule. It is not clear what cause this phenomenon. Because limited study time, this peculiar phenomenon is neglected. It can, therefore, conclude that under the condition described ΦAh is the controlling factor on flow from the multilayer system before the presence of free gas in the reservoir.

Table 5-5 Rock and fluid properties for system under influence of ΦAh (k_1h_1 = 6000 md-ft, k_2h_2 = 2000 md-ft, and q_T = 100 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	100	50
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	6000	2000
ΦAh, (MMcuft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	100	100
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

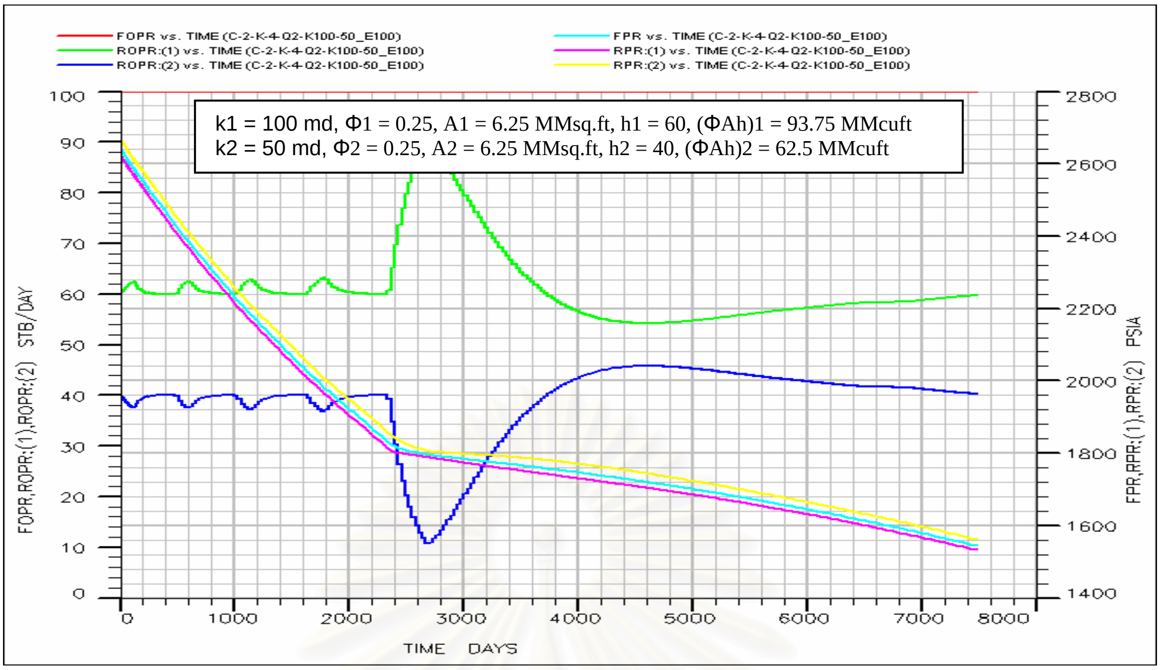


Figure 5-19 Flow from multilayer system partially under influence of ΦAh

(q_T = 100 STB/D, k_1h_1 = 6000 md-ft., k_2h_2 = 4000 md-ft)

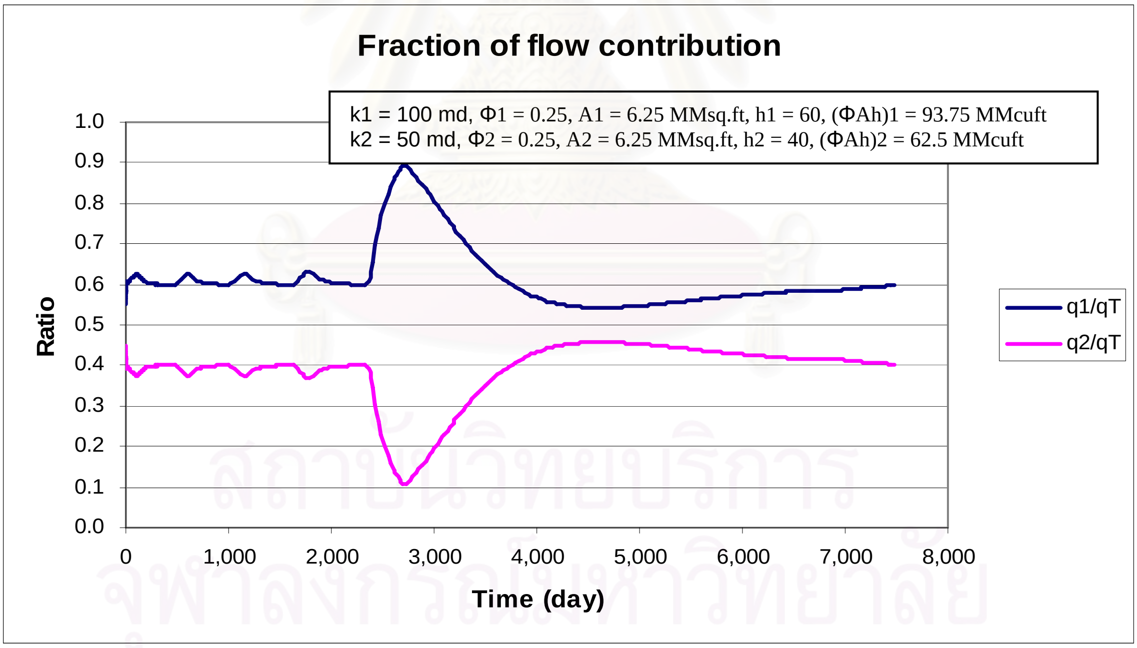


Figure 5-20 q_1/q_T and q_2/q_T ratios at various times with clear influence of ΦAh

(q_T = 100 STB/D, k_1h_1 = 6000 md-ft., k_2h_2 = 4000 md-ft)

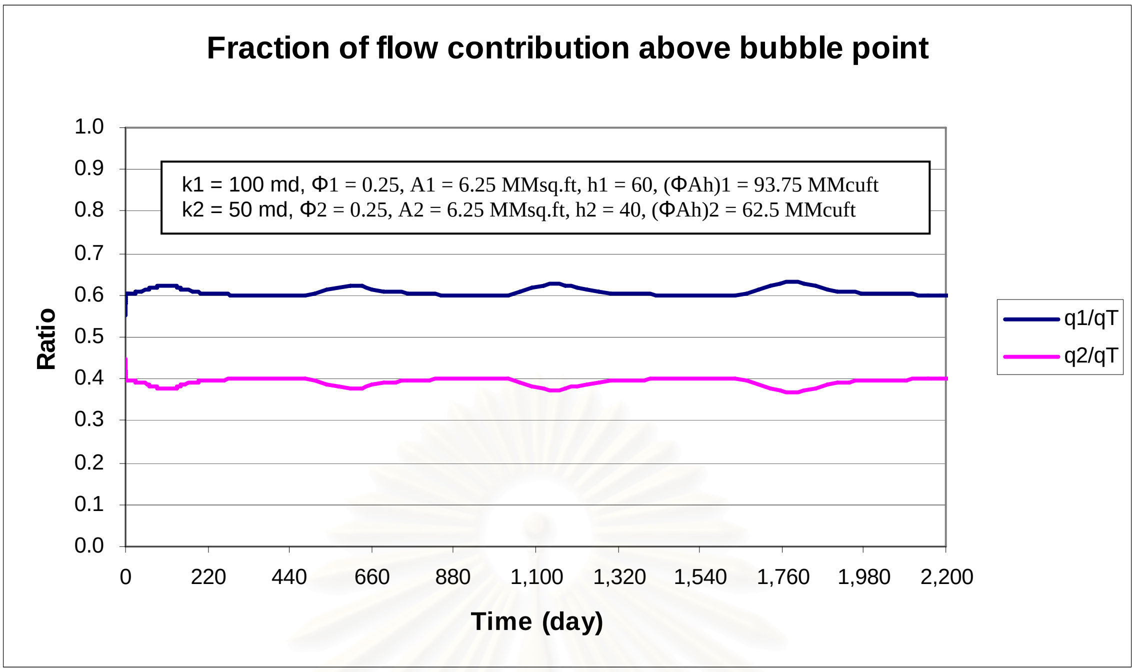


Figure 5-21 q_1/q_T and q_2/q_T ratios at early time with clear influence of ΦAh (q_T = 100 STB/D, k_1h_1 = 6000 md-ft., k_2h_2 = 4000 md-ft)

After solution gas is liberated from oil, influence of gas expansion over shadows influence of expansion of oil (with volume of ΦAh, neglecting expansion of connate water). Therefore, ΦAh is not the main controlling factor after the presence of free gas. Similar to these described in the previous section, after the presence of free gas, gas expansion, pressure depletion, and other fluid expansion all have influence on flow from a multilayer system. The conclusion is also similar.

However, in fact, it should be noted that for the case of high flow capacity (high kh) and flow into wells is limited with ΦAh being identified as a controlling factor, the real controlling factor is likely to be the energy available in each layer to push oil out. Comments on the available energy are discussed in the previous chapter is applicable here.

Figures 5-22 to 5-24 and 5-25 to 5-27 show other two systems that flow from a multilayer system is under the influence of ΦAh. Table 5-6 and 5-7 show rock and fluid properties for these two systems. The more cases for this part will be shown in Appendix D.

From the discussion, the following conclusions can be drawn:

1. ΦAh is a controlling factor for flow from the multilayer system when flow from each layer is lower than the flow capacity (kh) of each layer.
2. Influence of ΦAh is, in fact, exercised in the form of oil expansion.
3. Conclusions 3 to 6 in the previous section are also applicable here.

Table 5-6 Rock and fluid properties for system under influence of ΦAh (k_1h_1 = 30000 md-ft, k_2h_2 = 10000 md-ft, and q_T = 500 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	500	250
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	30000	10000
ΦAh, (MMcuft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	500	500
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

Table 5-7 Rock and fluid properties for system under influence of ΦAh (k_1h_1 = 3000 md-ft, k_2h_2 = 1000 md-ft, and q_T = 50 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	50	25
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	3000	1000
ΦAh, (MMcuft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	50	50
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

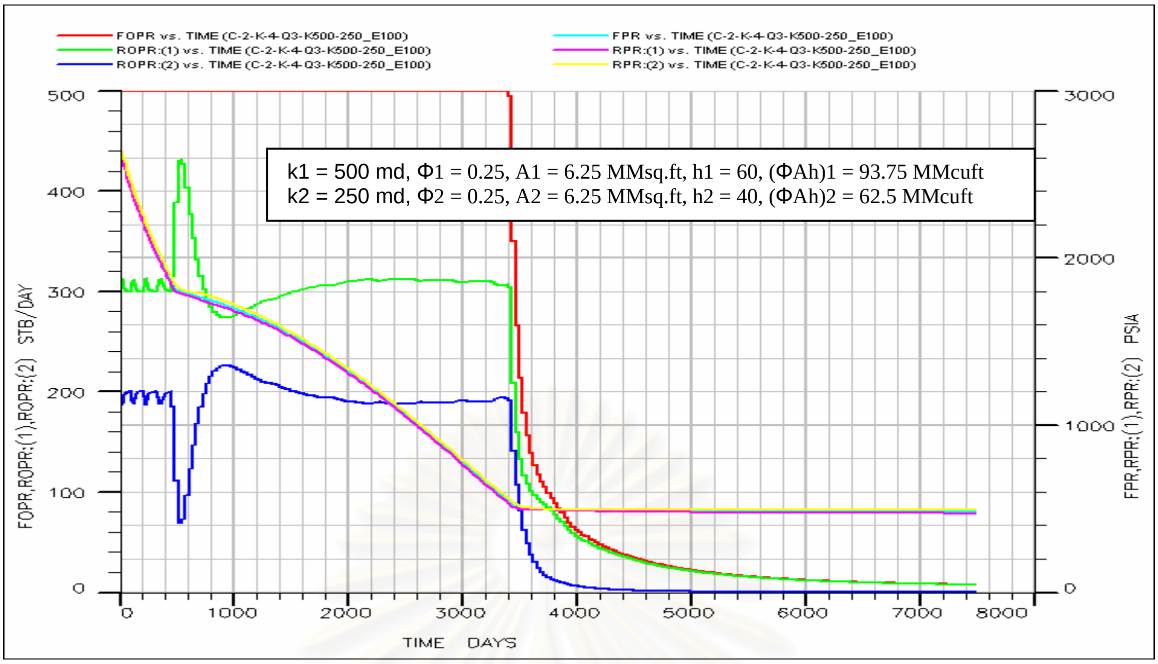


Figure 5-22 Flow from multilayer system partially under influence of ΦAh

(q_T = 500 STB/D, k_1h_1 = 30000 md-ft., k_2h_2 = 10000 md-ft)

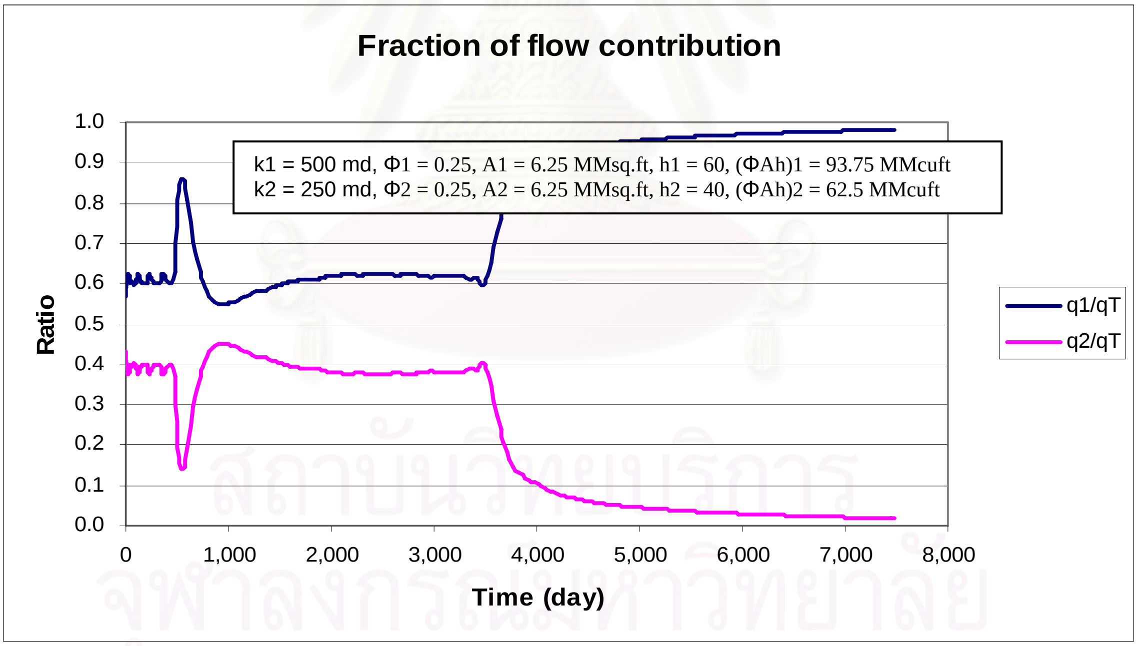


Figure 5-23 q_1/q_T and q_2/q_T ratios at various times with clear influence of ΦAh

(q_T = 500 STB/D, k_1h_1 = 30000 md-ft., k_2h_2 = 10000 md-ft)

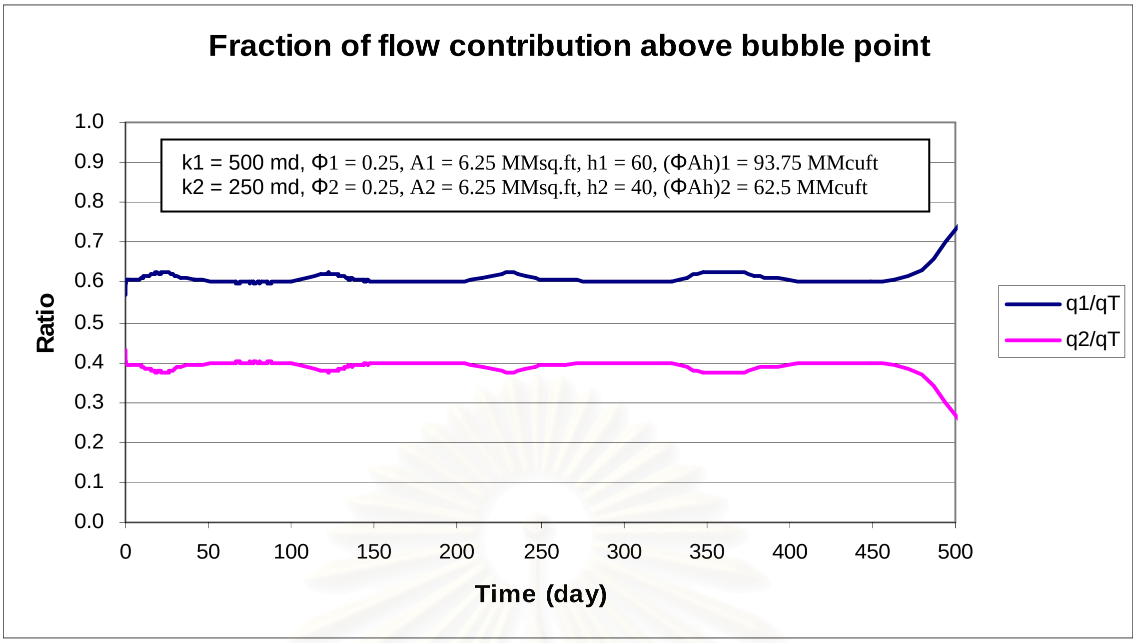


Figure 5-24 q_1/q_T and q_2/q_T ratios at early time with clear influence of ΦAh (q_T = 500 STB/D, k_1h_1 = 30000 md-ft., k_2h_2 = 10000 md-ft)

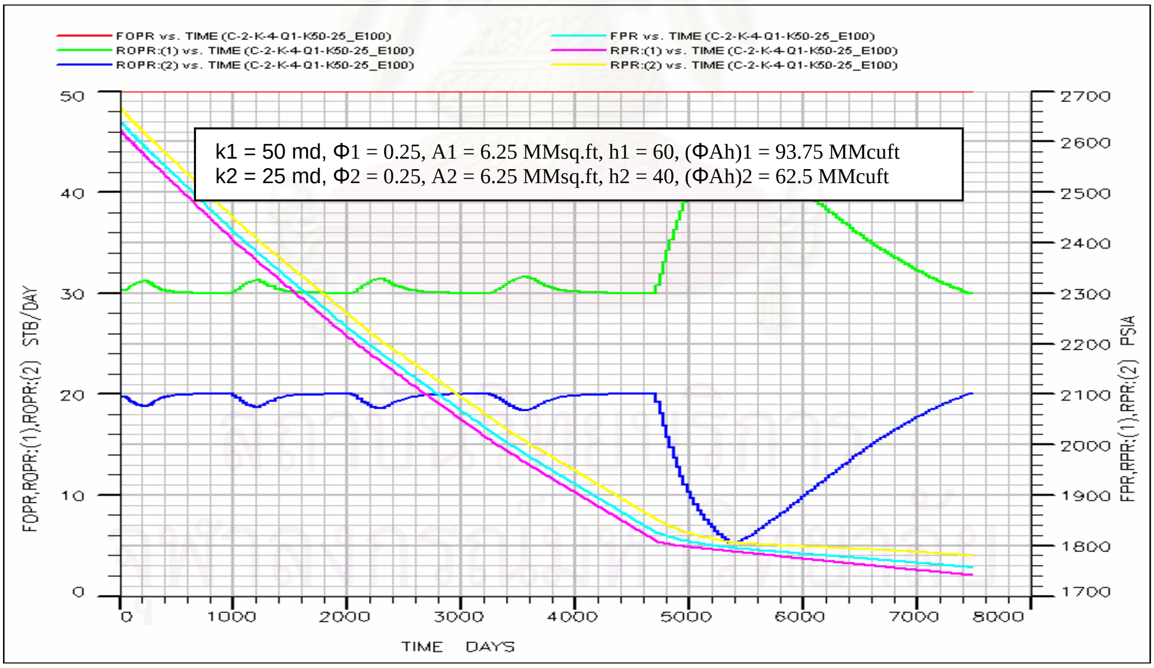


Figure 5-25 Flow from multilayer system partially under influence of ΦAh (q_T = 50 STB/D, k_1h_1 = 3000 md-ft., k_2h_2 = 1000 md-ft)

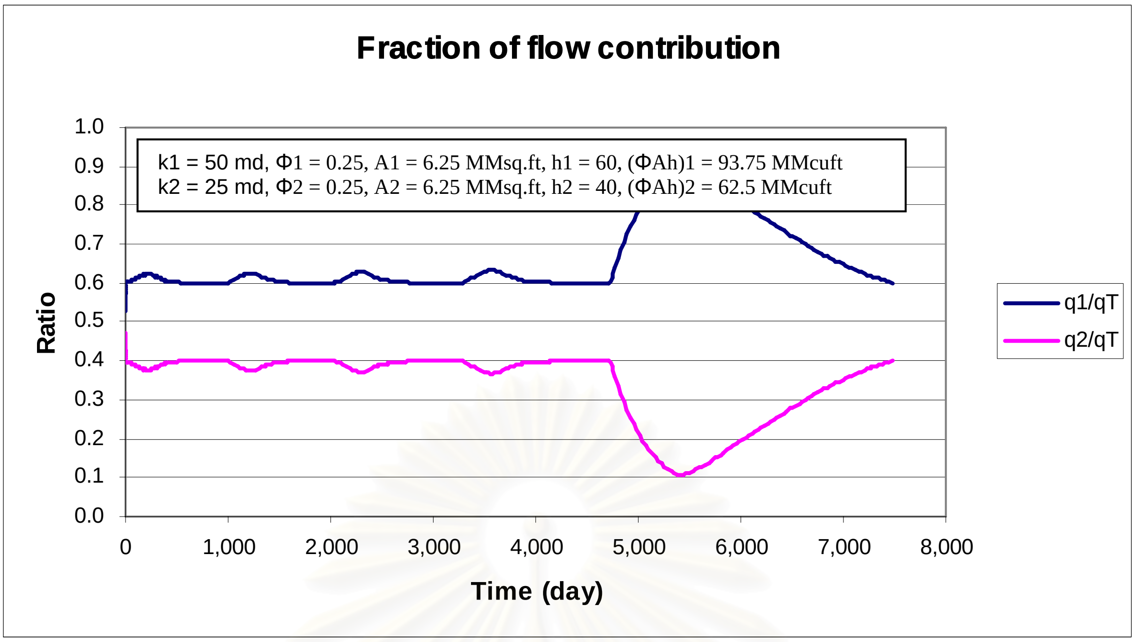


Figure 5-26 q_1/q_T and q_2/q_T ratios at various times with clear influence of ΦAh (q_T = 50 STB/D, k_1h_1 = 3000 md-ft., k_2h_2 = 1000 md-ft)

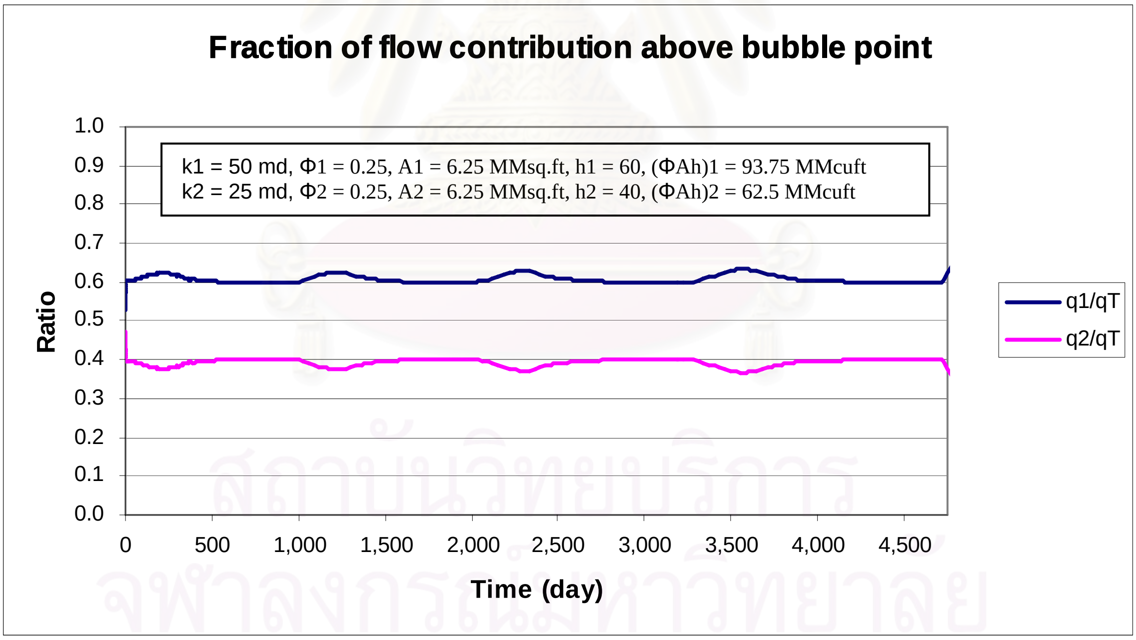


Figure 5-27 q_1/q_T and q_2/q_T ratios at early time with clear influence of ΦAh (q_T = 50 STB/D, k_1h_1 = 3000 md-ft., k_2h_2 = 1000 md-ft)

5.4 Three-layer system

The applications of several conclusions for two-layer system to more layers of the reservoir are investigated. The simple system to check the application is three-layer system. There are three permeable layers or sands and two impermeable shales. The general properties for two-layer system are applicable for this system. The cases are separated into two systems that are low kh value and sizable total flow rate case and high kh value and not too high total flow rate case.

In case that kh values are low and total flow rate is sizable Figure 5-28 shows oil flow rates and pressure for each layer and for the system. The rock and fluid properties use for this is shown in table 5-8. In this case, kh are low (k_1h_1 = 225 md-ft, k_2h_2 = 55 md-ft, and k_3h_3 = 93 md-ft) which total flow rate is set at 1000 STB/D. However, the set total flow rate of 1000 STB/D is too high for this system as can be seen from Figure 5-28 that the initial total flow rate form the system is only approximately 590 STB/D (q_1 = 350 STB/D, q_2 = 90 STB/D, and q_3 = 150 STB/D). This implies that flow rate from each layer is limited by its kh. Hence, flow from this system is controlled by kh. Figure 5-28 also shows that q_1, q_2, and q_3 continuously decrease with time. This implies pressure in each layer is also decreasing.

The ratio of layer flow rate to total flow rate, q_1/q_T, q_2/q_T, and q_3/q_T, are shown in Figures 5-29 and 5-30. It can be seen from Figure 5-29 which shows the ratios at early time that q_1/q_T are close to 0.6, q_2/q_T are close to 0.15, and q_3/q_T are close to 0.25 for same time, approximately less than 40 days. There are some erratic shapes as well as two-layer system in early. The explanation for this error of two-layer system can be applicable here, besides this error neglected. Hence, it can be said that during the period of 40 days, q_1/q_T, q_2/q_T, and q_3/q_T obey the kh rule. However, after 40 days, q_1/q_T and q_2/q_T deviate from the kh rule due to the previous reason from two-layer system.

Table 5-8 Rock and fluid properties for three-layer system under influence of kh

Properties	**Layer 1**	**Layer 2**	**Layer 3**
k, md	5	2.2	3.1
h, ft	45	25	30
Φ	0.25	0.25	0.25
A, (MMsq.ft)	6.25	6.25	6.25
kh, (md-ft)	225	55	93
ΦAh, (MMcuft)	70.31	39.06	46.88
Pi, (psia)	2610	2642	2653
μ_o, (cp)	0.62	0.62	0.62
Pb, (psia)	1800	1800	1800
API	35	35	35
OIIP, (MMSTB)	7.96	4.42	5.3
q_T, (STB/D)	1000	1000	1000
$k_1h_1/(k_1h_1+k_2h_2+k_3h_3)$	0.6	-	-
$k_2h_2/(k_1h_1+k_2h_2+k_3h_3)$	-	0.15	-
$k_3h_3/(k_1h_1+k_2h_2+k_3h_3)$	-	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2+\Phi_3A_3h_3)$	0.45	-	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2+\Phi_3A_3h_3)$	-	0.25	-
$\Phi_3A_3h_3/(\Phi_1A_1h_1+\Phi_2A_2h_2+\Phi_3A_3h_3)$	-	-	0.3

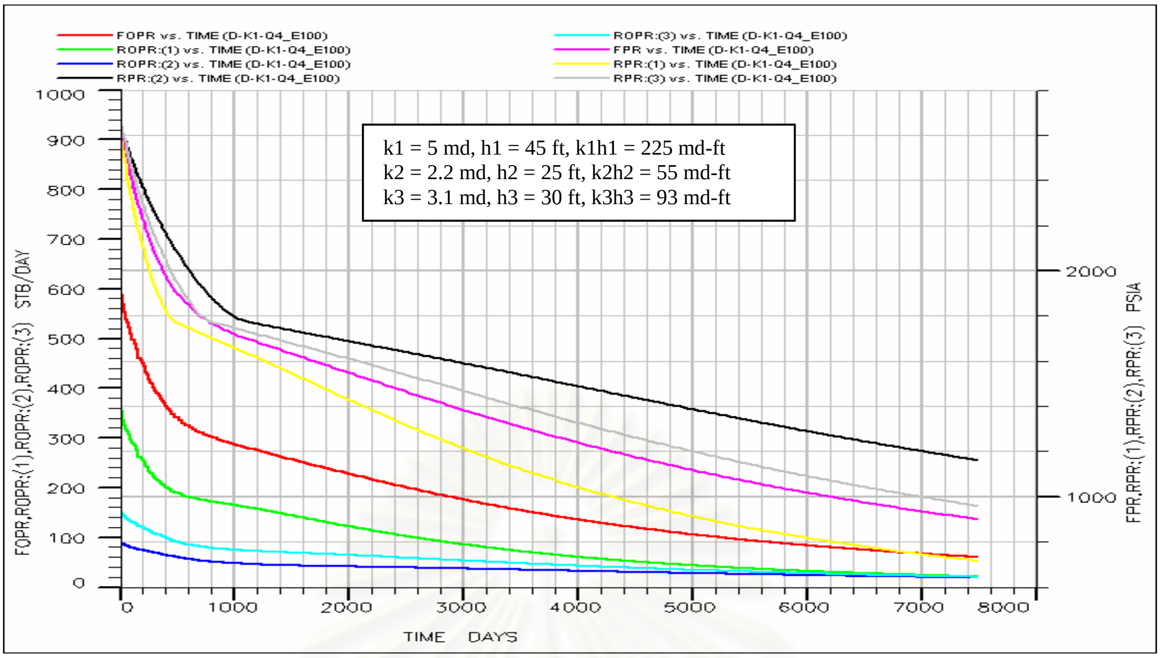


Figure 5-28 Flow from three-layer system partially under influence of kh (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 70.31 MMcuft, $(\Phi Ah)_2$ = 39.06 MMcuft, and $(\Phi Ah)_3$ = 46.88 MMcuft)

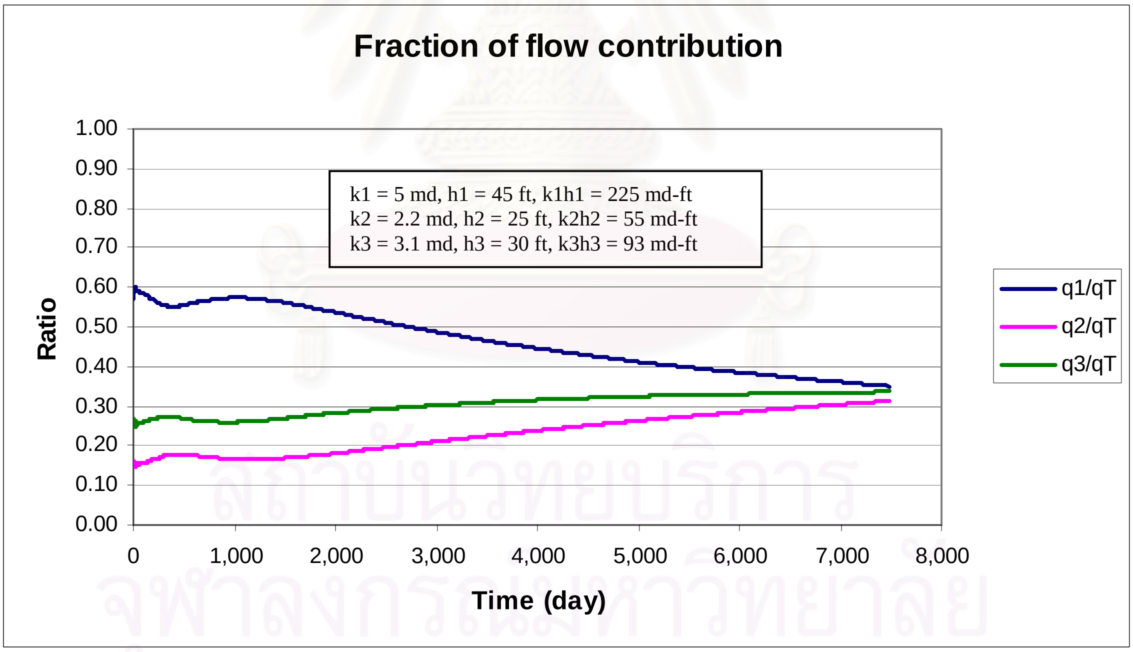


Figure 5-29 q_1/q_T and q_2/q_T ratios at various times (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 70.31 MMcuft, $(\Phi Ah)_2$ = 39.06 MMcuft, and $(\Phi Ah)_3$ = 46.88 MMcuft)

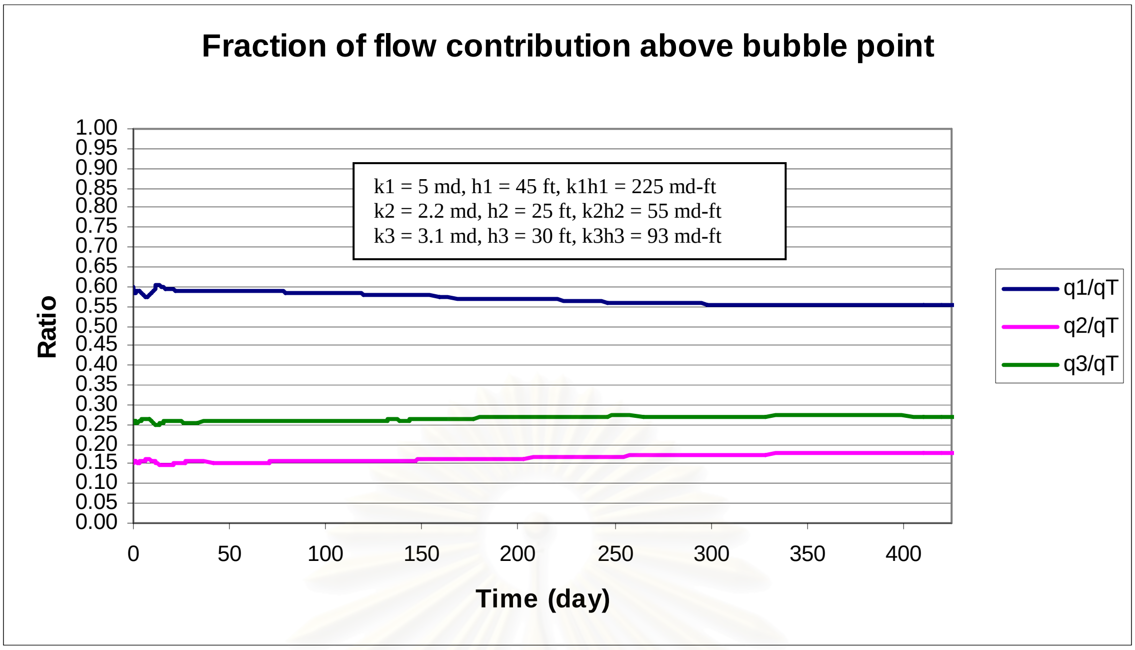


Figure 5-30 q_1/q_T and q_2/q_T ratios at early time (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 70.31 MMcuft, $(\Phi Ah)_2$ = 39.06 MMcuft, and $(\Phi Ah)_3$ = 46.88 MMcuft)

Figures 5-31 to 5-33 show clearly that ΦAh is the controlling factor during the period before solution liberated from the oil. Rock and fluid properties of the system being described are shown in Table 5-9. It should be noted that fluid properties for both layers are the same, hence effect of oil expansion is cancelled out and only ΦAh remaining.

Figures 5-31 to 5-33 show that before the presence of free gas in the reservoir, q_1/q_T = 0.45, q_2/q_T = 0.25, q_3/q_T = 0.3 and which are exactly equal to $(\Phi Ah)_1/(\Phi Ah)_T$ = 0.45, $(\Phi Ah)_2/(\Phi Ah)_T$ = 0.25, and $(\Phi Ah)_3/(\Phi Ah)_T$ = 0.3 respectively. In all these Figures, there are several short periods within the period that ΦAh is the controlling factor (up to approximately 2400 days) that the q_1/q_T, q_2/q_T, and q_3/q_T do not obey the ΦAh rule. It is not clear what cause this phenomenon. Because limited study time, this peculiar phenomenon is neglected. Therefore, it can conclude that under the condition described ΦAh is the controlling factor on flow from the multilayer system before the presence of free gas in the reservoir.

For understanding of abnormal phenomenon in more layer system, further study is required.

The conclusions for this section are as follow:

1. In case that kh as controlling factor the study can be applied for three-layer system.
2. In case that ΦAh as controlling factor the study can be applied for three-layer system.
3. The study is applicable for more layers in multilayer system.

Table 5-9 Rock and fluid properties for three-layer system under influence of ΦAh

Properties	Layer 1	Layer 2	Layer 3
k, md	500	220	310
h, ft	45	25	30
Φ	0.25	0.25	0.25
A, (MMsq.ft)	6.25	6.25	6.25
kh, (md-ft)	22500	5500	9300
ΦAh, (MMcuft)	70.31	39.06	46.88
Pi, (psia)	2610	2642	2653
μ_o, (cp)	0.62	0.62	0.62
Pb, (psia)	1800	1800	1800
API	35	35	35
OIIP, (MMSTB)	7.96	4.42	5.3
q_T, (STB/D)	100	100	100
$k_1h_1/(k_1h_1+k_2h_2+k_3h_3)$	0.6	-	-
$k_2h_2/(k_1h_1+k_2h_2+k_3h_3)$	-	0.15	-
$k_3h_3/(k_1h_1+k_2h_2+k_3h_3)$	-	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2+\Phi_3A_3h_3)$	0.45	-	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2+\Phi_3A_3h_3)$	-	0.25	-
$\Phi_3A_3h_3/(\Phi_1A_1h_1+\Phi_2A_2h_2+\Phi_3A_3h_3)$	-	-	0.3

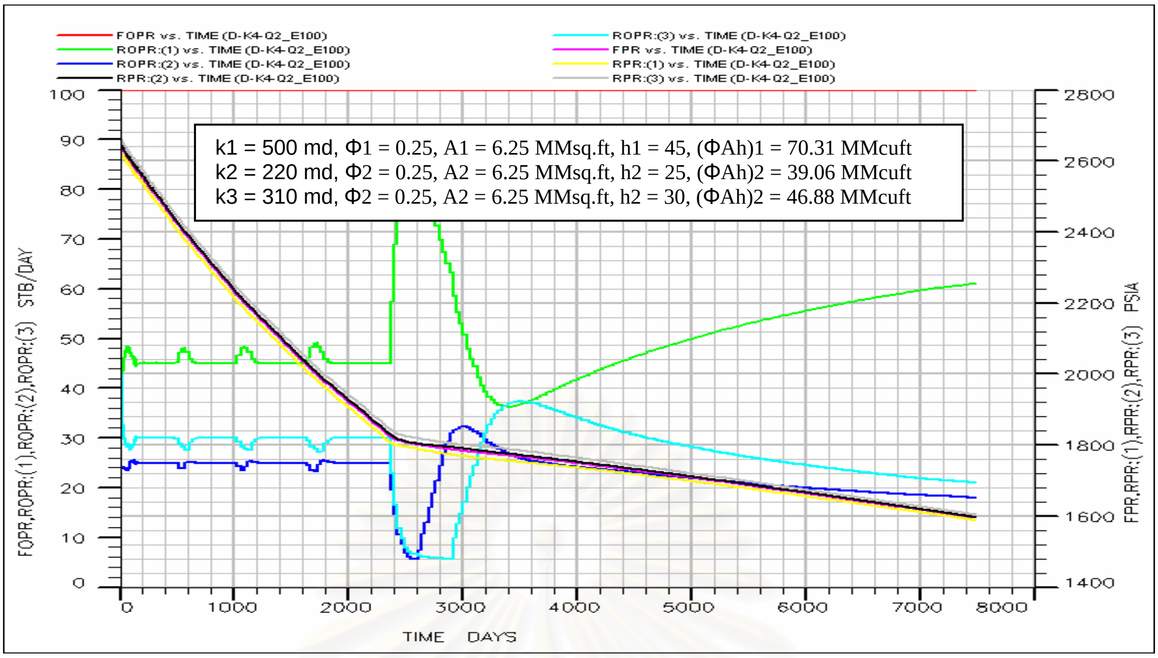


Figure 5-31 Flow from multilayer system partially under influence of ΦAh

(q_T = 100 STB/D, k_1h_1 = 22500 md-ft., k_2h_2 = 5500 md-ft, and k_3h_3 = 9300 md-ft)

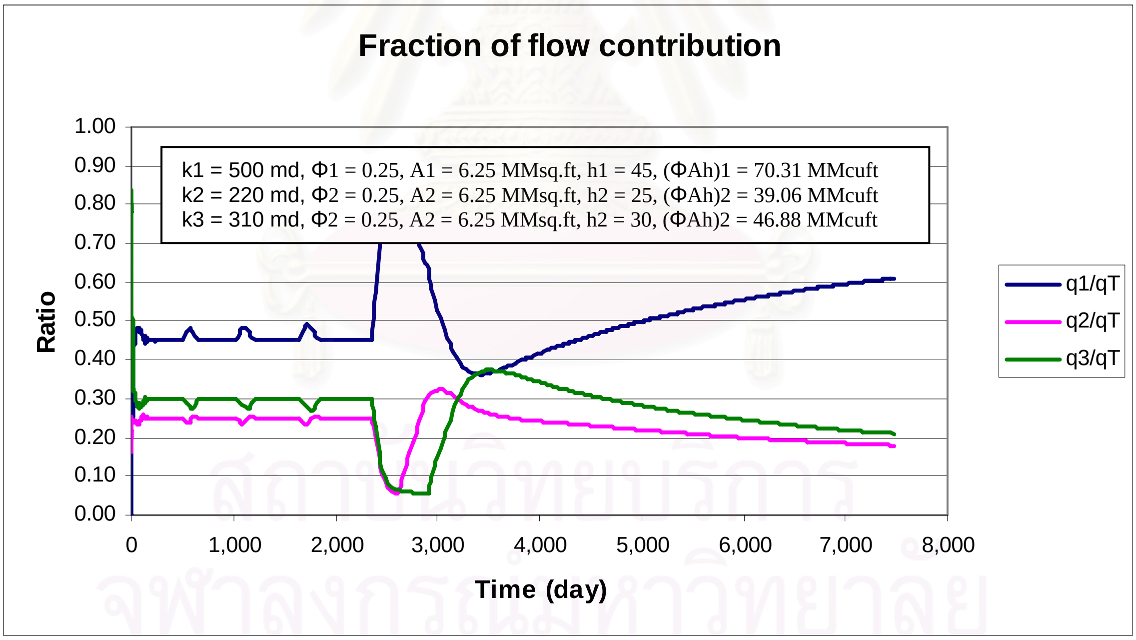


Figure 5-32 q_1/q_T and q_2/q_T ratios at various times with clear influence of ΦAh

(q_T = 100 STB/D, k_1h_1 = 22500 md-ft., k_2h_2 = 5500 md-ft, and k_3h_3 = 9300 md-ft)

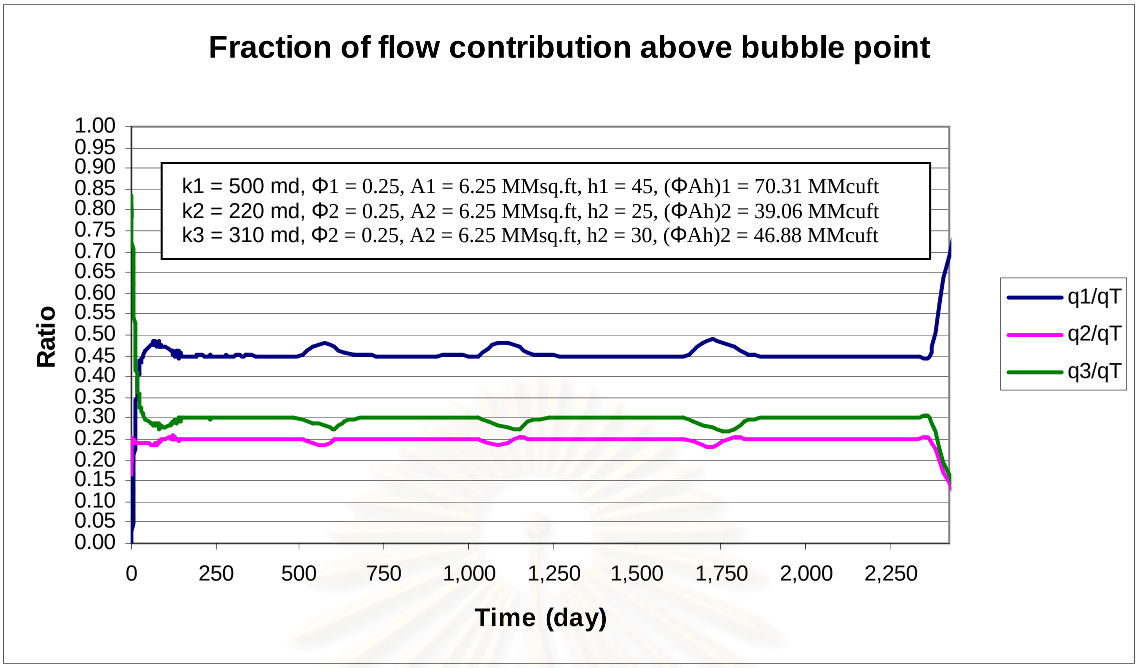


Figure 5-33 q_1/q_T and q_2/q_T ratios at early time with clear influence of ΦAh (q_T = 100 STB/D, k_1h_1 = 22500 md-ft., k_2h_2 = 5500 md-ft, and k_3h_3 = 9300 md-ft)

5.5 Effect of fluid properties

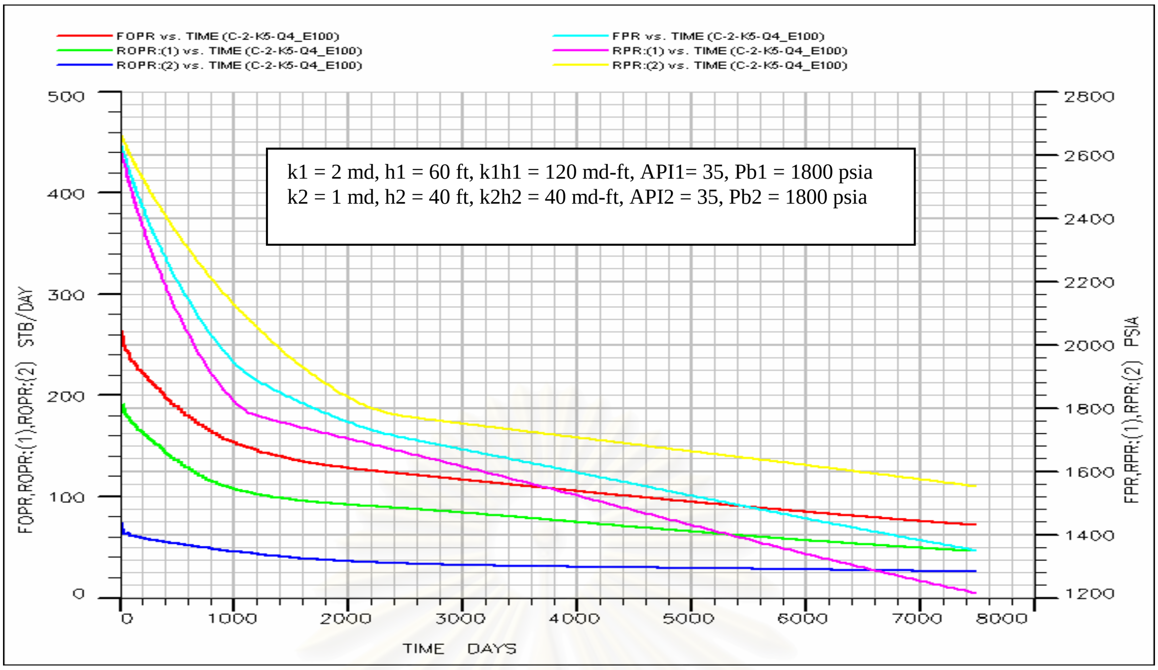
The applications of various conclusions for two-layer system and three-layer system to the difference of fluid properties are investigated. The differences of fluid properties of the system, while fluid properties of each layer are the same, are studied in the two-layer system. The studies are separated into two cases that are kh as controlling factor system and ΦAh as controlling factor system. The variable parameter values for this section are shown in table 5-10.

Figure 5-34 to 5-36 show flow rate of each layer and the ratio of layer flow rate to total flow rate of two systems which have the fluid property value for each layer but different fluid property values for each system.

Figure 5-34 shows that with various values fluid properties that are API and Pb are different for each system. The system that has API = 35 and Pb = 1800 psia has already concluded in case of kh as controlling factor. Another system has API = 30 and Pb = 1600 psia. Figure 5-35 confirms the mentioned conclusions as the ratios q_1/q_T and q_2/q_T for each system are the same for early time period (less than 2000 days). However, after 2000 days the ratios of q_1/q_T and q_2/q_T for each system start being different because of probably influence of presence of free gas and pressure depletion.

Table 5-10 Rock and fluid properties for studying effect of fluid under influence of kh

Properties	**Layer 1**	**Layer 2**
k, md	2	1
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	120	40
ΦAh, (MMcu.ft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62, 0.954	0.62, 0.954
Pb, (psia)	1600, 1800	1600, 1800
API	30, 35	30, 35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	1000	1000
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4



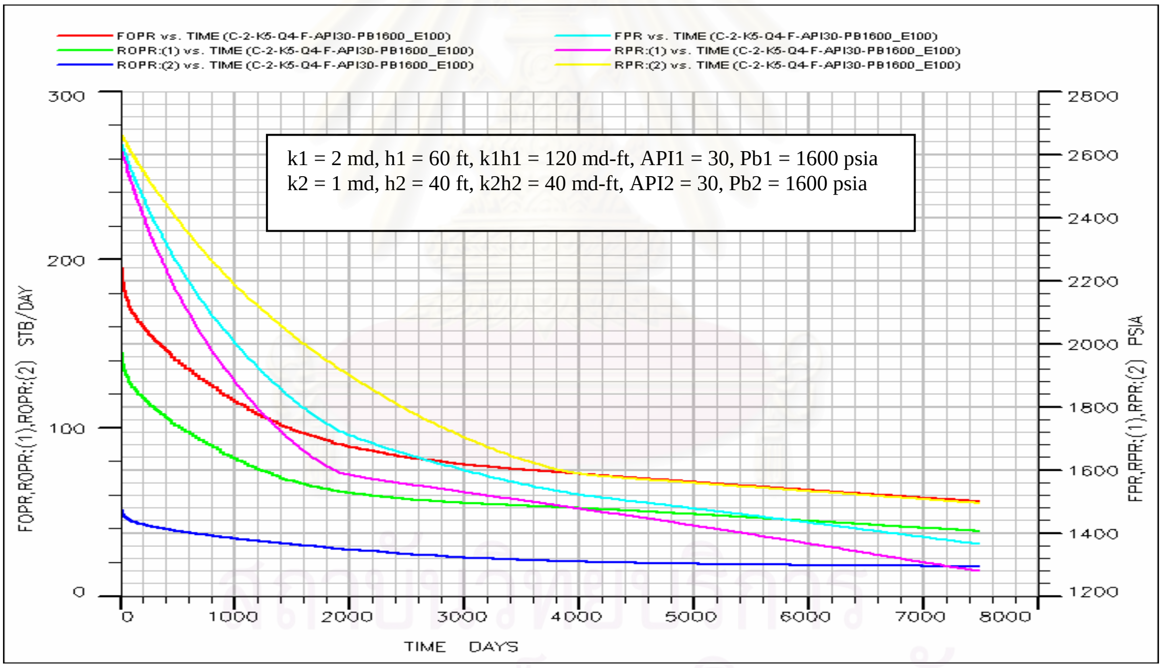


Figure 5-34 Layer flow rates (green and blue) obeying kh rule and not affected by difference of fluid properties (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

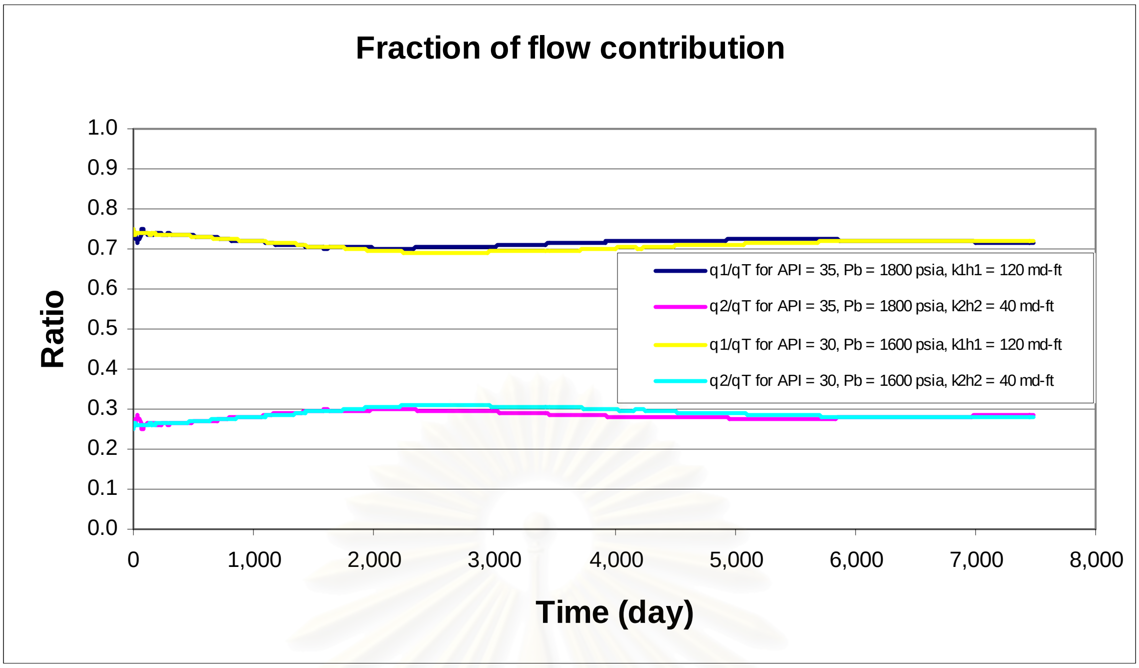


Figure 5-35 q_1/q_T and q_2/q_T ratios obeying kh rule and not affected by difference of fluid properties (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

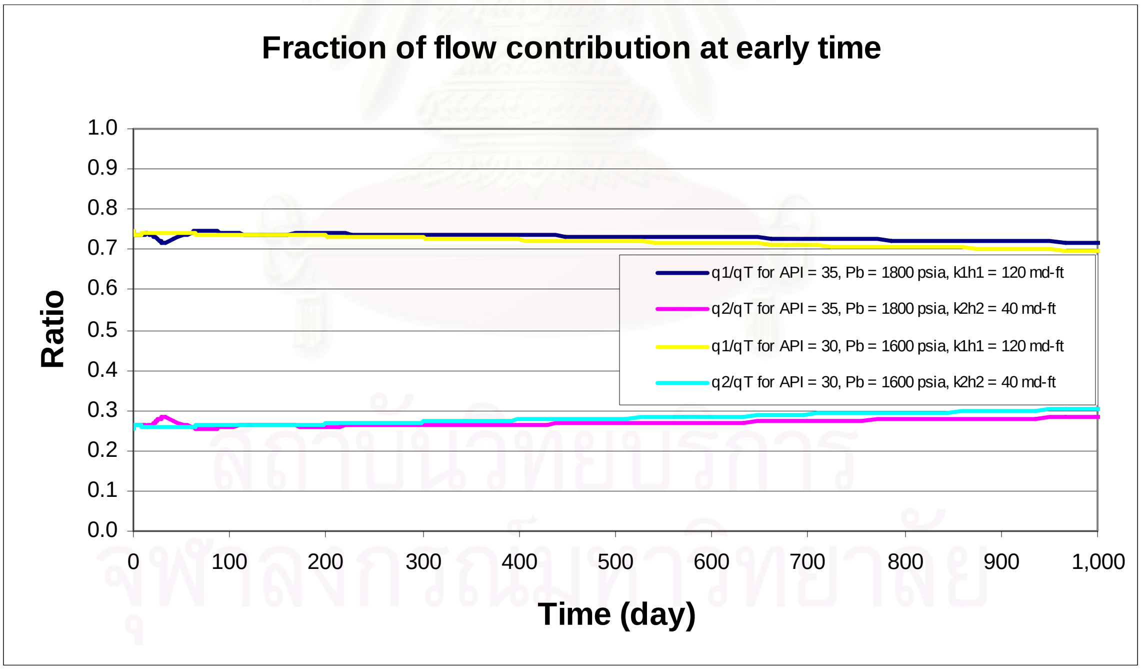


Figure 5-36 q_1/q_T and q_2/q_T ratios at early time (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft)

Table 5-11 shows the rock and fluid properties for studying effect of fluid properties under influence of ΦAh. Figure 5-37 shows flow rate of each layer and total flow rate. It can be seen that the difference of fluid properties of each system is the same as long as ΦAh of each layer is the same. The region of ripple shapes are neglected as mentioned conclusions, so the regions outside the regions of ripple shapes between two systems are investigated for studying effect of fluid properties.

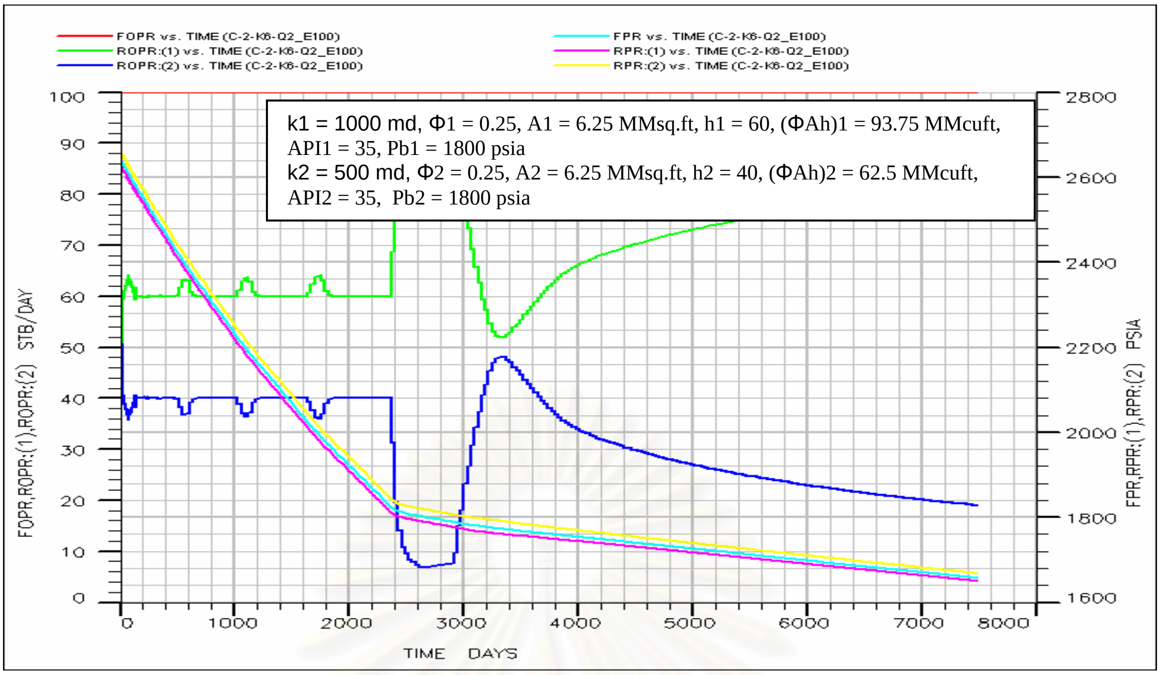
Figure 5-38 shows q_1/q_T and q_2/q_T ratios of both systems q_1/q_T and q_2/q_T ratios obey the ΦAh rule in the period before presence of free gas (less than 650 days), neglecting the ripple shape regions and the very early region where another peculiarity in observes.

Figure 5-39 further concluded that when the fractional flow of each region obeys the ΦAh rule, it will not be affected by difference of fluid properties between two systems.

The conclusion is that there is effect of fluid properties to flow from each layer, but flow contribution is still under influence of kh or ΦAh.

Table 5-11 Rock and fluid properties for studying effect of fluid under influence of ΦAh

Properties	Layer 1	Layer 2
k, md	1000	500
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	60000	20000
ΦAh, (MMcu.ft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62, 0.954	0.62, 0.954
Pb, (psia)	1600, 1800	1600, 1800
API	30, 35	30, 35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	100	100
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4



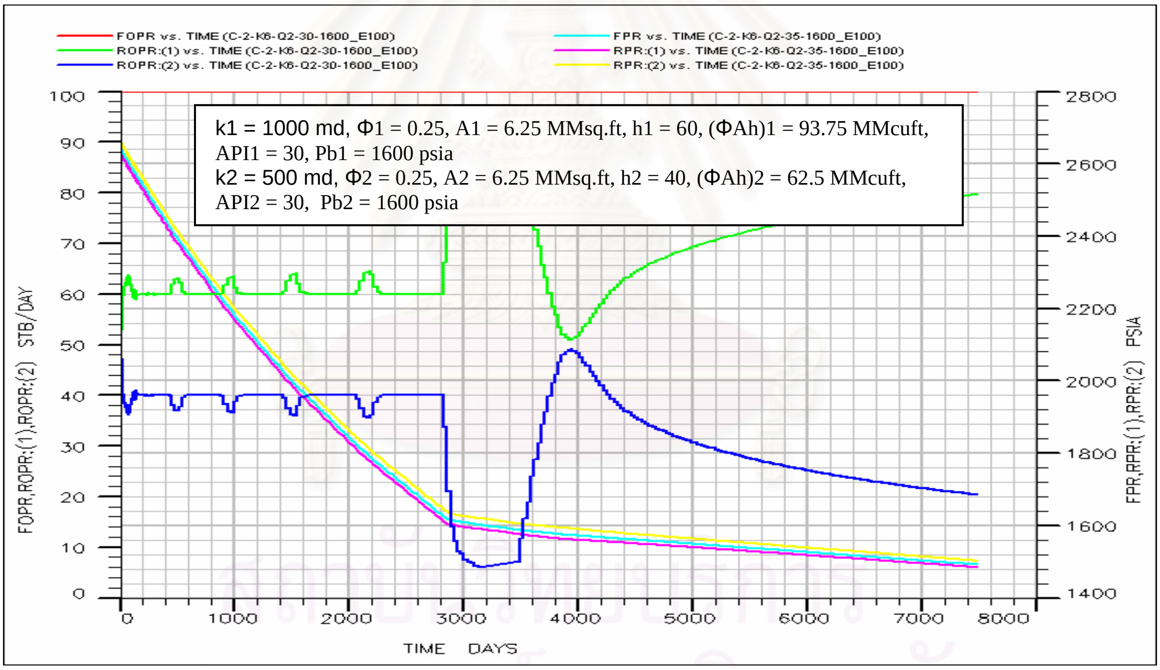


Figure 5-37 Layer flow rate obeying ΦAh rule and not affected by difference of fluid properties (q_T = 100 STB/D, k_1h_1 = 60000 md-ft., k_2h_2 = 20000 md-ft)

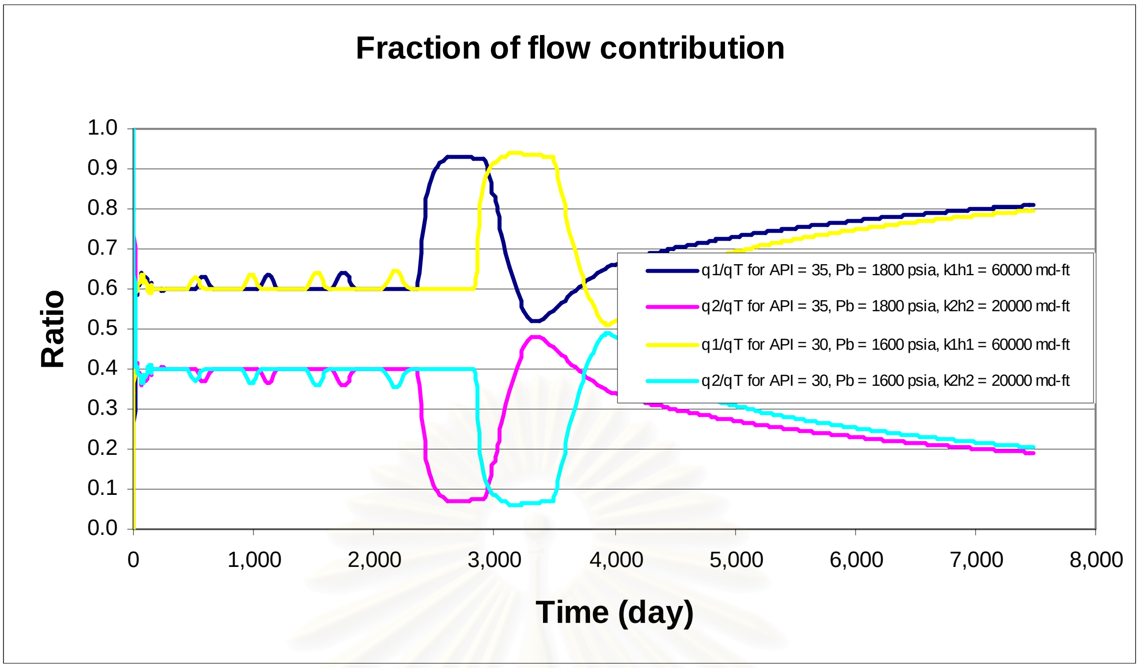


Figure 5-38 q_1/q_T and q_2/q_T ratios obeying ΦAh rule and not affected by difference of fluid properties (q_T = 100 STB/D, k_1h_1 = 60000 md-ft., k_2h_2 = 20000 md-ft)

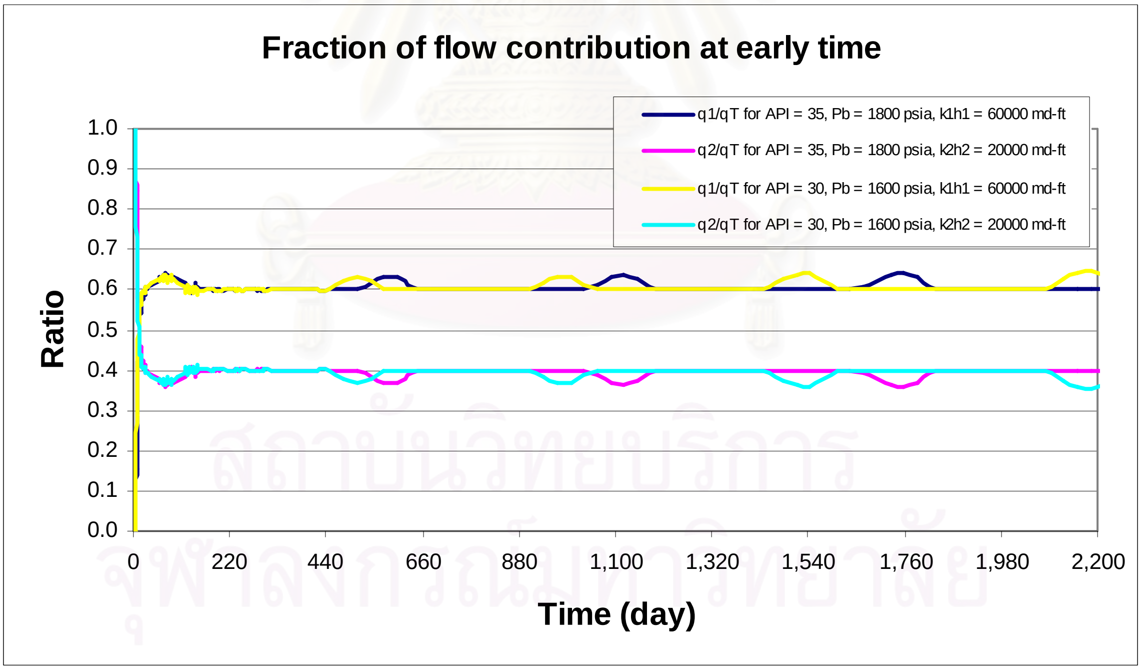


Figure 5-39 q_1/q_T and q_2/q_T ratios at early time (q_T = 100 STB/D, k_1h_1 = 60000 md-ft., k_2h_2 = 20000 md-ft)

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

This study is intended to investigate flow contribution of each layer in oil multi-layer system. The conditions that kh rule can be applied is demonstrated. The controlling factors and influence of them are illustrated in case that kh rule cannot be applied. The two-layer system is mainly studied for investigation of various cases for this study. Three-layer system is studied for test of application of this study.

Two controlling factors that are emphatically studied are kh and ΦAh. However, the individual parameters of these controlling factors are investigated. The details of conclusions are as follow:

1. Each parameter in kh and ΦAh does not individually affect flow contribution of each layer.
2. kh is a controlling factor for flow contribution when the flow is at fully flow capacity and at the starting period of production time
3. ΦAh is a controlling factor for flow contribution when the flow from multilayer system is lower than flow capacity. In addition, the influence of ΦAh as controlling factor affects flow contribution due to oil expansion.
4. The other controlling factors affecting flow contribution are presence of free gas, pressure depletion, and expandable fluid.
5. The kh that is one of controlling factors is not related to the available energy in the reservoir while the other factors are.
6. The conditions that flow contribution obeys either kh or ΦAh rule can be applied for more layers in multilayer system.
7. There is effect of fluid properties to flow contribution for each system, but flows from each layer are under influence of either kh rule or ΦAh rule.
8. For understanding of how available energy influences flow contribution the further study is required.
9. Further study is needed in some cases of abnormal phenomenon, e.g. ripple shape, erratic shape.
10. The flow contributions that is controlled by neither kh nor ΦAh obviously are investigated next study.

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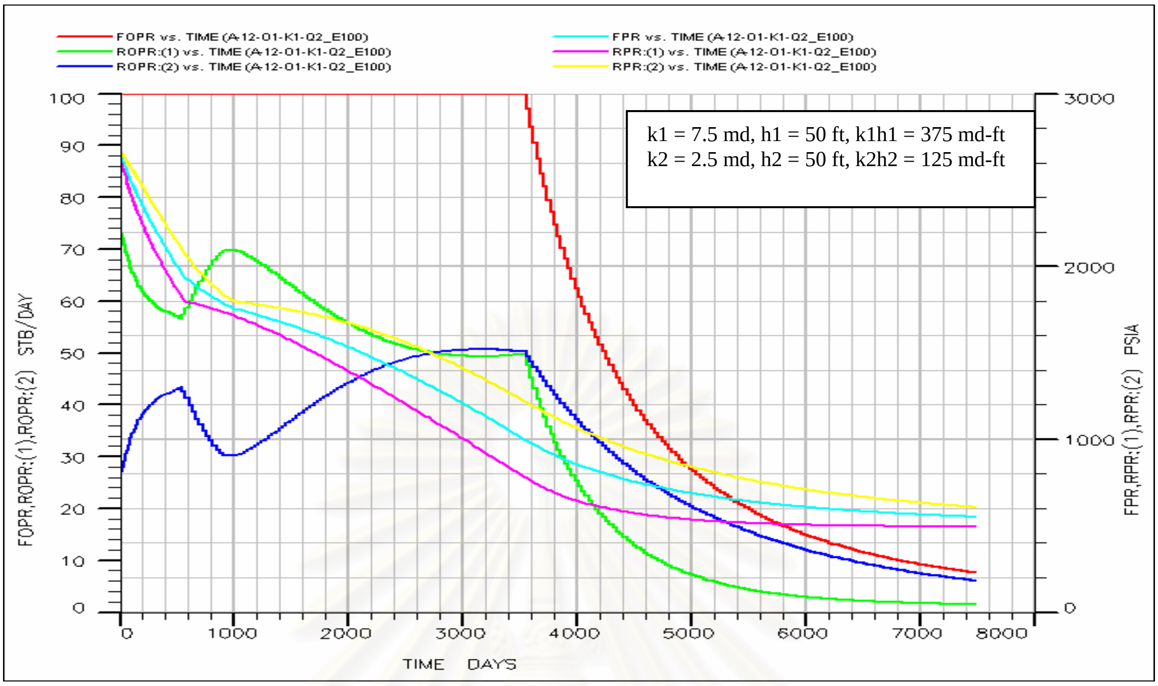
APPENDICES

APPENDIX A

ADDITIONAL CASES FROM kh AS A CONTROLLING FACTOR (5.1.1)



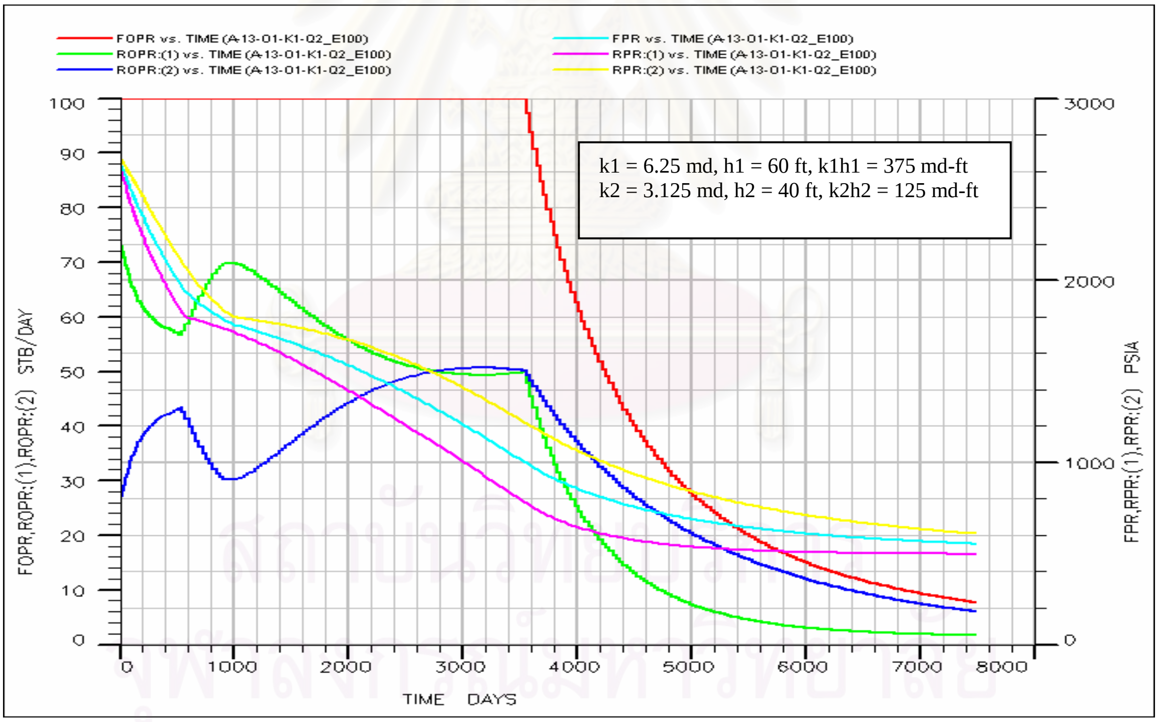


Figure A-1 Layer flow rates obeying kh rule and not affected by individual value of k or h (q_T = 100 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

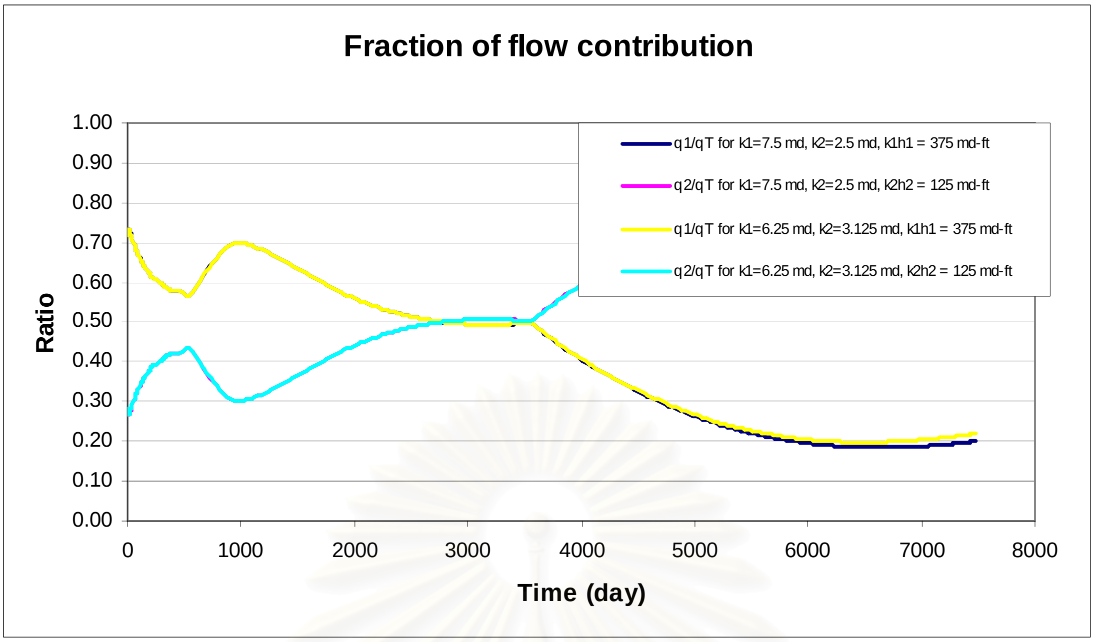


Figure A-2 q_1/q_T and q_2/q_T ratios obeying kh rule and not affected by individual value of k or h (q_T = 100 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

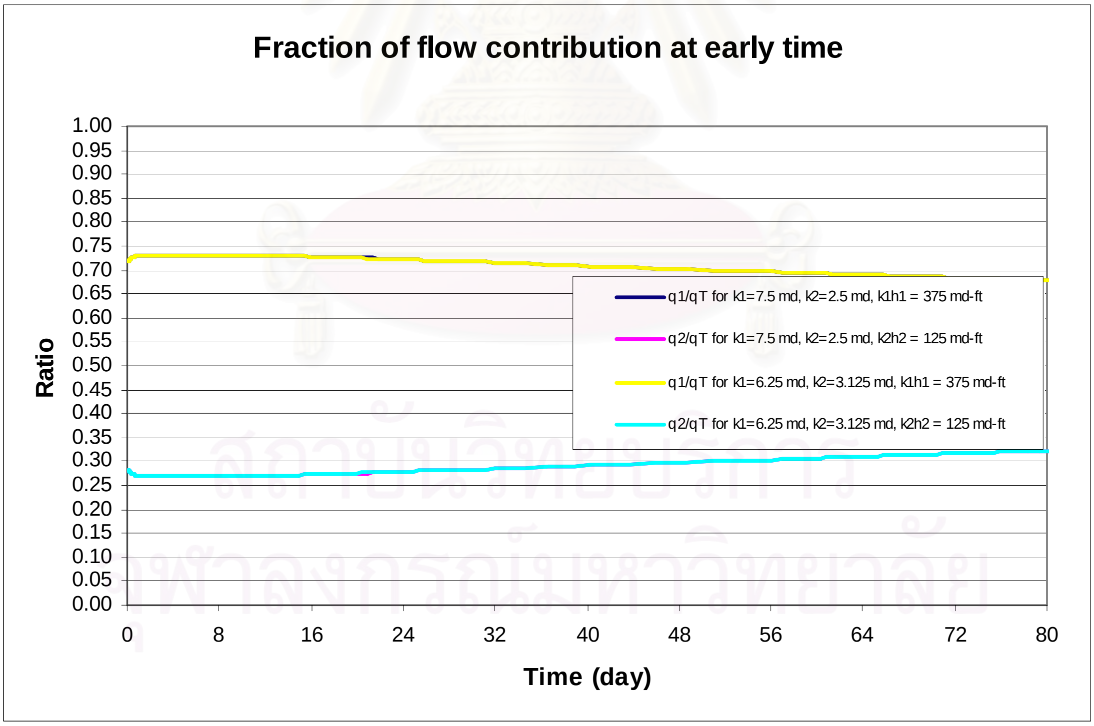
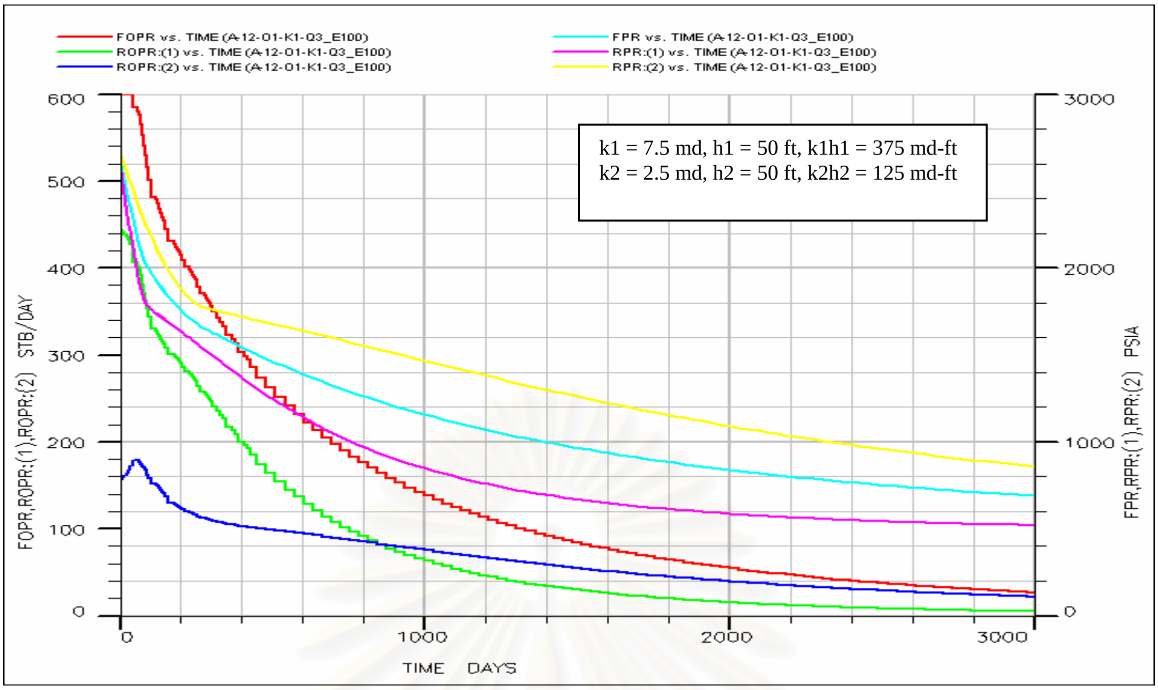


Figure A-3 q_1/q_T and q_2/q_T ratios at early time (q_T = 100 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)



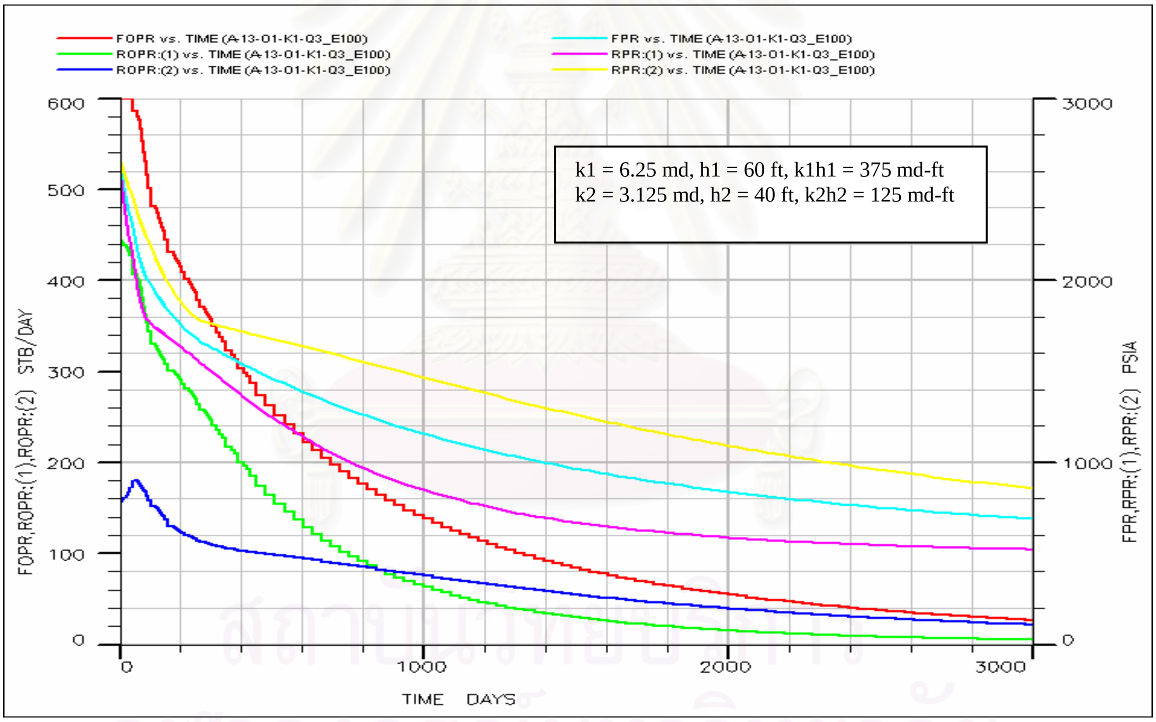


Figure A-4 Layer flow rates obeying kh rule and not affected by individual value of k or h (q_T = 600 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

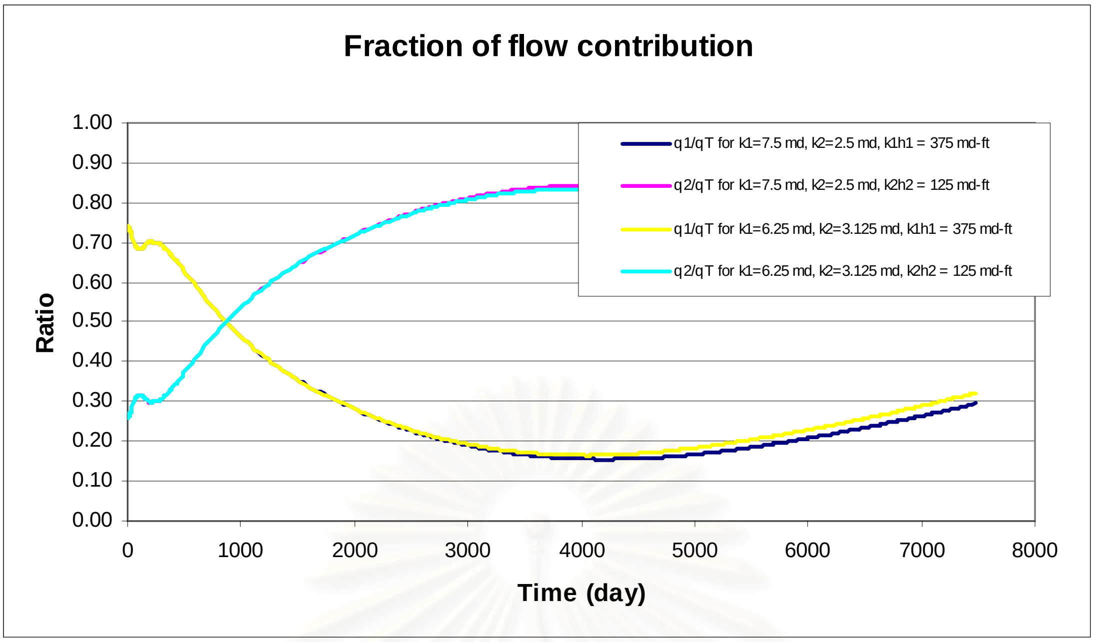


Figure A-5 q_1/q_T and q_2/q_T ratios obeying kh rule and not affected by individual value of k or h (q_T = 600 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

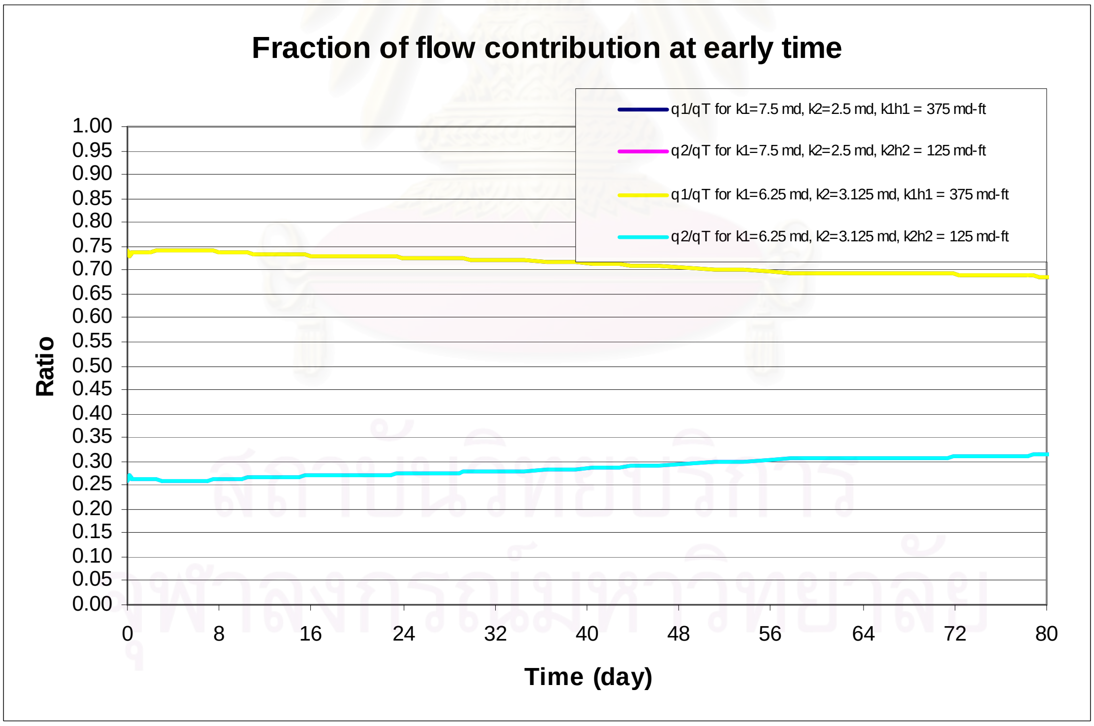


Figure A-6 q_1/q_T and q_2/q_T ratios at early time (q_T = 600 STB/D, $(\Phi Ah)_1$ = 22.36 MMcuft, $(\Phi Ah)_2$ = 22.36 MMcuft)

APPENDIX B

ADDITIONAL CASES FROM ΦAh AS A CONTROLLING FACTOR (5.1.2)

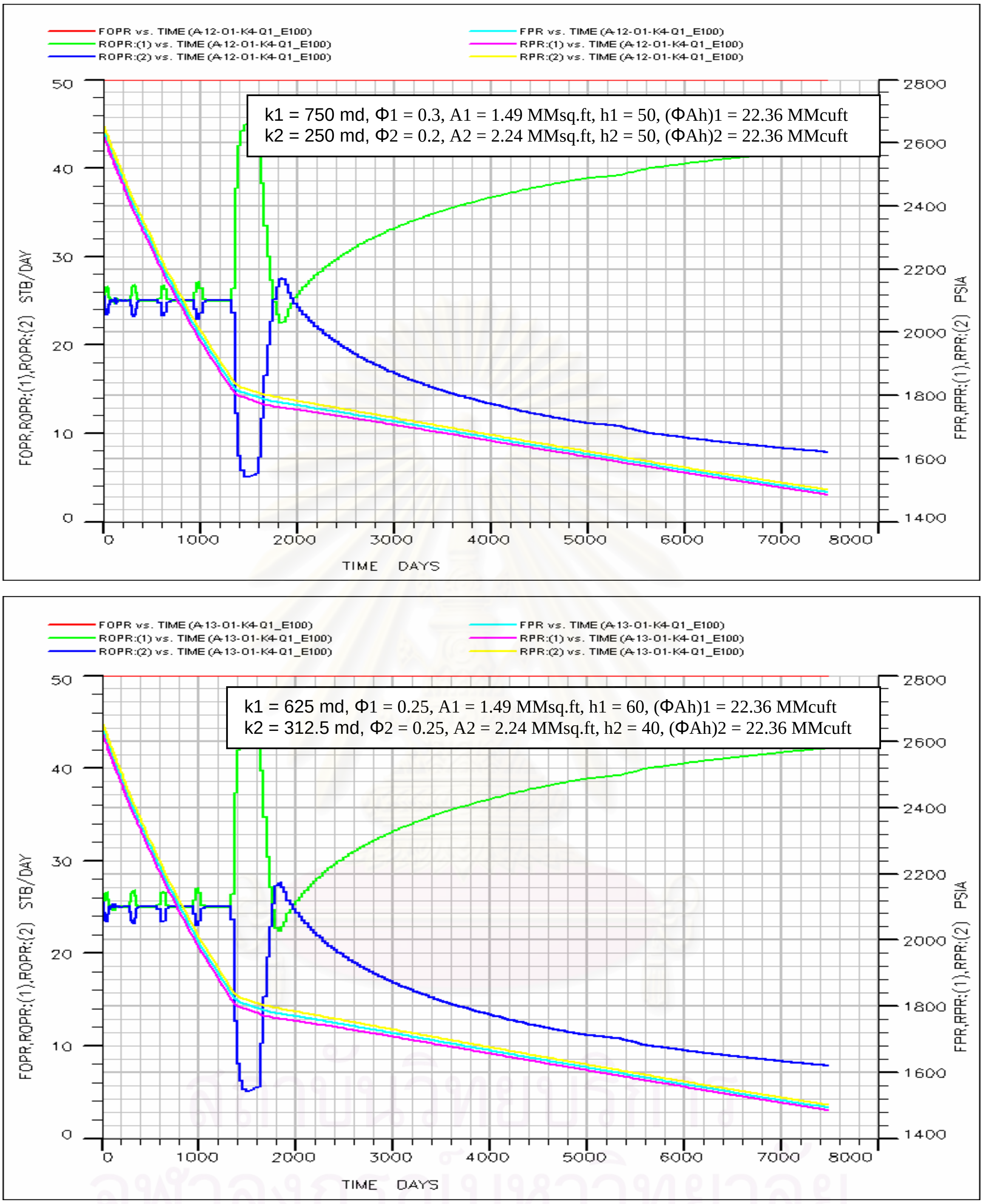


Figure B-1 Layer flow rate obeying ΦAh rule and not affected by individual value of Φ, A, or h (q_T = 50 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

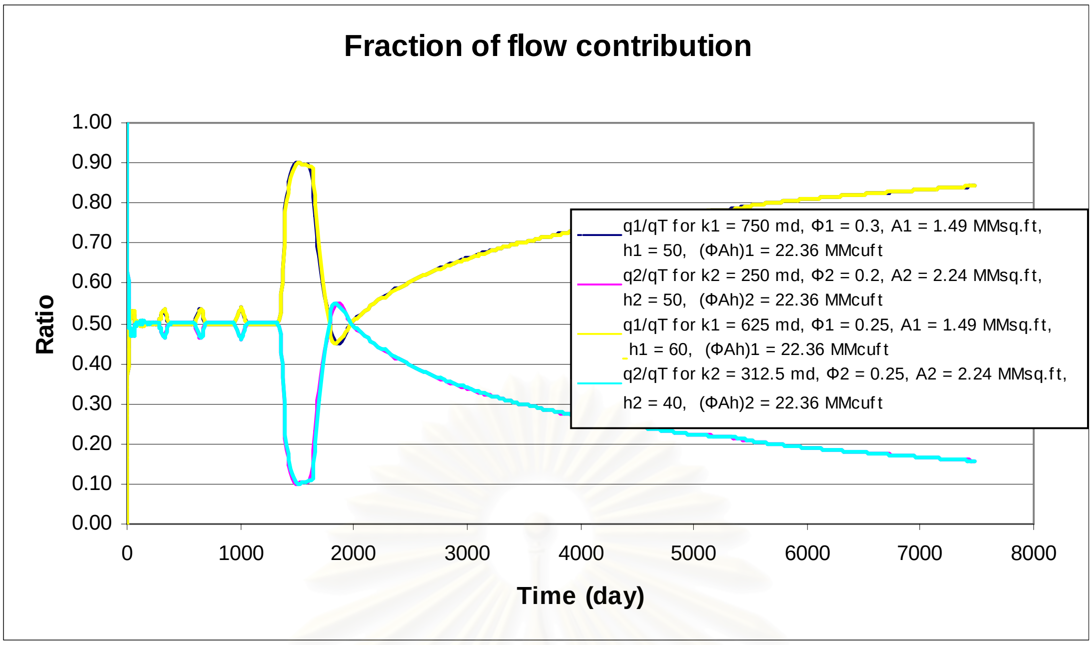


Figure B-2 q_1/q_T and q_2/q_T ratios obeying ΦAh rule and not affected by individual value of Φ, A, or h (q_T = 50 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

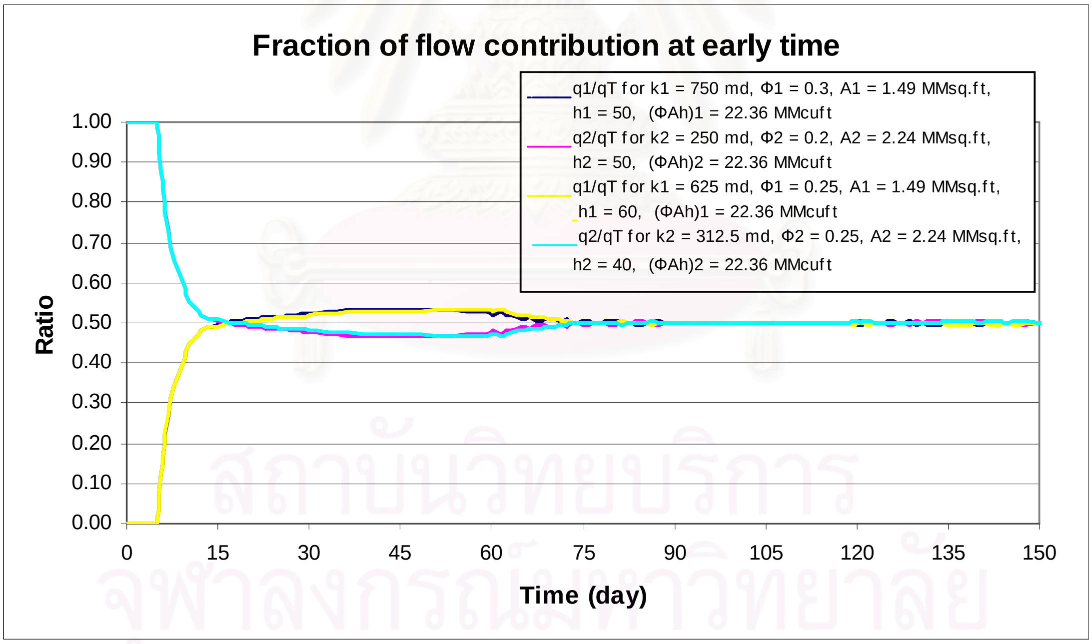
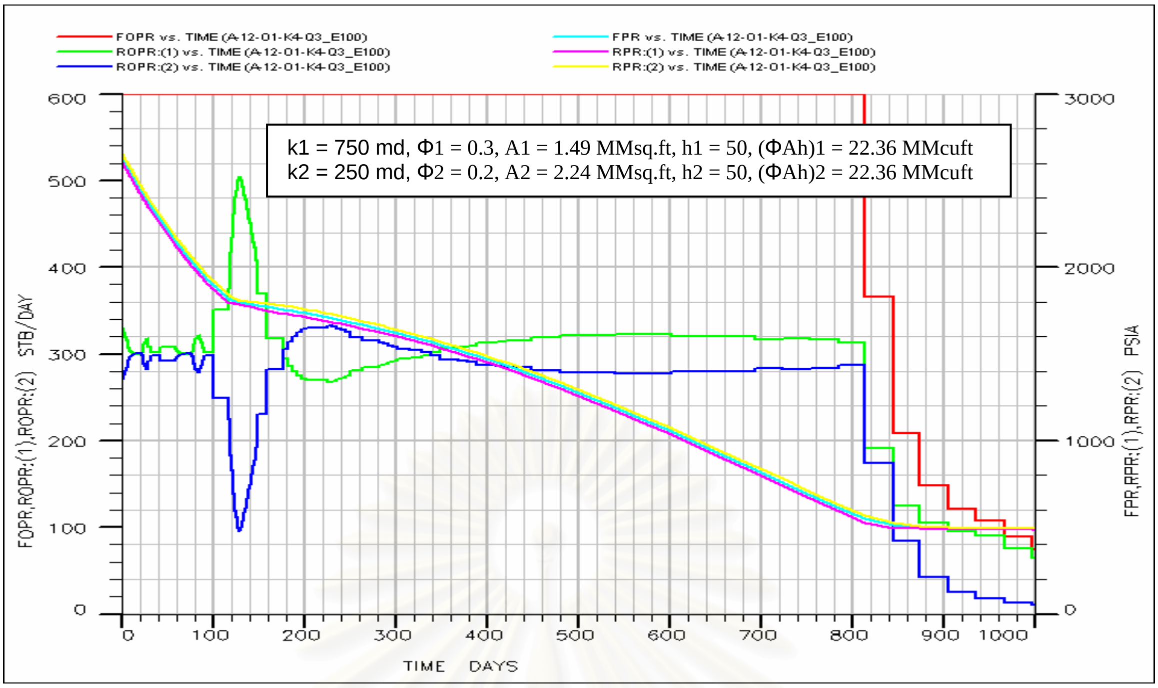


Figure B-3 q_1/q_T and q_2/q_T ratios at early time (q_T = 50 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)



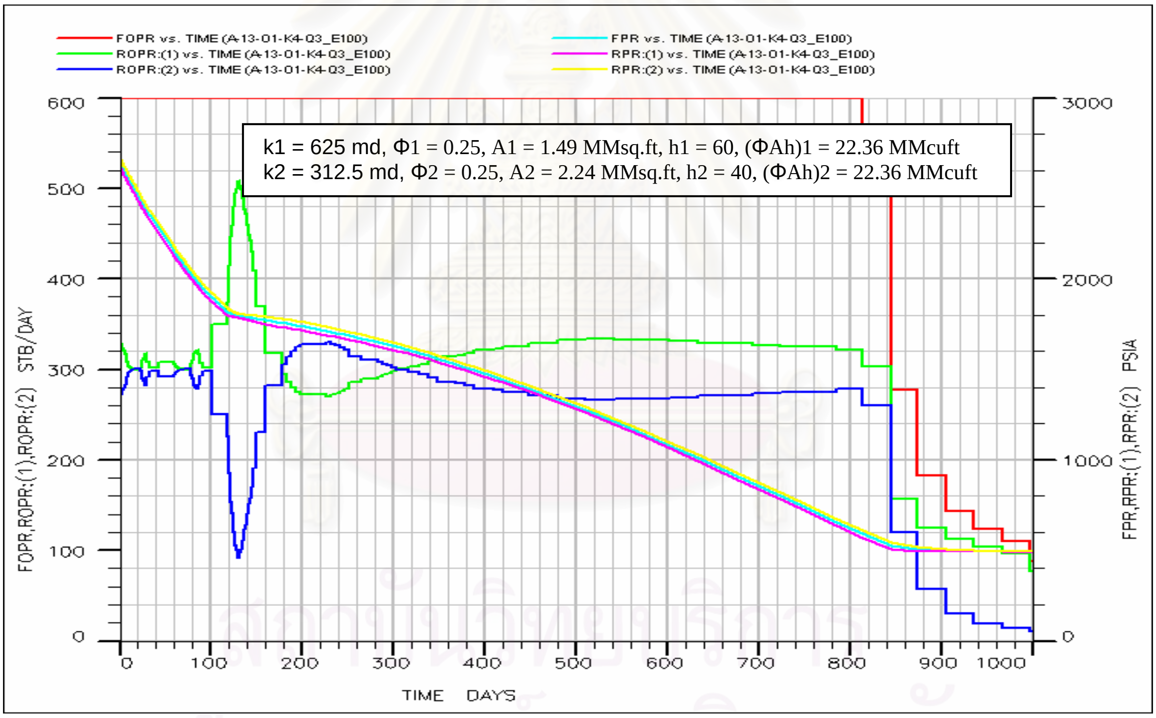


Figure B-4 Layer flow rate obeying ΦAh rule and not affected by individual value of Φ, A, or h (q_T = 600 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

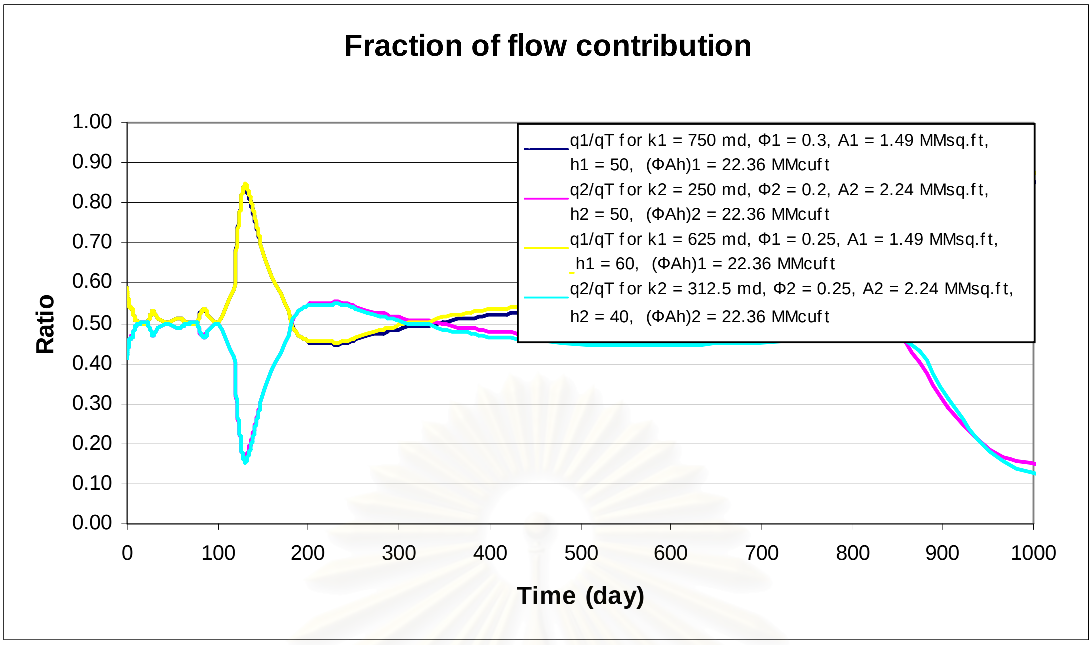


Figure B-5 q_1/q_T and q_2/q_T ratios obeying ΦAh rule and not affected by individual value of Φ, A, or h (q_T = 600 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

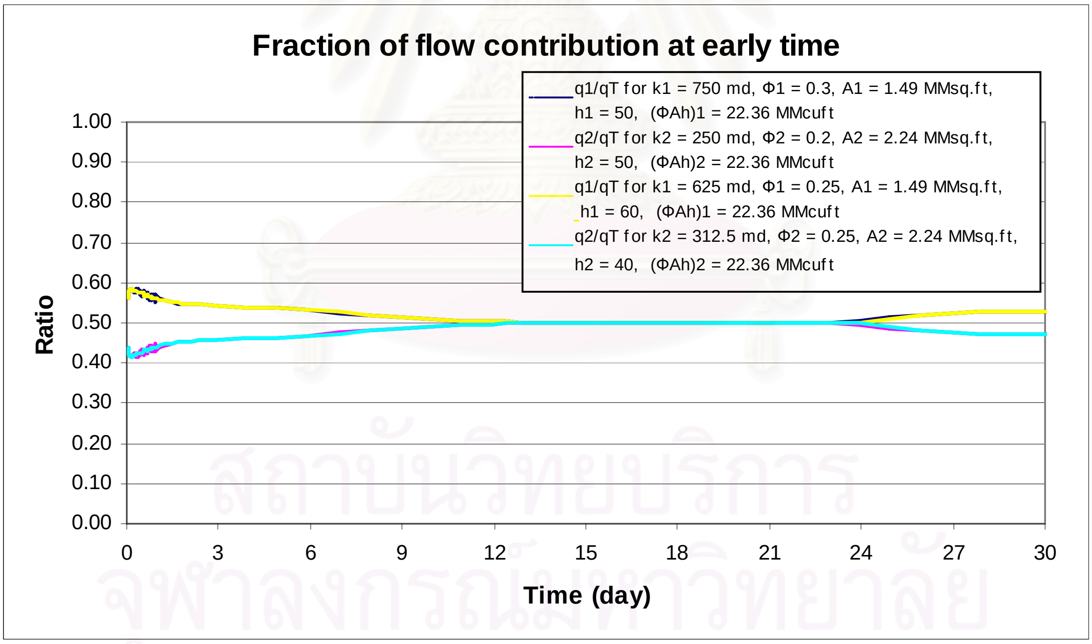


Figure B-6 q_1/q_T and q_2/q_T ratios at early time (q_T = 600 STB/D, k_1h_1 = 37500 md-ft., k_2h_2 = 12500 md-ft)

APPENDIX C

ADDITIONAL CASES FROM kh AS CONTROLLING FACTOR (5.2)

Table C-1 Rock and fluid properties for system under influence of kh (k_1h_1 = 60 md-ft, k_2h_2 = 20 md-ft, and q_T = 1000 STB/D)

Properties	Layer 1	Layer 2
k, md	1	0.5
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	60	20
ΦAh, (MMcu.ft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	1000	1000
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

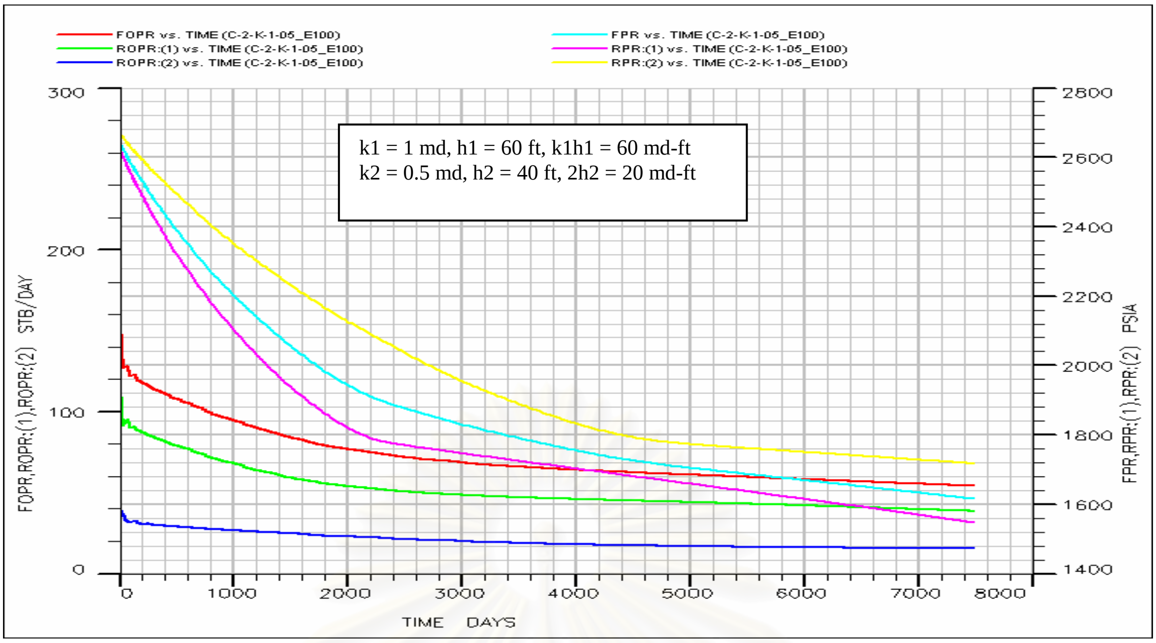


Figure C-1 Flow from multilayer system partially under influence of kh (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft, $(kh)_1$ = 60 md-ft, $(kh)_2$ = 20 md-ft)

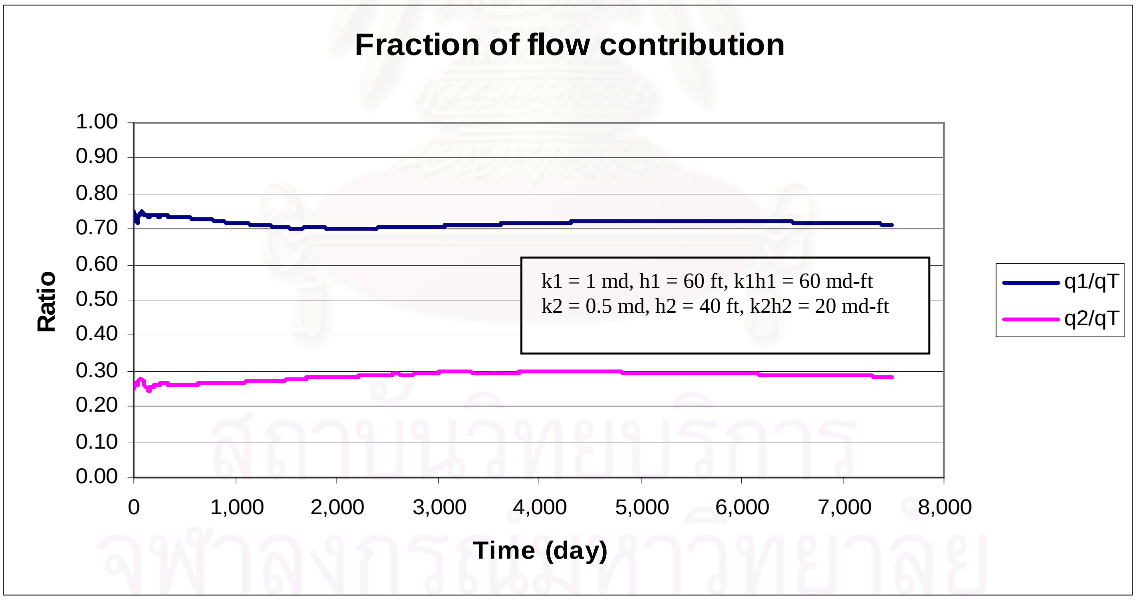


Figure C-2 q_1/q_T and q_2/q_T ratios at various times (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft, $(kh)_1$ = 60 md-ft, $(kh)_2$ = 20 md-ft)

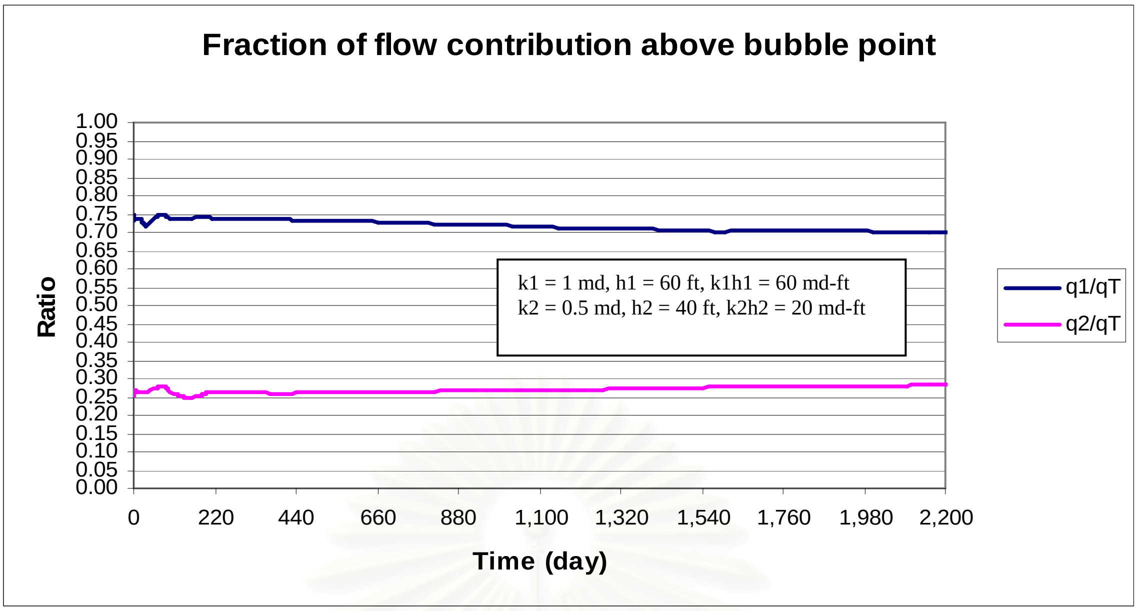


Figure C-3 q_1/q_T and q_2/q_T ratios at early time (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft, $(kh)_1$ = 60 md-ft, $(kh)_2$ = 20 md-ft)

Table C-2 Rock and fluid properties for system under influence of kh (k_1h_1 = 30 md-ft, k_2h_2 = 10 md-ft, and q_T = 1000 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	0.5	0.25
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	30	10
ΦAh, (MMcu.ft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	1000	1000
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

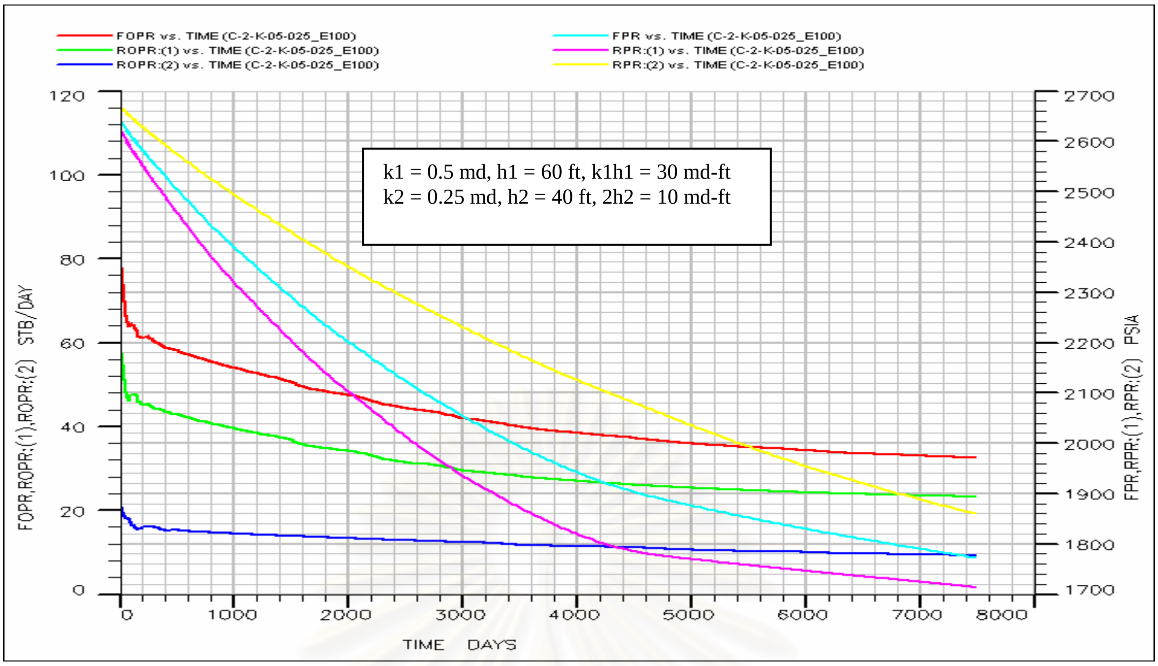


Figure C-4 Flow from multilayer system partially under influence of kh (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft, $(kh)_1$ = 30 md-ft, $(kh)_2$ = 10 md-ft)

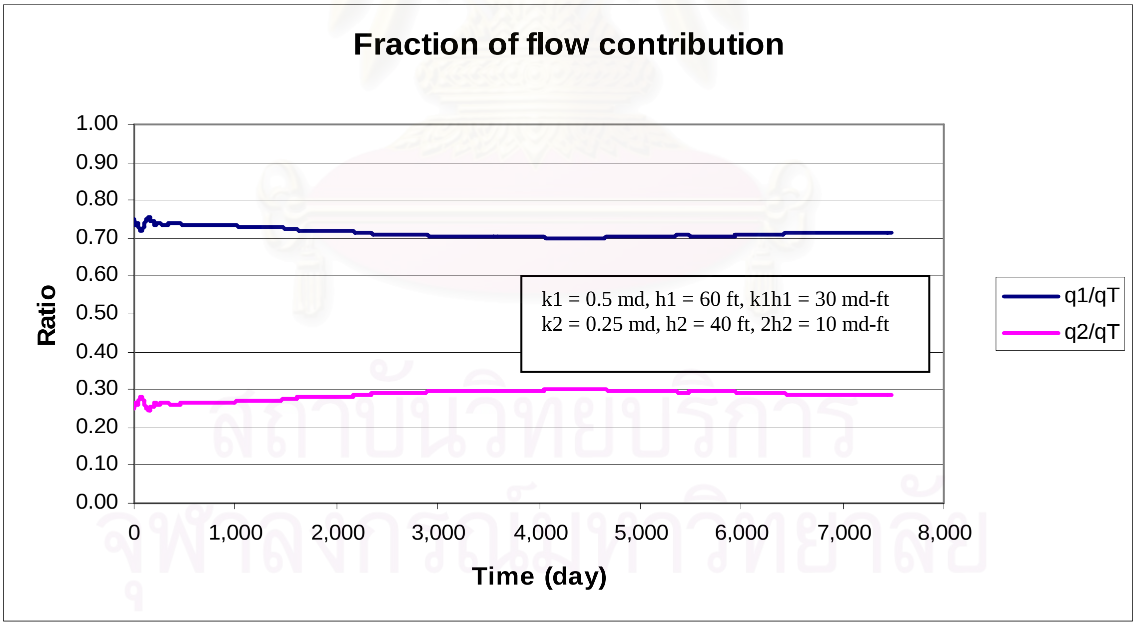


Figure C-5 q_1/q_T and q_2/q_T ratios at various times (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft, $(kh)_1$ = 30 md-ft, $(kh)_2$ = 10 md-ft)

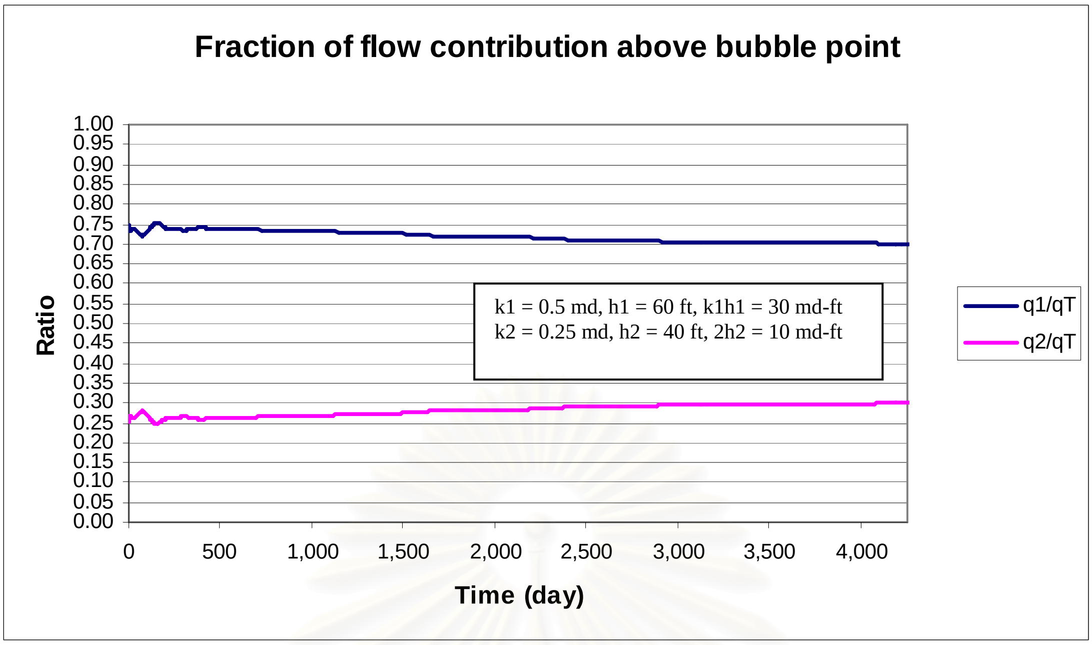


Figure C-6 q_1/q_T and q_2/q_T ratios at early time (q_T = 1000 STB/D, $(\Phi Ah)_1$ = 93.75 MMcuft, $(\Phi Ah)_2$ = 62.5 MMcuft, $(kh)_1$ = 30 md-ft, $(kh)_2$ = 10 md-ft)

APPENDIX D

ADDITIONAL CASES FROM ΦAh AS CONTROLLING FACTOR

Table D-1 Rock and fluid properties for system under influence of ΦAh (k_1h_1 = 1800 md-ft, k_2h_2 = 600 md-ft, and q_T = 50 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	30	15
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	1800	600
ΦAh, (MMcu.ft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	50	50
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

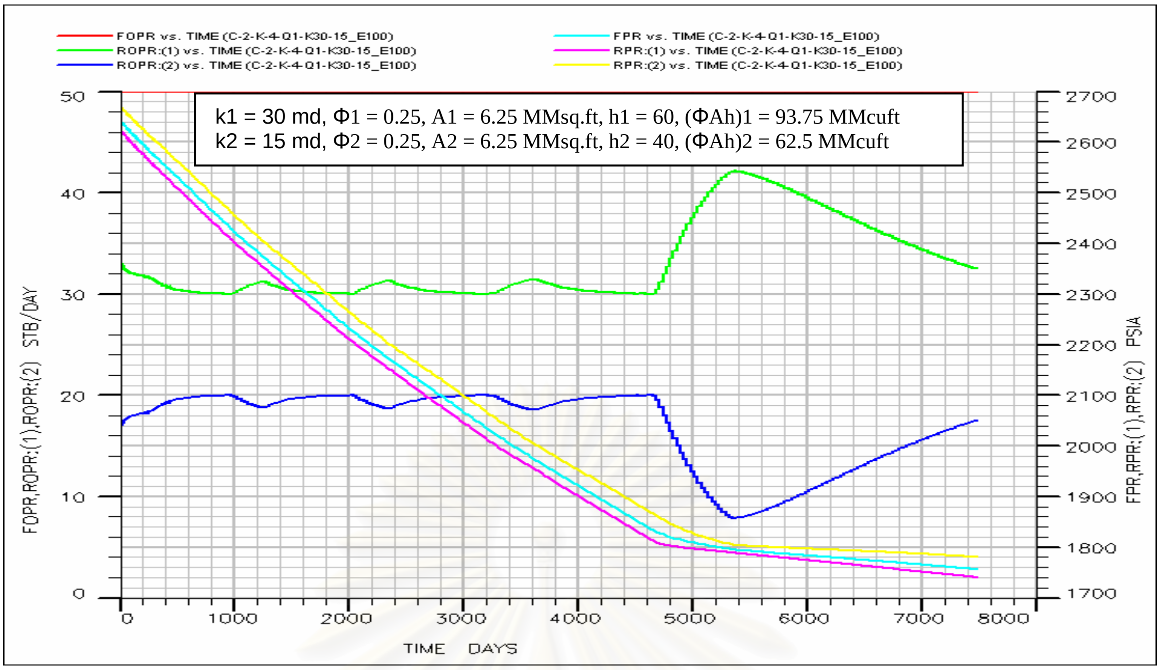


Figure D-1 Flow from multilayer system partially under influence of ΦAh

(q_T = 50 STB/D, k_1h_1 = 1800 md-ft., k_2h_2 = 600 md-ft)

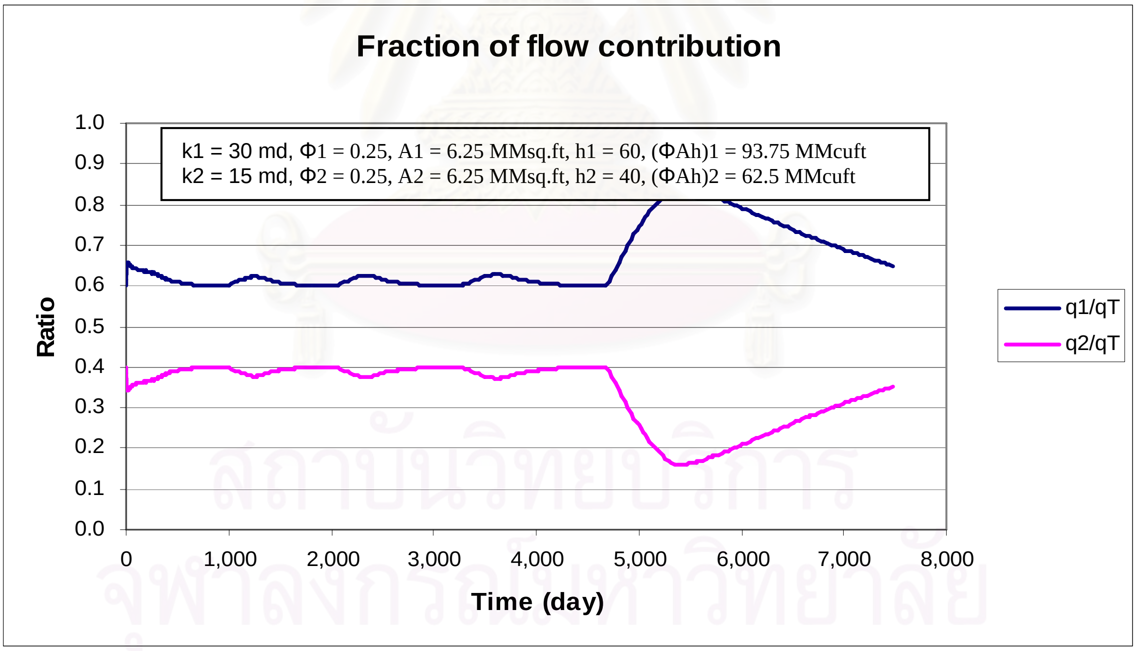


Figure D -2 q_1/q_T and q_2/q_T ratios at various times with clear influence of ΦAh

(q_T = 50 STB/D, k_1h_1 = 1800 md-ft., k_2h_2 = 600 md-ft)

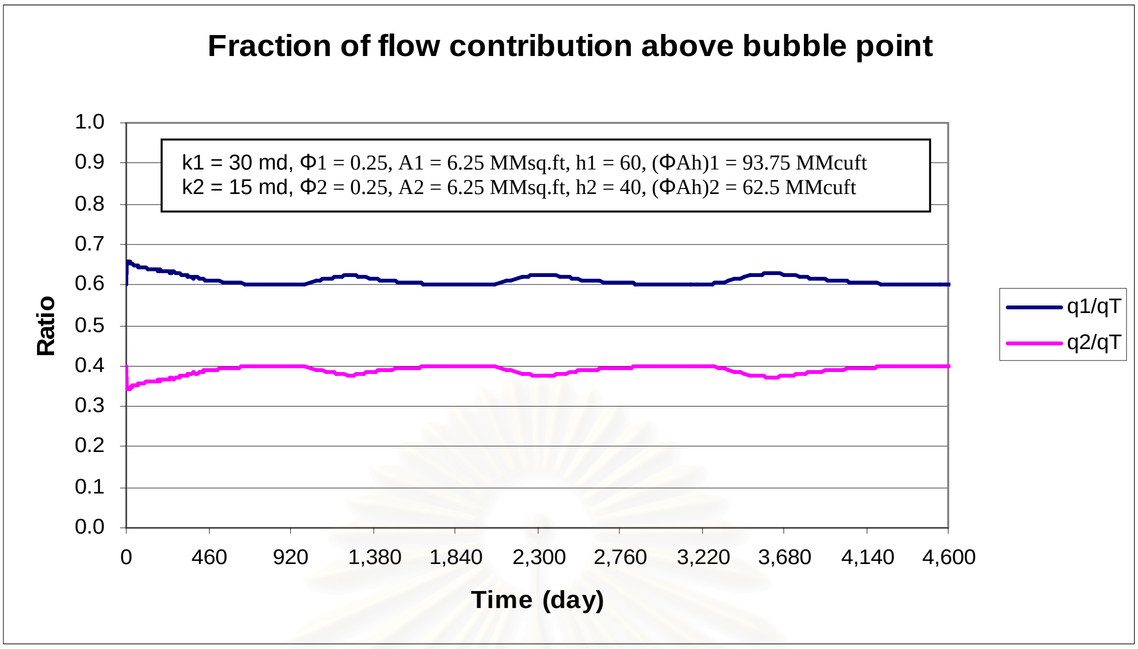


Figure D-3 q_1/q_T and q_2/q_T ratios at early time with clear influence of ΦAh (q_T = 50 STB/D, k_1h_1 = 1800 md-ft., k_2h_2 = 600 md-ft)

Table D-2 Rock and fluid properties for system under influence of ΦAh (k_1h_1 = 3600 md-ft, k_2h_2 = 1200 md-ft, and q_T = 100 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	60	30
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	3600	1200
ΦAh, (MMcu.ft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	100	100
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

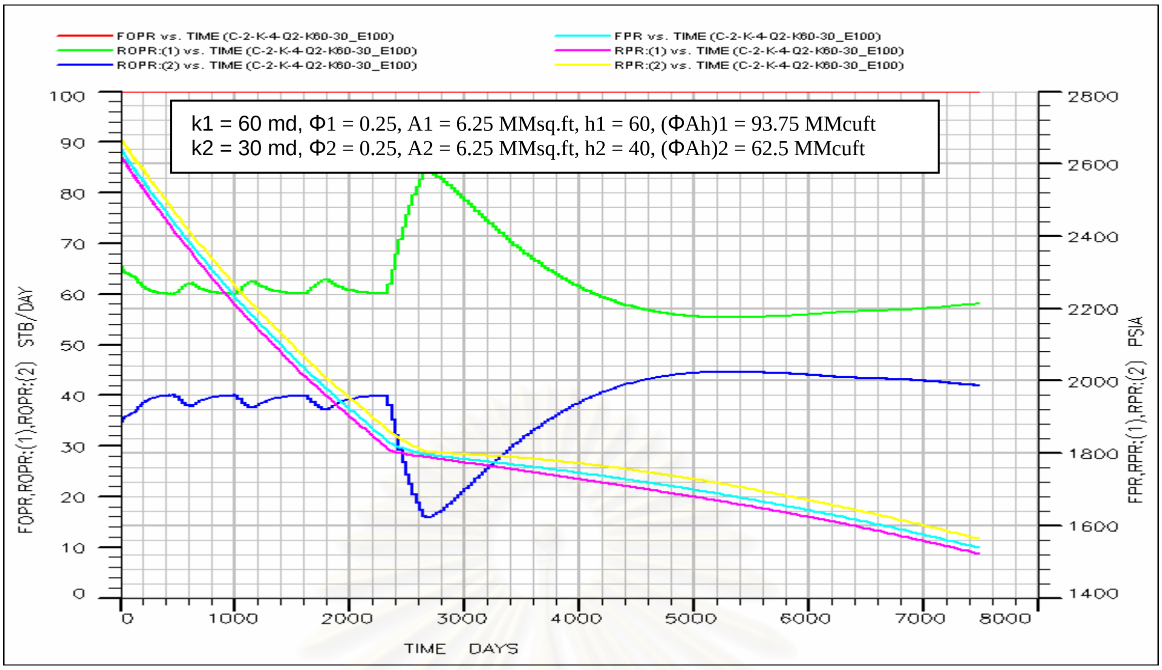


Figure D-4 Flow from multilayer system partially under influence of ΦAh

(q_T = 100 STB/D, k_1h_1 = 3600 md-ft., k_2h_2 = 1200 md-ft)

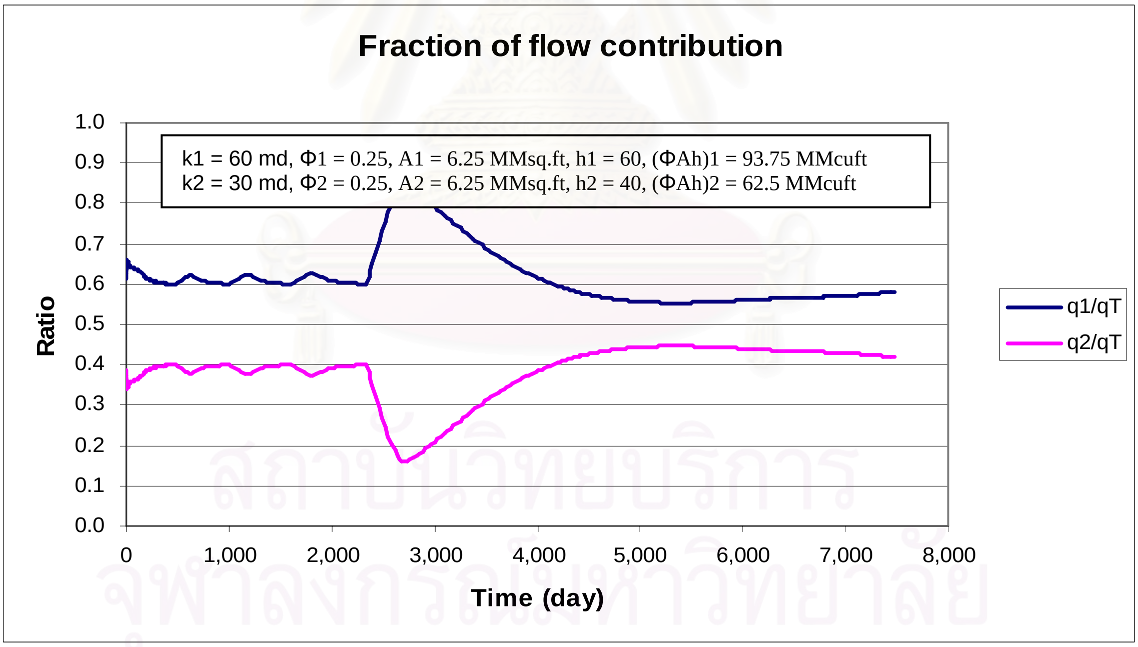


Figure D -5 q_1/q_T and q_2/q_T ratios at various times with clear influence of ΦAh

(q_T = 100 STB/D, k_1h_1 = 3600 md-ft., k_2h_2 = 1200 md-ft)

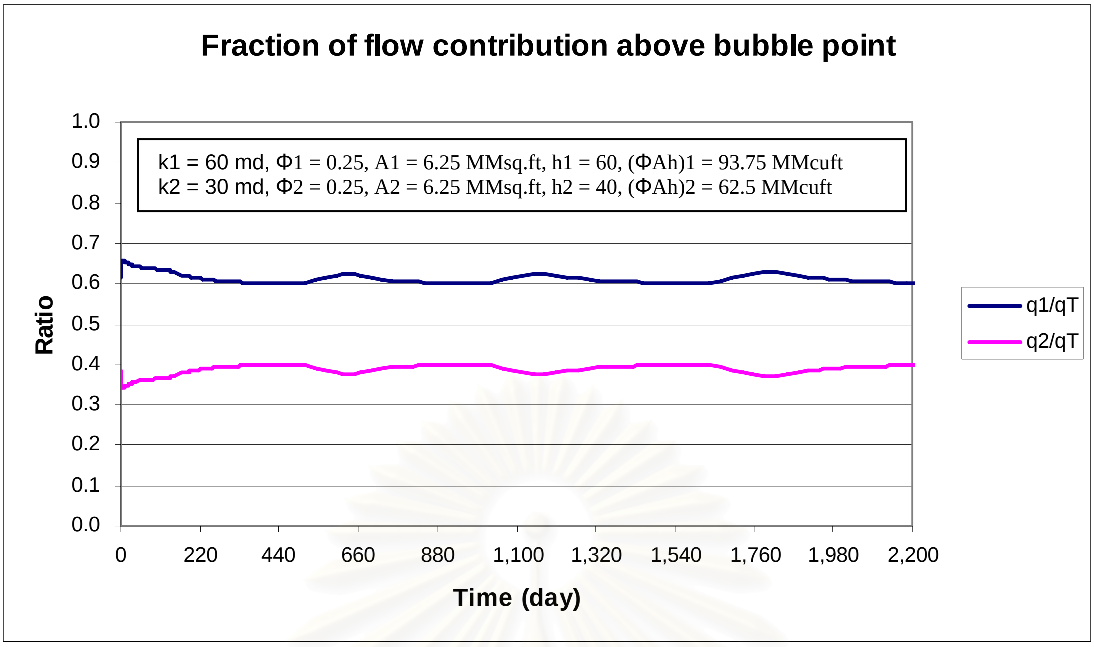


Figure D-6 q_1/q_T and q_2/q_T ratios at early time with clear influence of ΦAh (q_T = 100 STB/D, k_1h_1 = 3600 md-ft., k_2h_2 = 1200 md-ft)

Table D-3 Rock and fluid properties for system under influence of ΦAh (k_1h_1 = 24000 md-ft, k_2h_2 = 8000 md-ft, and q_T = 500 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	400	200
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	24000	8000
ΦAh, (MMcu.ft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	500	500
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

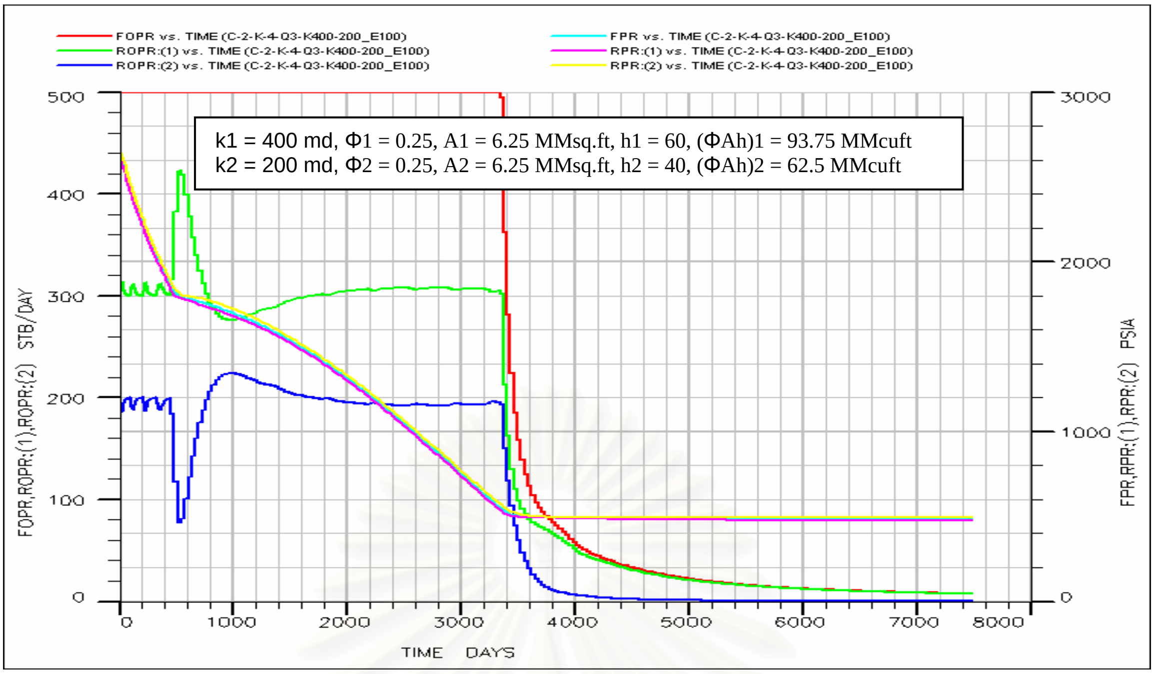


Figure D-7 Flow from multilayer system partially under influence of ΦAh

(q_T = 500 STB/D, k_1h_1 = 24000 md-ft., k_2h_2 = 8000 md-ft)

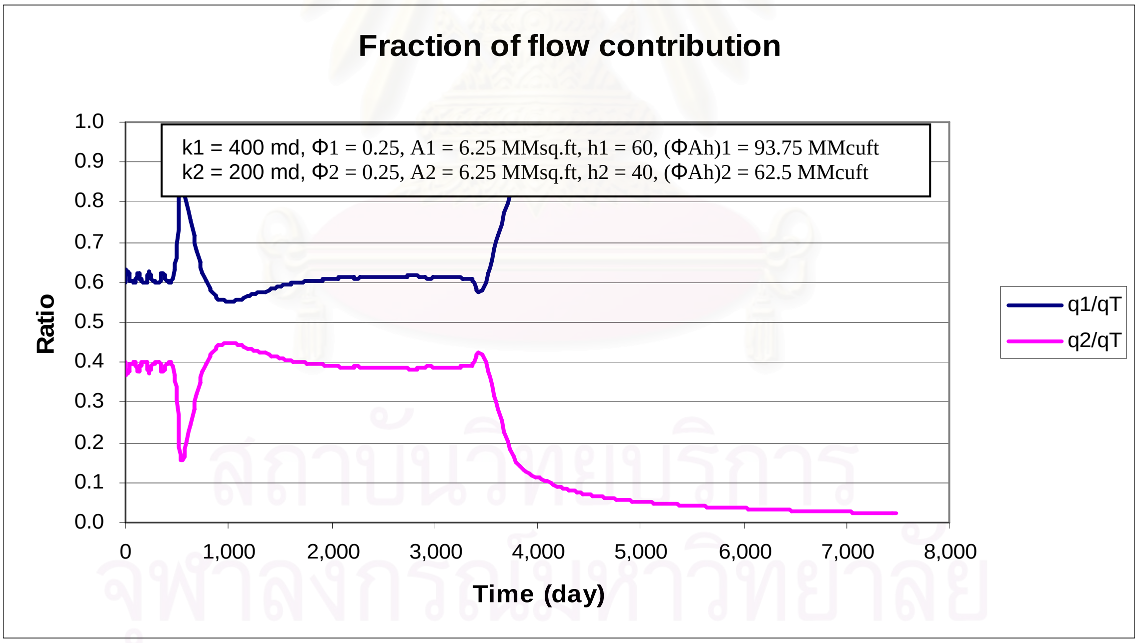


Figure D -8 q_1/q_T and q_2/q_T ratios at various times with clear influence of ΦAh

(q_T = 500 STB/D, k_1h_1 = 24000 md-ft., k_2h_2 = 8000 md-ft)

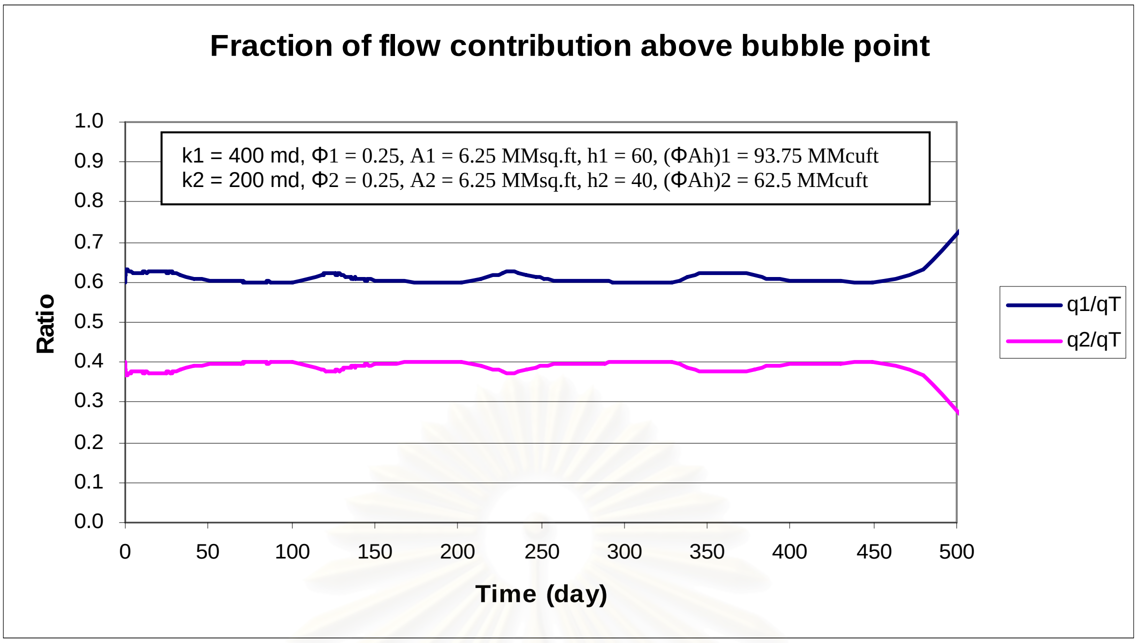


Figure D-9 q_1/q_T and q_2/q_T ratios at early time with clear influence of ΦAh (q_T = 500 STB/D, k_1h_1 = 24000 md-ft., k_2h_2 = 8000 md-ft)

Table D-4 Rock and fluid properties for system under influence of ΦAh (k_1h_1 = 51000 md-ft, k_2h_2 = 17000 md-ft, and q_T = 1000 STB/D)

Properties	**Layer 1**	**Layer 2**
k, md	850	425
h, ft	60	40
Φ	0.25	0.25
A, (MMsq.ft)	6.25	6.25
kh, (md-ft)	51000	17000
ΦAh, (MMcu.ft)	93.75	62.5
Pi, (psia)	2610	2659.5
μ_o, (cp)	0.62	0.62
Pb, (psia)	1800	1800
API	35	35
OIIP, (MMSTB)	10.5	6.99
q_T, (STB/D)	1000	1000
$k_1h_1/(k_1h_1+k_2h_2)$	0.75	-
$k_2h_2/(k_1h_1+k_2h_2)$	-	0.25
$\Phi_1A_1h_1/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	0.6	-
$\Phi_2A_2h_2/(\Phi_1A_1h_1+\Phi_2A_2h_2)$	-	0.4

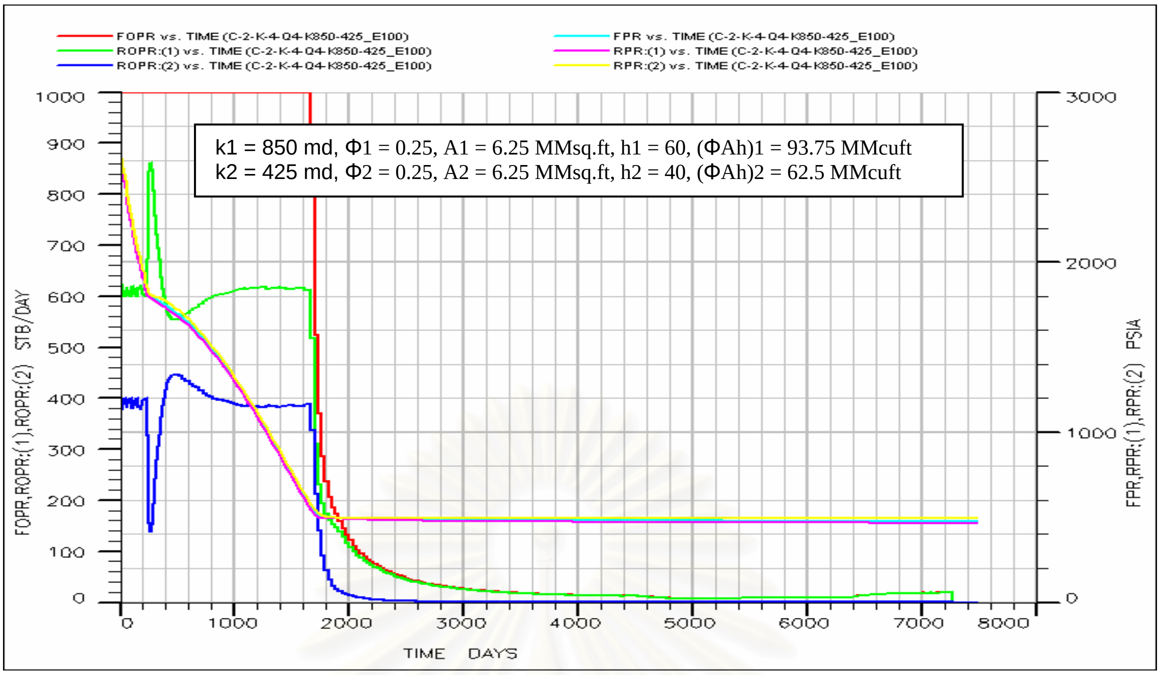


Figure D-10 Flow from multilayer system partially under influence of ΦAh (q_T = 1000 STB/D, k_1h_1 = 51000 md-ft., k_2h_2 = 17000 md-ft)

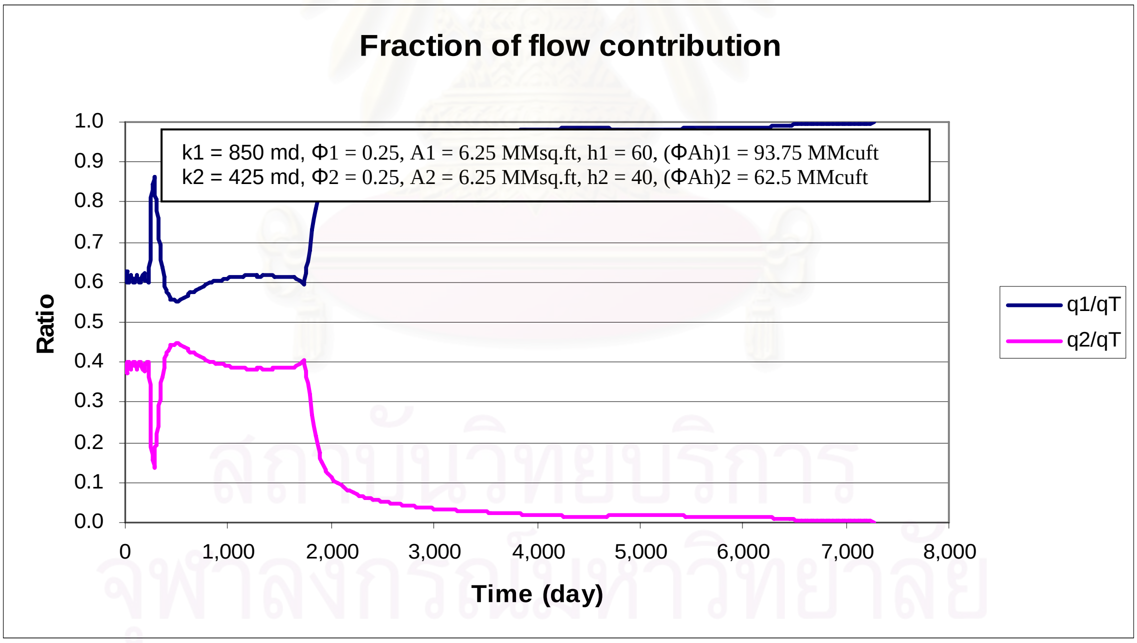


Figure D -11 q_1/q_T and q_2/q_T ratios at various times with clear influence of ΦAh (q_T = 1000 STB/D, k_1h_1 = 51000 md-ft., k_2h_2 = 17000 md-ft)

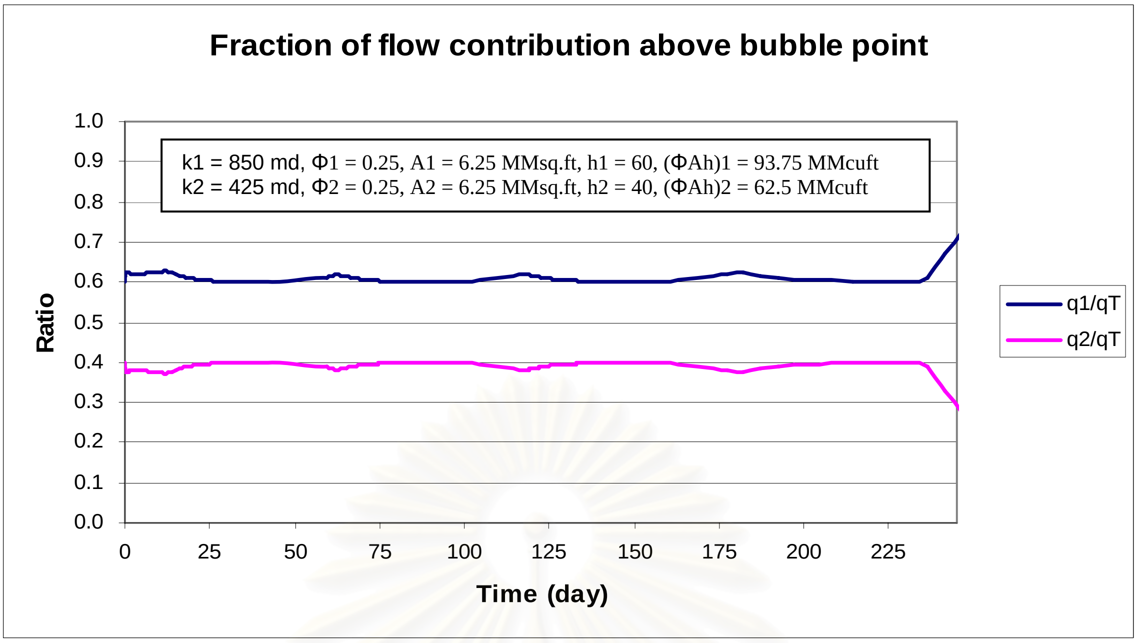


Figure D-12 q_1/q_T and q_2/q_T ratios at early time with clear influence of ΦAh (q_T = 1000 STB/D, k_1h_1 = 51000 md-ft., k_2h_2 = 17000 md-ft)

Vitae

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