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PRODUCTION STRATEGY FOR MULTILAYER RESERVOIRS

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สิ่งที่ท้าทายสำหรับการผลิตก๊าซและน้ำมันจากแหล่งกักเก็บหลายชั้น คือการเลือกกลยุทธ์การผลิตที่ถูกต้อง ซึ่งในแหล่งผลิตและหลุมผลิตต่าง ๆ กัน ก็จะมีวิธีที่ดีที่สุดไม่เหมือนกัน กลยุทธ์การผลิตชนิดหนึ่งที่นิยมใช้กันในหลาย ๆ หลุมที่มีแหล่งกักเก็บหลายชั้น คือการผลิตแบบร่วมกันระหว่างชั้น อย่างไรก็ตามกลยุทธ์นี้ก็มีข้อจำกัด โดยเฉพาะอย่างยิ่งเมื่อหลุมนั้น ๆ มีความซับซ้อน กล่าวคือ มีของเหลวหลาย ๆ ชนิดอยู่ในแหล่งกักเก็บนั้น การตัดสินใจเลือกใช้กลยุทธ์การผลิตแบบต่าง ๆ มักเป็นการลองผิดลองถูก และบ่อยครั้งที่พบว่ากลยุทธ์ที่ลองใช้ไม่เหมาะสมกับหลุมผลิตในที่สุด วิธีการแก้ปัญหานี้คือการสร้างแบบจำลองที่เลียนแบบการไหลของปิโตรเลียมในแหล่งกักเก็บหลายชั้น แล้วทดลองผลิตด้วยกลยุทธ์การผลิตต่าง ๆ กัน แล้วจึงสรุปกลยุทธ์การผลิตที่ดีที่สุดสำหรับแหล่งกักเก็บหลายชั้นแบบต่าง ๆ

การศึกษาครั้งนี้ใช้แบบจำลองที่เลียนแบบการไหลของปิโตรเลียม เพื่อเปรียบเทียบผลที่ได้จากการใช้กลยุทธ์การผลิตต่าง ๆ ในแหล่งกักเก็บแบบสองชั้นที่ภายในมีของเหลวชนิดต่าง ๆ อยู่ร่วมกันหลาย ๆ แบบ จากผลการผลิตด้วยแบบจำลองที่สร้างขึ้นพบว่า ไม่มีกลยุทธ์ใดกลยุทธ์หนึ่งที่ดีที่สุดสำหรับแหล่งกักเก็บหลายชั้นทุก ๆ แบบ กลยุทธ์ที่ 1 คือแบบร่วมกันระหว่างชั้น เป็นการผลิตของเหลวจากทั้งสองชั้นพร้อม ๆ กัน เป็นกลยุทธ์ที่ดีที่สุดในกรณีที่แหล่งกักเก็บทั้งสองชั้นมีน้ำมันอยู่ภายใน กลยุทธ์ที่ 2 คือแบบแยกผลิต โดยผลิตของเหลวจากชั้นล่างก่อน เป็นกลยุทธ์ที่ดีที่สุดในกรณีที่แหล่งกักเก็บชั้นบนมีก๊าซอยู่ภายใน ซึ่งของเหลวที่อยู่ในชั้นล่างอาจจะเป็นน้ำมัน ก๊าซและน้ำมัน น้ำมันและน้ำ หรือ ก๊าซและน้ำ ก็ได้ กลยุทธ์ที่ 3 เป็นการแยกผลิตของเหลวจากชั้นล่างก่อน จนกระทั่งอัตราการผลิตลดลงเหลือครึ่งหนึ่งของอัตราเริ่มต้น แล้วจึงค่อยผลิตของเหลวจากทั้งสองชั้นพร้อม ๆ กัน กลยุทธ์นี้เป็นกลยุทธ์ที่ดีที่สุดในกรณีที่แหล่งกักเก็บทั้งสองชั้นมีน้ำมันอยู่ภายใน ซึ่งเหมือนกับกรณีของกลยุทธ์ที่ 1 ส่วนกลยุทธ์ที่ 4 จะคล้ายกับกลยุทธ์ที่ 3 ต่างตรงที่จะแยกผลิตจากชั้นบนก่อน เป็นกลยุทธ์ที่ดีที่สุดในกรณีที่แหล่งกักเก็บชั้นบน มีน้ำมันอยู่ภายใน และแหล่งกักเก็บชั้นล่างมีก๊าซและน้ำอยู่ภายใน เนื่องจากกลยุทธ์การผลิตแบบนี้ทำให้น้ำไหลเข้ามาในหลุมได้ช้าลงและรักษาความดันในแหล่งกักเก็บได้นานกว่า

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The problem addressed here is the challenge of determining the best production strategy for multilayered reservoirs which varies from field to field as well as from well to well. Commingled production strategy is one of the most commonly used for several multilayered wells. However, there are some limitations to this method. Mostly, when very complex multilayer wells which contain different types of fluid in each productive layer are identified, the selection process of production approach is basically trial and error and later found to be a poor choice. One attempted solution to choosing the optimal production strategy is using numerical reservoir simulation.

In this study, we used reservoir simulation to compare the performance of four different production strategies for different combinations of types of fluid present in a two-layer system. Strategy 1 in which the fluid is produced from two layers simultaneously is the best production approach when oil is present in the top and bottom layers. Strategy 2 in which the fluid is produced from one layer at a time starting with the bottom layer is the best production approach when reservoir fluid at the top layer is gas while fluids present in the bottom layer can vary from oil, gas&oil, gas&water and oil&water. Strategy 3 produces fluid from one layer at a time, starting with the bottom layer. When the production rate decreases to half of the original rate, the two zones are produced in a commingled fashion. Similar to strategy 1, strategy 3 is also the best production approach when oil is present in the top and bottom layers. Strategy 4 is similar to strategy 3 but starting with the top layer. This strategy is the best production approach when oil is present in the top layer and gas&water in the bottom layer. This approach can delay water production and sustain reservoir pressure.

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LIST OF ABBREVIATIONS

3D	3 - dimension
BOE	barrel of oil equivalent
cp	centipoises
ft	feet
GLR	gas-liquid ratio
GOC	gas oil contact
GOR	gas-oil ratio
lb/ft3	pound per cubic feet
mD	millidarcy
MMSCF/D	million standard cubic feet per day
MSCF/D	thousand standard cubic feet per day
MSCF/STB	thousand standard cubic feet per stock-tank barrels
MSTB	thousand stock-tank barrel
MSTB/D	thousand stock-tank barrels per day
NPV	net present value
OGIP	original gas in-place
OOIP	original oil in-place
psia	pounds per square inch absolute
psia-1	per pounds per square inch absolute
PVT	pressure-volume-temperature
PVTG	pressure-volume-temperature of gas
PVTO	pressure-volume-temperature of oil
RB/STB	reservoir barrel per stock-tank barrels
SCAL	special core analysis
SCF	standard cubic foot
SCF/STB	standard cubic feet per stock-tank barrels
SGFN	gas saturation functions
SGOF	gas/oil saturation functions
SWFN	water saturation functions
SWOF	water/oil saturation functions

TAP	treat and produce
VFP	vertical lift performance
WOC	water oil contact

NOMENCLATURES

k_{rg}	gas relative permeability
k_{ro}	oil relative permeability
k_{rw}	water relative permeability
P_{wf}	wellbore flowing pressure
R_s	gas solubility

CHAPTER I

INTRODUCTION

Most oil and gas reservoirs are stratified and divided into multiple zones as a result of sedimentary deposition. Since thousands of these reservoirs are being drilled every year to meet the increasing energy needs, many productive zones have often been produced by commingling them to maximize reservoir production and ultimate recovery [1].

The problem addressed here is the challenge of determining the best production strategy for multilayer reservoirs which varies from field to field as well as well to well. Commingled production strategy is one of the most commonly used for several multilayer reservoirs. However there are some limitations to this method and the method does not always yield the highest recovery. Commingled production should not be applied when incompatible fluid such as oil and water are presented in multi zones. In addition, commingled production can be less attractive when sub-surface well completion and surface equipment is constrained [2]. Another commonly used strategy for multilayer system is a separate layer production which can solve problems due to a large difference of inter-layer pressure and heterogeneity such as a rapid decline in production, a crossflow between layers, as well as a quick increase in water cut [3]. In many cases, when very complex multilayer reservoirs which contain different types of fluid in each productive layer are identified, the selection of production approach may end up with a poor choice.

One attempted solution to choosing the optimal production strategy is using numerical reservoir simulation since the wrong production strategies may have been selected due to a limited understanding of each strategy or even of the reservoir behavior itself. The numerical reservoir simulation software has made it possible to evaluate different strategies in order to achieve the highest ultimate hydrocarbon recovery. Importantly, understanding the fundamental multilayer reservoirs first is essential to understand those complicated ones in an actual field. Consequently, reservoir simulation models implemented in the study represent only two homogenous layers of reservoirs.

The purpose of this study is to investigate the impact of different production strategies for multilayer reservoirs containing different kinds of fluid in order to maximize the ultimate recovery of hydrocarbon.

1.1 Methodology

1. Gather and prepare data for simulation model.
2. Constructed a hypothetical Eclipse 100 simulation model for different types of multilayer reservoirs.
3. Run simulation for 15 base cases to verify the integrity of each model.
4. Conducted sensitivity on production strategy for seven cases to observe the impact of different production strategies for multilayer reservoirs and developed the best guideline for each case.
5. Analyzed the simulation results and conclude.

1.2 Thesis outline

This thesis consists of six chapters. The outlines of each chapter are listed below:

Chapter II reviews previous studies related to production problems and production strategies used in the multilayer reservoirs

Chapter III describes theory and concepts related to this study.

Chapter IV describes the methodology for this study.

Chapter V describes production performance from simulation results case by case, as well possible reasons that support their performances.

Chapter VI provides conclusion and recommendation of the study.

CHAPTER II
LITERATURE REVIEW

This chapter discusses some works related to multilayer reservoirs and the development of production of multilayer reservoirs. Unfortunately, reservoir simulation on production strategy to enhance recovery has not been broadly investigated. Thus, most of the following literatures discuss related works in the actual filed.

2.1 Previous works

Prokhorov [1] introduced a success of taking a technique of commingled oil production in the Uvat project in Russia. Some fields in the project contain not one, but several productive zones. At the initial life of the field, the company operates such zones separate. However, this is very costly in terms of money and time. His solution to the problem is commingled oil production which makes it possible to develop two reservoirs at the same time via a single well, without drilling additional grid or disconnecting the reservoirs. At the wellhead, the flow rates are measured and all the hydrodynamics tests are performed. With commingled production, even with a high water cut and not much of production from the lower reservoir, the more productive higher formation can be developed at the same time, doubling the flow rate from a single well and boosting the oil recovery factor.

Al-Shehri, Rabaa, Duenas and Ramanathan [2] investigated the criteria used to select suitable candidates for commingled production in Khuff reservoir. They found that the implementation of a successful commingled production strategy depends on several factors. These include 1) proper candidate selection 2) implementing the correct stimulation/completion strategy and 3) correct evaluation of data and post treatment performance. To select the best candidate wells for commingled production from the Khuff zones, a reservoir and production engineers has to carefully study and evaluate all available data. The most vital parameters are porosity, permeability, and reservoir pressure that determine the potential of each zone.

They also investigated the production performance from each individual zone in Khuff reservoir after commingling the production. Two wells had commingled production implemented since wells start-up, while the other two wells had the commingled production implemented at a later stage. They found that completing gas wells commingled with all productive zones meets the corporate mission of maximizing Khuff production, ultimate recovery and reducing costs. Moreover, delaying completing Khuff-B or A (when available) will accelerate well decline making it necessary to offset this decline with additional drilling. Additional risks, associated with delaying completing other Khuff zones, are deteriorating well conditions that might render Khuff-B fracturing impractical, and the possibility of damaging Khuff-C at lower reservoir pressure in presence of condensate banking.

Yupu and He [3] introduced oil production engineering for heterogeneous, multilayer sandstone oil field in the basis of separate zone production. Daqing is a giant, heterogeneous and multilayer sandstone oilfield whose reservoirs can be divided into 80-120 small layers. From the initial increasing the production process to the later stabilizing production process, separate zone production theory has been created for reservoir engineering. As a result, it makes an important contribution for keeping stable production of 50 million tons for 27 years. This technology is a basic technical means to keep reservoir pressure, adjust interlayer and horizontal contradiction, control casing damage and rising of water cut, and improve recovery factor.

Jiraratwaro [4] investigated the optimization of completion strategy in multilayer reservoirs. In this study, reservoir models were built based on history matching on the production profiles using Integrated Production Model software. Then, six perforation strategies are applied to the same well in order to see the difference. The strategy delivering the highest oil recovery for most well was considered top performer for the condition in which the research was based on. The results obtained indicate that no single strategy appears to consistently deliver the highest oil recovery. For recovery of gas, the actual perforation that includes plug and patches yields the lowest water recovery and the bottom up perforation is the most favorable.

Rytlewski [5] proposed a new successful method of completing multiple-layer formations which is called Treat And Produce (TAP) Completion. The Treat And Produce (TAP) Completion system has been developed to allow the efficient treatment of individual layers one at time without any interventions. The TAP valves are near full bore and do not require incremental reductions of internal diameter and thus allow normal cementing operations.

According to the study, this work is valuable and practical when separate layer production strategy is employed in the multilayer reservoirs because TAP Completion can save days of completion time and provides mean to efficiently treat all layers independently for optimum production.

CHAPTER III
THEORY AND CONCEPTS

3.1 Multilayer reservoirs

The multilayer reservoirs can be divided into two types according to whether there is crossflow between layers. One is commingled system which means the layers have been isolated by non-permeable interbed no crossflow exists, the other is crossflow system where there is connectivity between layers.

3.1.1 Commingled system

Commingled reservoirs are the reservoirs that are connected only in the wellbore. These reservoir systems do not have cross flow within the reservoir boundaries [6].

3.1.2. Crossflow system

Whenever there is a pressure difference between two layers, crossflow will occur if there is communication between layers. Generally, differences in radial permeability and skin factor are the most important reasons for causing the formation crossflow. A more permeable layer produces rapidly, which causes bigger pressure drop. Thus at the same distance from the wellbore, the formation pressure becomes higher in the less permeable layer than that in the more permeable layer, and the reservoir fluid starts flowing from the less to the more permeable layer. This crossflow phenomenon has many characteristic effects both on the response of the wellbore pressure and on the production rate from each layer [7].

3.2 Commingled production

3.2.1 Application of commingled production

Commingled production has been often applied for depleted stratified reservoirs, where production rates of individual zones are very low and economically unattractive. However, commingled production has recently been applied for other purposes listed below [2]:

1) Reservoir production close to economic limit.

2) Reservoirs under water or gas drive. Commingled production can lead to a better volumetric replacement balance and delay fluid breakthrough without reducing the total production rate.

3) Reservoir with sand production, fine migration of coning problem, where fluid velocity in the wellbore needs to be controlled without reducing the total production rate.

4) Reservoir where higher production rate are required.

3.2.2 Advantages of commingled production

Generally, commingled production in oil and gas reservoirs has the following tangible benefits [2]:

1) Enhancing production utilizing existing assets to minimize capital expenditure.

2) Maximizing the Net Present Value (NPV) by accelerating reserves recovery from multi zone reservoirs.

3) Improving lifting efficiency to prolong the well's economical life.

Additionally, commingled production has the following intangible benefits:

1) Improving volumetric sweep efficiency and delaying premature fluid breakthrough.

2) Minimizing the sand production without impacting the well's performance.

3.2.2 Commingled production limitations

There are limitations associated with commingled production, which should be recognized and planned in advance. Commingled production can be less attractive when [8]:

1) Incompatible fluids are produced from multi-zones.

2) Cross-flow occurs between/among zones due to large differential pressures. This condition might induce cross flow, if P_{wf} of the system at the face of particular zone is greater than its static reservoir pressure.

3) Significant differences in GLR, water cut, oil gravity and production mechanism. Commingled production work best when zone conditions are similar, but it does not mean that they cannot produce together. It only implies that the process requires close monitoring.

4) Long separation between producing intervals. Long distance between zones means large pressure differences that can lead to crossflow conditions.

5) Sub-surface well completion and surface equipment are constrained.

6) Requiring a good geological model describing the zones to be commingled.

The key factor for successful commingled production is to keep the flowing bottomhole pressure of the system below the lowest static reservoir pressure. The best result would be achieved when similar static pressure zones are combined or when the lower static pressure zone exhibits higher productivity index [8].

From the reservoir management perspective, having no downhole permanent monitoring systems installed or conventional production logs run periodically, it would be difficult to quantify and allocate production from the individual zones. Knowing the contribution is essential for constructing a good simulation model to sensitize various strategies on commingling production [3].

3.3 Selective completion for multilayer reservoirs [9]

3.3.1 Mechanically isolated selective completions

Mechanically isolated selective completions are frequently used for the purpose of selectively producing and selectively isolating completion intervals. From a design standpoint, these completions are mechanically very similar to dual completions but with only one production string.

3.3.2 Packerless selective completions

Packerless selective completions are a less expensive attempt to selectively produce or selectively isolate two or more zones or sections of the same completion interval. The mechanical design is essentially that of a single-zone gravel pack completion. In this completion design, all of the zones are perforated at once and one gravel pack is placed, using two or more sections of screen each separated by a length of blank liner. Usually the lower screen section is a selective screen. There is no annular isolation between the sections other than the settled gravel column. This design relies solely on the permeability of the gravel column to restrain flow between the sections until the selective is utilized. Packerless selectives do not provide total isolation and, therefore, their use should take this aspect fully into consideration.

3.3.3 Multi-zone completions

Multi-zone completions involve several zones to be gravel packed in one trip. Production from all of the zones is commingled into one production string. Hydraulic packers set inside production casing to separate each zone, allowing each to be separately gravel packed.

3.3.4 Through-tubing completions

Through-tubing gravel packed completions are becoming an increasingly important method of remedial sand control and as a repair alternative to failed gravel packs. Workover costs can be dramatically reduced, since the equipment can be run with a small work string or coiled tubing for short intervals by wireline. Through-tubing completions are especially desirable for low rate wells or where remaining reserves are low.

3.4 Reservoir Drive mechanisms [10]

Producing oil and gas needs energy. Usually some of this required energy is supplied by nature. The hydrocarbon fluids are under pressure because of their depth. The gas and water in petroleum reservoirs under pressure are the two main sources that help move the oil to the well bore and sometimes up to the surface. Depending on the original characteristics of hydrocarbon reservoirs, the type of driving energy is different.

3.4.1 Depletion-drive reservoirs

When a newly discovered reservoir is below the bubble point pressure, there will be free gas as bubbles within the oil phase in reservoir. The reservoir pressure decreases as production goes on and this causes emerging and expansion of gas bubbles creating extra energy in the reservoir. These kinds of reservoirs are called as depletion-drive or solution gas drive reservoirs. Crude oil under high pressure may contain large amounts of dissolved gas. When the reservoir pressure is reduced as fluids are withdrawn, gas comes out of the solution and displaces oil from the reservoir to the producing wells. The efficiency of depletion-drive depends on the amount of gas in solution, the rock and fluid properties and the geological structure of the reservoir. Recoveries are low, on the order of 10-15 % of the original oil in place (OOIP). Recovery is low, because the gas phase is more mobile than the oil phase in the reservoir. Depletion-drive reservoirs are usually good candidates for water-flooding.

3.4.2 Gas-cap-drive reservoirs

Sometimes, the pressure in the reservoir is below the bubble point initially, so there is more gas in the reservoir than the oil can retain in solution. This extra gas, because of density difference, accumulates at the top of the reservoir and forms a cap. These kinds of reservoirs are called a gas-cap-drive reservoir. In gas-cap-drive reservoirs, wells are drilled into the crude oil producing layer of the formation. As oil production causes a reduction in pressure, the gas in gas cap expands and pushes oil into the well bores. Expansion the gas cap is limited by the desired pressure level in the reservoir and by gas production after gas comes into production wells.

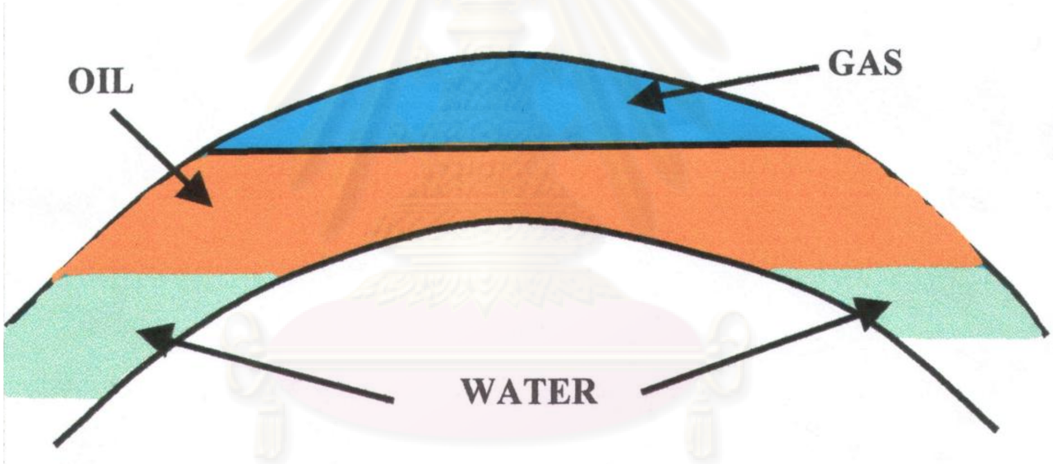

Figure 3.1: Schematic of a typical gas-cap-drive reservoir [11]

3.4.3 Water-drive Reservoirs

Most oil or gas reservoirs have water aquifers. When this water aquifer is an active one, continuously fed by incoming water, then this bottom water will expand as pressure of the oil/gas zone is reduced because of production causing an extra driving energy. This kind of reservoir is called water drive reservoirs. The expanding water also moves and displaces oil or gas in an upward direction from lower parts of the reservoir, so the pore spaces vacated by oil or gas produced are filled by water. The oil and gas are progressively pushed towards the well bore. Recovery efficiencies of 70 to 80 % of the original oil in place (OOIP) are possible in some water drive reservoirs.

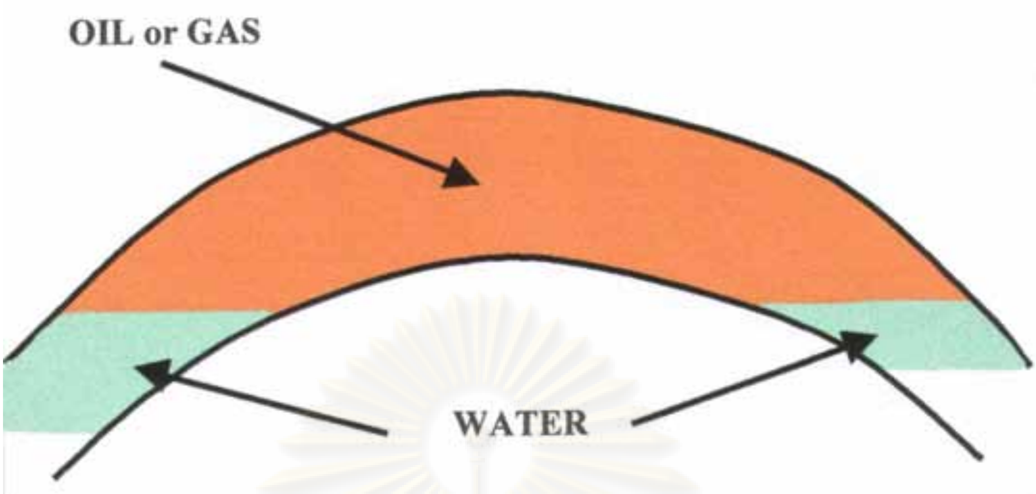

Figure 3.2: Schematic of a typical water-drive reservoir [11]

3.4.4 Gravity Drainage reservoirs

Gravity drainage may be a primary producing mechanism in thick reservoirs that have a good vertical communication or in steeply dipping reservoirs. Gravity drainage is a slow process because gas must migrate up structure or to the top of the formation to fill the space formerly occupied by oil. Gas migration is fast relative to oil drainage so those oil rates are controlled by the rate of oil drainage.

3.4.5 Under-saturated reservoirs

A crude oil is under-saturated when it contains less gas than is required to saturate the oil at the pressure and temperature of the reservoir. When the oil is highly under-saturated much of the reservoir energy is stored in the form of fluid and rock compressibility. Pressure declines rapidly as fluids are withdrawn from the under-saturated reservoir until the bubble point is reached. Then, solution gas drive becomes the source of energy for fluid displacement. Reservoir fluid analysis, PVT behavior and the pressure data will identify an under-saturated reservoir. Those reservoirs are good candidates for water injection to maintain a high pressure to increase oil recovery.

CHAPTER IV

METHODOLOGY

The proposed methodology to investigate the impact of production strategy on the ultimate recovery factor for different kinds of reservoir fluid in multilayer system, reservoir simulator is used as a tool to mimic different types of reservoir and predict the production performance. As a result, the best strategy for each reservoir type can be obtained.

We used ECLIPSE 100 reservoir simulator for black oil to simulate different multilayer reservoirs containing different kinds of fluid. Totally, fifteen cases of multilayer reservoirs were put into the study in order to fulfill the objective. Then, sensitivity analysis is conducted to observe the performance of different production strategies.

4.1 Case description

A hypothetical reservoir simulation model used in the current study represents two layers of homogeneous commingled reservoirs. At initial condition of the reservoirs, six different combinations of fluid can possibly exist in each layer of reservoir. These combinations include 1) oil, 2) gas, 3) gas&oil, 4) oil&water, 5) gas&water, and 6) gas/oil/water. As a consequence, fifteen cases of multilayer reservoirs were constructed as defined in Table 4.1.

Table 4.1: Fluid description of 15 different cases

CASE	DESCRIPTION
Case 1: G – O	The top layer contains single-phase gas while the bottom layer contains single-phase oil.
Case 2: G – G&O	The top layer contains single-phase gas while the bottom layer contains two-phase gas and oil.
Case 3: O – G&O	The top layer contains single-phase oil while the bottom layer contains two-phase gas and oil.

Table 4.1: Fluid description of 15 different cases (cont.)

Case	Description
Case 4: O – O&W	The top layer contains single-phase oil while the bottom layer contains two-phase oil and water.
Case 5: G – G&W	The top layer contains single-phase gas while the bottom layer contains two-phase gas and water.
Case 6: G – O&W	The top layer contains single-phase gas while the bottom layer contains two-phase oil and water.
Case 7: O – G&W	The top layer contains single-phase oil while the bottom layer contains two-phase gas and water.
Case 8: G – G&O&W	The top layer contains single-phase gas while the bottom layer contains three-phase gas, oil and water.
Case 9: O – G&O&W	The top layer contains single-phase oil while the bottom layer contains three-phase gas, oil and water.
Case 10: G&O – G&W	The top layer contains two-phase of gas and oil while the bottom layer contains two-phase gas and water.
Case 11: G&O – O&W	The top layer contains two-phase of gas and oil while the bottom layer contains two-phase gas and water.
Case 12: G&W – O&W	The top layer contains two-phase of gas and water while the bottom layer contains two-phase oil and water.
Case 13: G&O – G&O&W	The top layer contains two-phase of gas and oil while the bottom layer contains three-phase gas, oil and water.
Case 14: G&W – G&O&W	The top layer contains two-phase of gas and water while the bottom layer contains three-phase gas, oil and water.
Case 15: O&W – G&O&W	The top layer contains two-phase of oil and water while the bottom layer contains three-phase gas, oil and water.

4.2 ECLIPSE input data

The data files in ECLIPSE are divided into sections and each input file is introduced by a keyword. Each section required a header word and the header words of the main sections are GRID, PVT, SCAL, INITIALIZATION, REGIONS, SCHEDULE, and SUMMARY. Moreover, these sections must be generated following the above order. Each section must contain minimum data required. The sections that are normally required for the input files are GRID, PVT, SCAL, and SCHEDULE.

4.2.1 GRID

In this section, the geometry of the reservoir and its permeability and porosity are specified. The reservoir model is constructed by amount of established volume elements namely 'grid blocks' that represent the geological reservoir construction. Cartesian grid model, which is commonly used to simulate the full field simulation model, will be used. The reservoir model is assumed to be homogenous. The top of structure is located at a depth of 2,350 ft, with dimensions of 5,000 ft x 5,000 ft and a thickness of 500 ft. The number of block is 50 x 50 x 50. The porosity of the reservoir is assumed to be 25%, the horizontal permeability is 100 mD, and vertical permeability is 10 mD. Figures 4.1, 4.2, and 4.3 illustrate the model used in the current study in terms of top view, side view and 3D view, respectively.

The reservoir model consists of 100 ft of productive zone at top layer and 100 ft of productive zone at bottom layer. The two layers are separated by 100 ft of impermeable zone (coal or shale). For that reason, impermeable zone was defined in the reservoir model by specifying them as inactive cell. Shale is in layer 1-10, 21-30 and 41-50 are specified as inactive cell in the model by using ACTNUM keyword. The constructed model with identified active and inactive cells is illustrated in Figure 4.3.

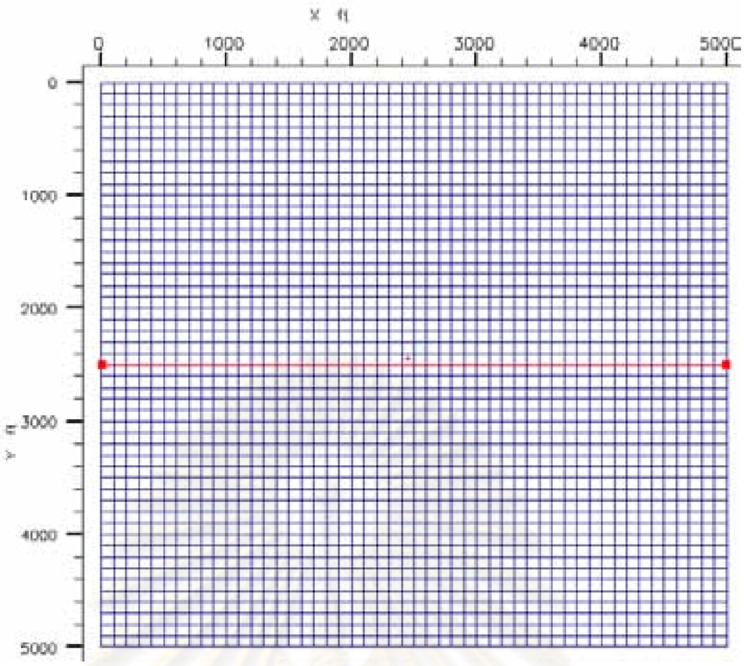

Figure 4.1: Top view of the reservoir model

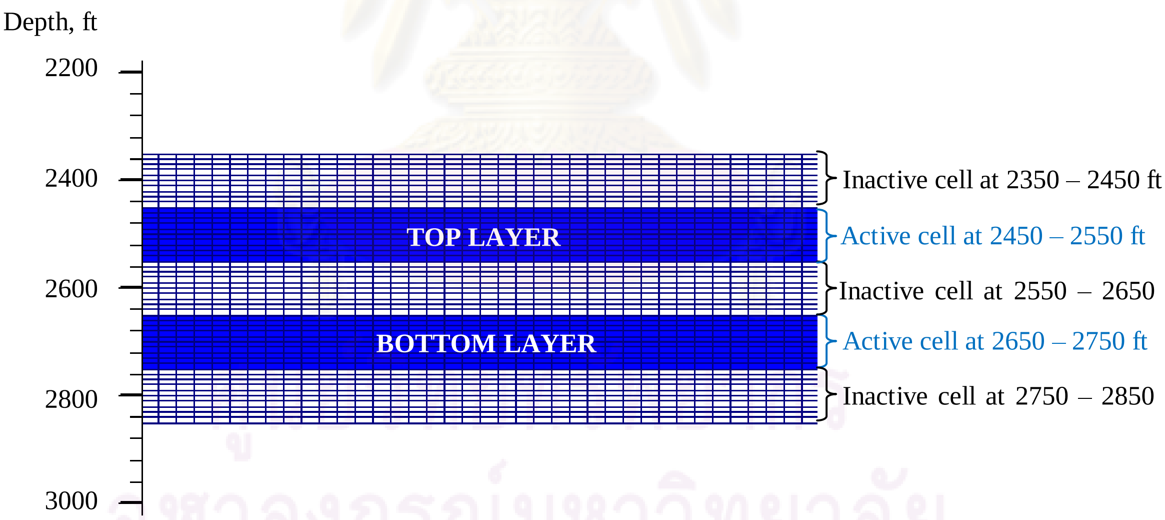

Figure 4.2: Side view of the reservoir model

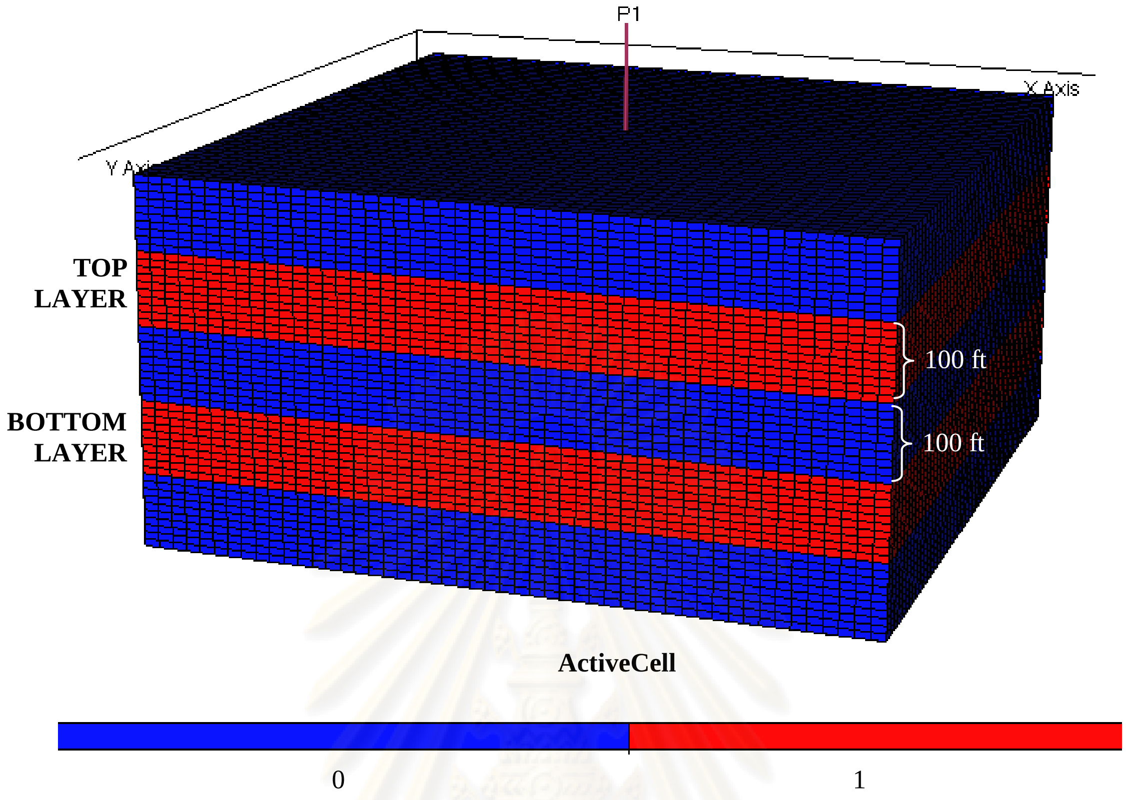

Figure 4.3: 3D view of the reservoir model

4.2.2 PVT

Since all cases use the same fluid property. For example, gas and oil properties in case 1: G_O is the same as gas and oil properties in case 2: G_G&O. Therefore, PVT properties of oil (PVTO) at above the bubble point pressure and PVT properties of dry gas (PVTG) were input to the ECLIPSE. The input data for PVTO and PVTG are shown in Table 4.2 and 4.3, respectively.

Because both top and bottom layers use the same PVT, thus different bubble point pressure was input to the ECLIPSE. The reason for different bubble point pressure between two layers is that the bubble point pressure is the reservoir pressure at GOC depth. Since each layer has the same fluid property but different GOC depths, therefore; the reservoir pressure at GOC depth or the bubble point pressure was different for each layer.

The bubble point pressure for the top layer is 1,062.2 psia at *Rs* of 0.973 MSCF/STB while the bubble point pressure for the bottom layer is 1,150 psia at *Rs* of 1.140 MSCF/STB.

At surface conditions, the oil density is 42.28 lb/ft^3, the density of water and gas is 62.43 lb/ft^3 and 0.0971 lb/ft^3, respectively. The initial solution gas-oil ratio is 973 SCF/STB. The water formation volume factor is 1.013 RB/STB at 3118 psia with constant water viscosity of 0.4 cp and compressibility of 2.74E-6 (psi)$^{-1}$.

Table 4.2: Input data for PVTO

```
PVTO
   0.03      100.0      1.19        0.116  /
   0.137     250.0      1.274       0.107 /
   0.368     500.0      1.459       0.094 /
   0.433     570.3      1.510       0.091 /
   0.449     587.8      1.523       0.090 /
   0.466     605.4      1.536       0.089 /
   0.500     640.5      1.562       0.088
             781.1      1.548       0.091
             1062.2     1.522       0.096
             1500.0     1.489       0.105
             1783.8     1.471       0.111
             2000.0     1.458       0.115
             2500.0     1.433       0.124
             3035.7     1.410       0.134
             3400.0     1.397       0.141 /
   0.642     781.1      1.674       0.083 /
   0.973     1062.2     1.934       0.073
             1500.0     1.871       0.081
             1783.8     1.838       0.085
             2000.0     1.816       0.089
             2500.0     1.773       0.097
             3035.7     1.735       0.105
             3400.0     1.714       0.111 /
   1.140     1150.0     2.040       0.070
             3400.0     1.820       0.100 /
   1.686     1500.0     2.508       0.060
             1783.8     2.437       0.064
             2000.0     2.392       0.067
             2500.0     2.309       0.074
             3035.7     2.240       0.081
             3400.0     2.202        0.086 /
   2.403     1783.8     3.107       0.052
             2000.0     3.025       0.055
             2500.0     2.881       0.061
             3035.7     2.770       0.067
             3400.0     2.709       0.071 /
   5.000     3300.0     3.500       0.041
             3400.0     3.460       0.042 /
/
```

Table 4.3: Input data for PVTG

```
PVDG
100         17          0.0115
250.0       12.65       0.012
500.0       6.076       0.013
570.3       5.662       0.013
587.8       5.558       0.013
605.4       5.455       0.013
640.5       5.248       0.013
781.1       4.420       0.013
1062.2      3.413       0.014
1150.0      3.180       0.0144
1500.0      2.037       0.016
1783.8      1.494       0.018
2000.0      1.326       0.019
2500.0      1.073       0.023
3035.7      0.916       0.026
3400.0      0.845       0.029
/
```

4.2.3 SCAL

In special core analysis section, four sets of saturation tables are specified. The first table is relative permeability with saturation function of oil and water defined in SWOF keyword, as detailed in Table 4.4 and graphically shown in Figure 4.4. This table was used when the reservoir contained both oil and water at initial reservoir condition which applied to all cases except case 5: G-GW.

Table 4.4: Input data for SWOF

```
SWOF
  Sw        Krw         Krow        Pcow

  0.20      0.000       0.900       0
  0.22      0.000       0.803       0
  0.30      0.001       0.487       0
  0.40      0.009       0.221       0
  0.50      0.045       0.078       0
  0.60      0.154       0.014       0
  0.70      0.387       0.001       0
  0.73      0.480       0.000       0
  0.80      0.800       0.000       0
  1.00      1.000       0.000       0
/
```

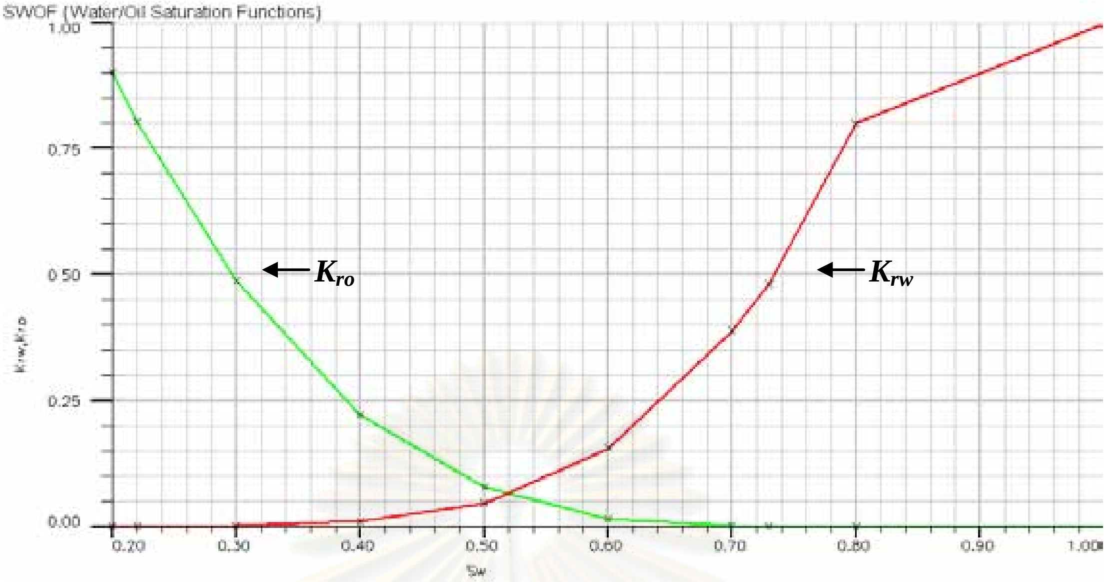

Figure 4.4: Relative permeability with saturation function of oil and water

The second table is relative permeability with saturation function of gas and oil defined in SGOF keyword, as detailed in Table 4.5 and graphically shown in Figure 4.5. This table was used when the reservoir has contained both gas and oil at initial reservoir condition which applied to all cases except case 5: G-GW.

Table 4.5: Input data for SGOF

```
SGOF
  Sg          Krg          Krog          Pcog

  0.00        0.000        0.900         0.0
  0.06        0.000        0.525         0.0
  0.10        0.000        0.375         0.0
  0.14        0.000        0.213         0.0
  0.19        0.002        0.106         0.0
  0.24        0.006        0.042         0.0
  0.29        0.013        0.011         0.0
  0.33        0.035        0.001         0.0
  0.37        0.061        0.000         0.0
  0.80        0.900        0.000         0.0
/
```

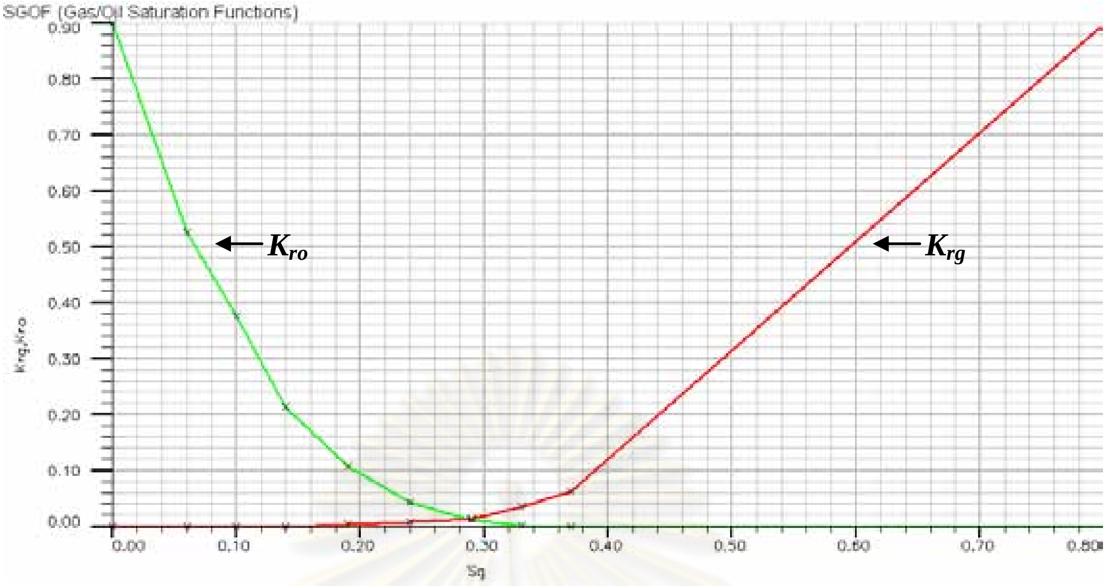

Figure 4.5: Relative permeability with saturation function of gas and oil

The third table is relative permeability with saturation function of water defined in SWFN keyword, as detailed in Table 4.6 and graphically shown in Figure 4.6. This table was used when the reservoir did not contained oil but water at initial reservoir condition which applied to case 5: G-GW only.

Table 4.6: Input data for SWFN

```
SWFN
   Sw          Krw          Pc
   0.20        0.000        0
   0.22        0.000        0
   0.30        0.001        0
   0.40        0.009        0
   0.50        0.045        0
   0.60        0.154        0
   0.70        0.387        0
   0.73        0.480        0
   0.80        0.800        0
   1.00        1.000        0
/
```

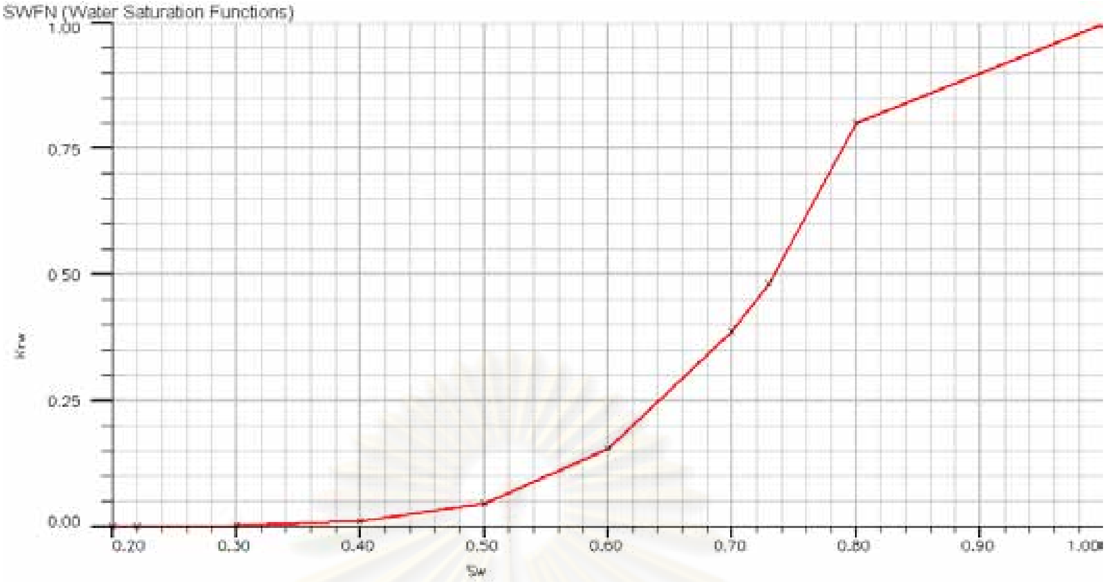

Figure 4.6: Relative permeability with saturation function of water

The last table is relative permeability with saturation function of gas defined in SGFN keyword, as detailed in Table 4.7 and graphically shown in Figure 4.7. This table was used when the reservoir did not contained oil but gas at initial reservoir condition which applied to case 5: G-GW only.

Table 4.7: Input data for SGFN

```
SGFN
   Sg        Krg        Pc
   0.00      0.000      0
   0.06      0.000      0
   0.10      0.000      0
   0.14      0.000      0
   0.19      0.002      0
   0.24      0.006      0
   0.29      0.013      0
   0.33      0.035      0
   0.37      0.061      0
   0.80      0.900      0
/
```

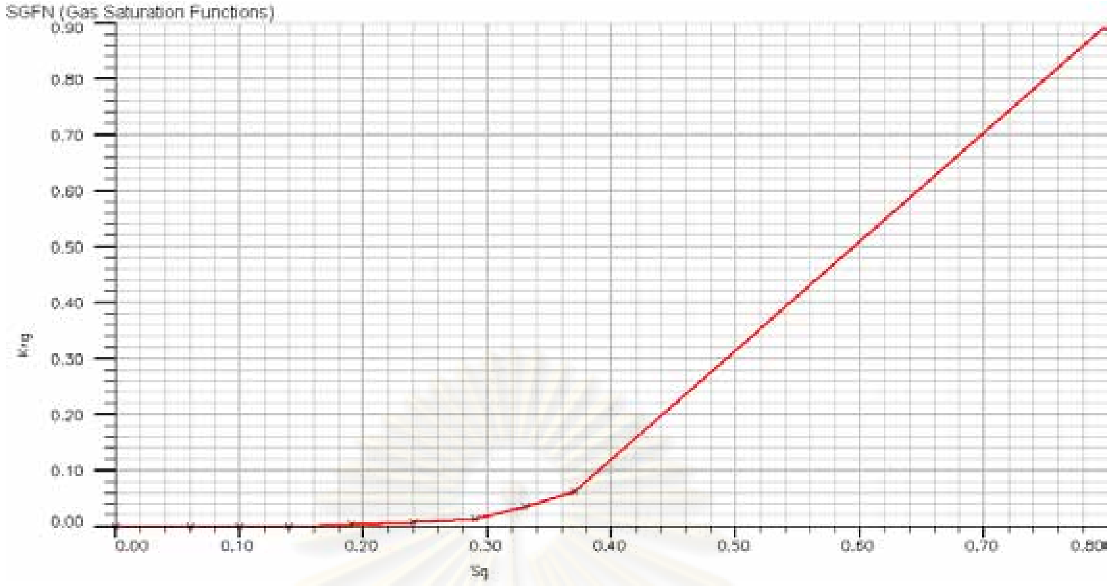

Figure 4.7: Relative permeability with saturation function of gas

4.2.3 INITIALIZATION

The equilibration method was used to define initial reservoir condition. Datum depth, pressure at datum depth, WOC depth and GOC depth were input into the simulator. In case the datum depth is the same as GOC depth, the pressure at that depth is the bubble point pressure. If not, table of *Rs* versus depth must be defined to let ECLIPSE calculates pressure from fluid density gradient for all grid cells. Depth of GOC and WOC is shown in Figure 4.8.

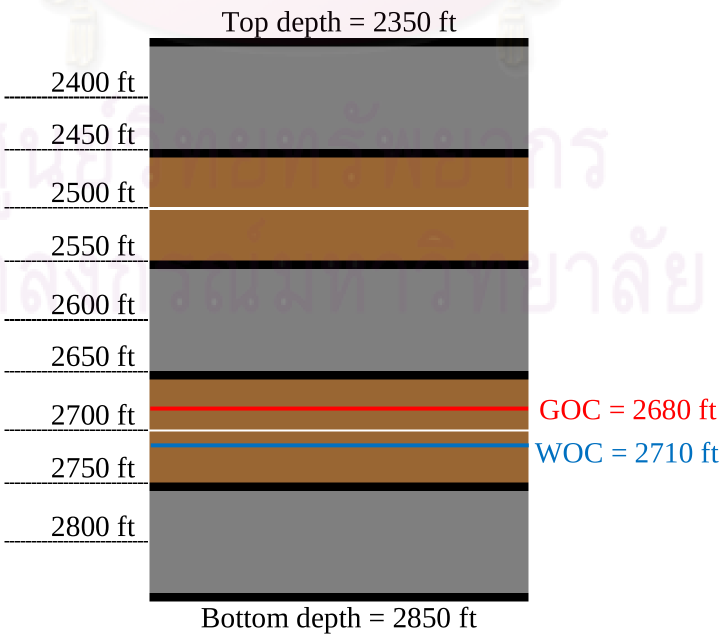

Figure 4.8: Depth of reservoir model

There are 2 equilibration data: one for the top layer and another one for the bottom layer as shown in Table 4.8.

Table 4.8: Input data for initialization of 15 different cases

Case	Layer	Datum depth (ft)	P at datum depth (psia)	WOC depth (ft)	GOC depth (ft)
Case 1: G – O	Top layer	2550	1062.2	2550	2550
	Bottom layer	2700	1163.6*	2750	2650
Case 2: G – G&O	Top layer	2550	1062.2	2550	2550
	Bottom layer	2700	1150	2750	2700
Case 3: O – G&O	Top layer	2500	1076.9*	2550	2450
	Bottom layer	2700	1150	2750	2700
Case 4: O – O&W	Top layer	2500	1076.9*	2550	2450
	Bottom layer	2700	1163.6*	2700	2650
Case 5: G – G&W	Top layer	2550	1062.2	2550	2550
	Bottom layer	2700	1150	2700	2700
Case 6: G – O&W	Top layer	2550	1062.2	2550	2550
	Bottom layer	2700	1163.6*	2700	2650
Case 7: O – G&W	Top layer	2500	1076.9*	2550	2450
	Bottom layer	2700	1150	2700	2700
Case 8: G – G&O&W	Top layer	2550	1062.2	2550	2550
	Bottom layer	2680	1150	2720	2680
Case 9: O – G&O&W	Top layer	2500	1076.9*	2550	2450
	Bottom layer	2680	1150	2720	2680
Case 10: G&O – G&W	Top layer	2500	1062.2	2550	2500
	Bottom layer	2700	1150	2700	2700
Case 11: G&O – O/&W	Top layer	2500	1062.2	2550	2500
	Bottom layer	2700	1163.6*	2700	2650
Case 12: G&W – O&W	Top layer	2500	1062.2	2500	2500
	Bottom layer	2700	1163.6*	2700	2650
Case 13: G&O – G&O&W	Top layer	2500	1062.2	2550	2500
	Bottom layer	2680	1150	2720	2680
Case 14:G&W – G&O&W	Top layer	2500	1062.2	2500	2500
	Bottom layer	2680	1150	2720	2680
Case 15: O&W – G&O&W	Top layer	2500	1083.9*	2500	2450
	Bottom layer	2680	1150	2720	2680

**This value is obtained from ECLIPSE using calculation from fluid density gradient.*

Model of each case at initialization was visualized by phase separation as shown in Figure 4.9 through Figure 4.23.

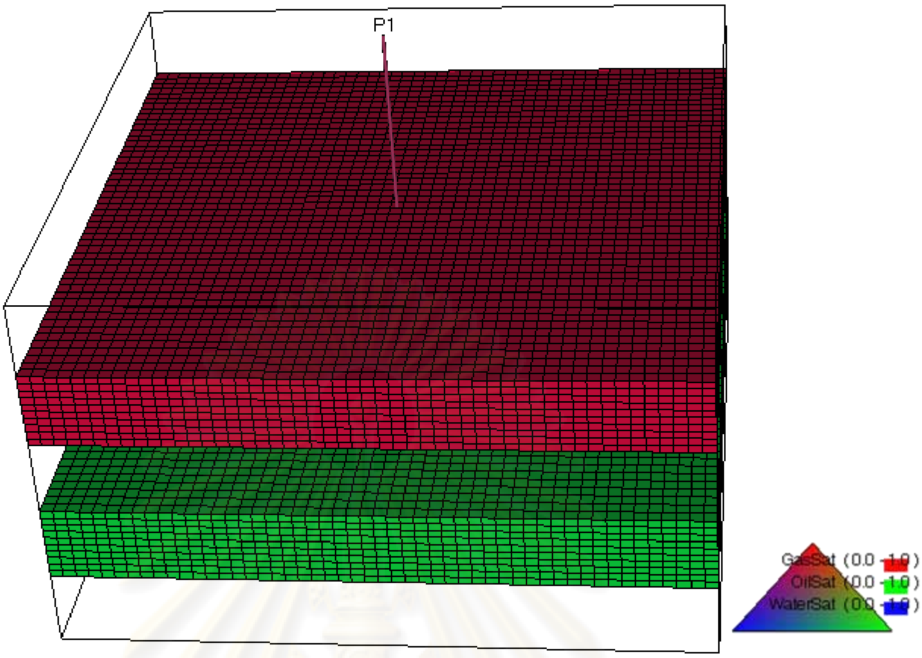

Figure 4.9: Initialized reservoir model for Case 1: G – O

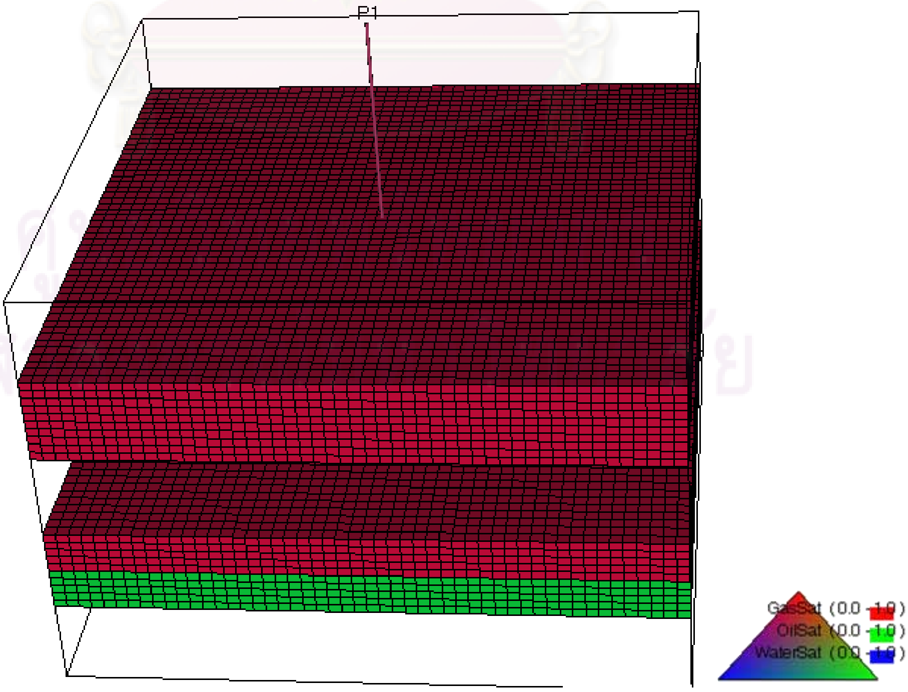

Figure 4.10: Initialized reservoir model for Case 2: G – G&O

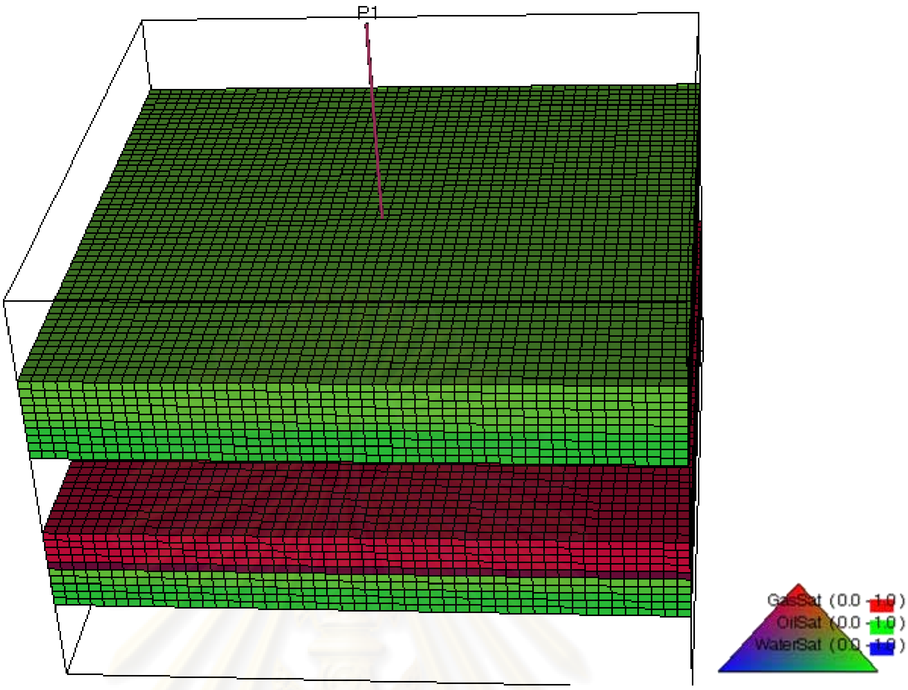

Figure 4.11: Initialized reservoir model for Case 3: O – G&O

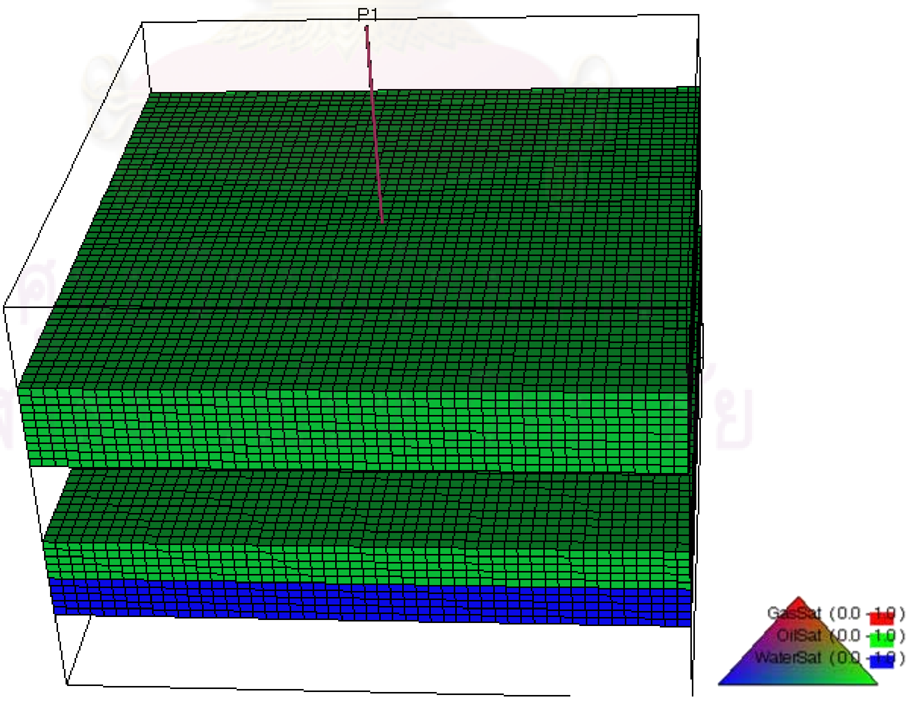

Figure 4.12: Initialized reservoir model for Case 4: O – O&W

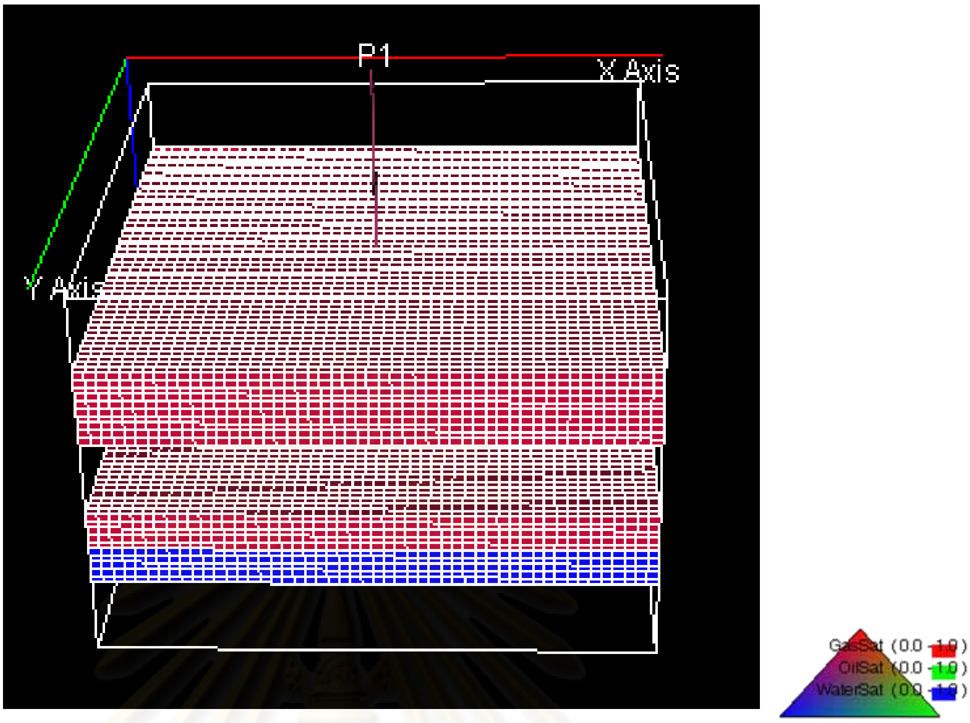

Figure 4.13: Initialized reservoir model for Case 5: G – G&W

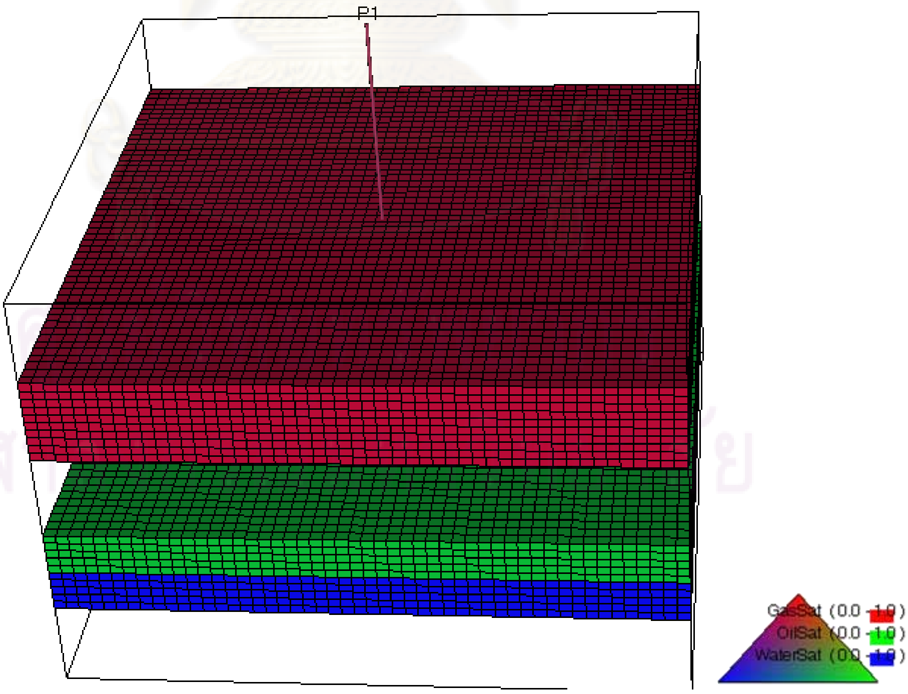

Figure 4.14: Initialized reservoir model for Case 6: G – O&W

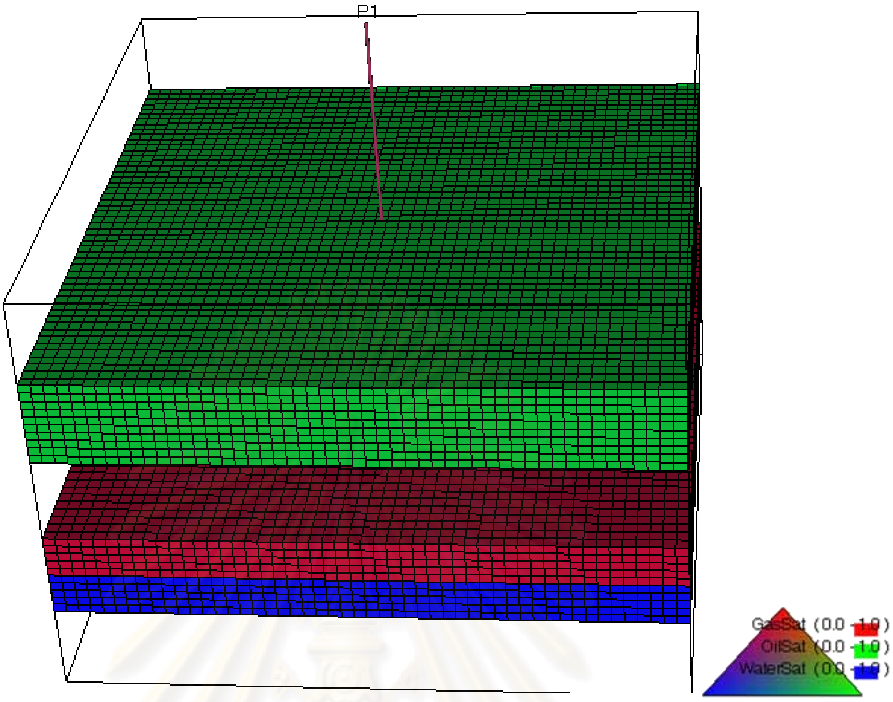

Figure 4.15: Initialized reservoir model for Case 7: O – G&W

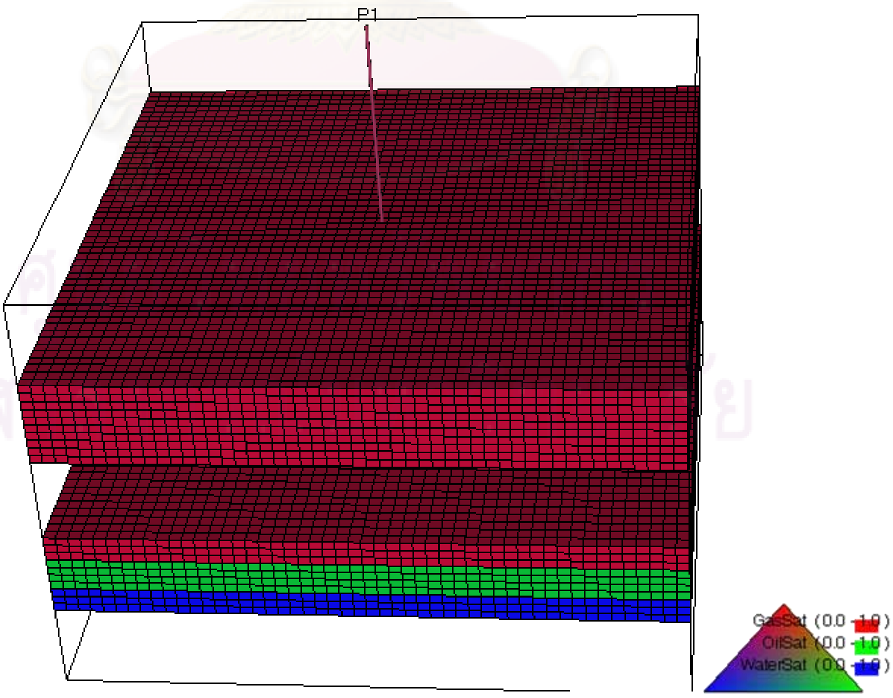

Figure 4.16: Initialized reservoir model for Case 8: G – G&O&W

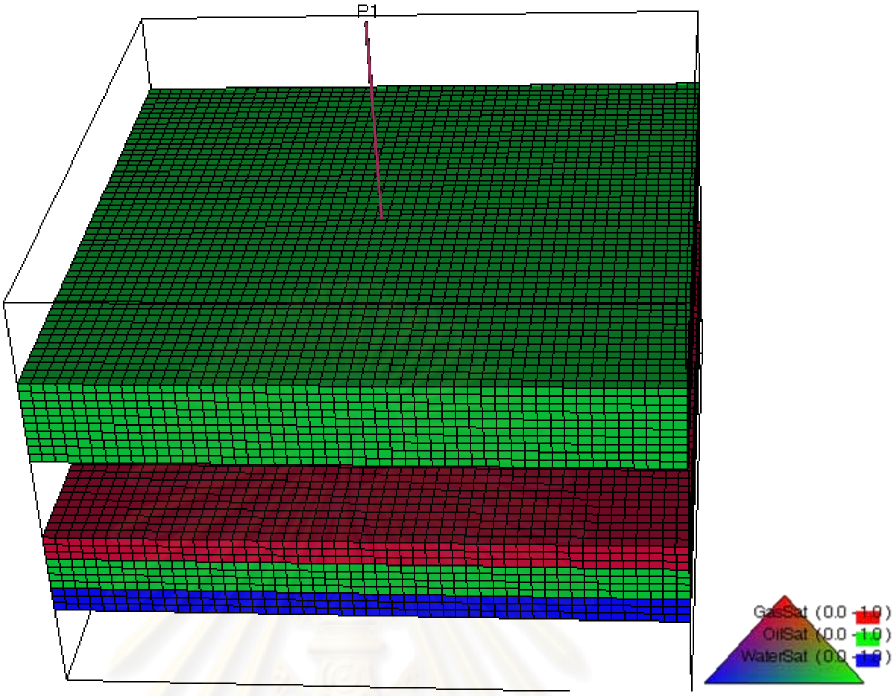

Figure 4.17: Initialized reservoir model for Case 9: O – G&O&W

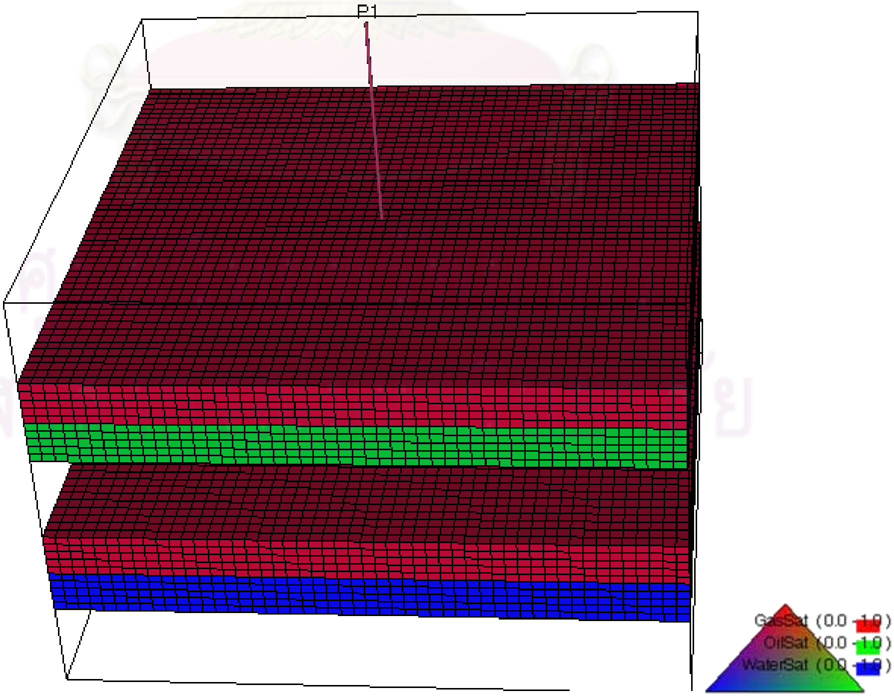

Figure 4.18: Initialized reservoir model for Case 10: G&O – G&W

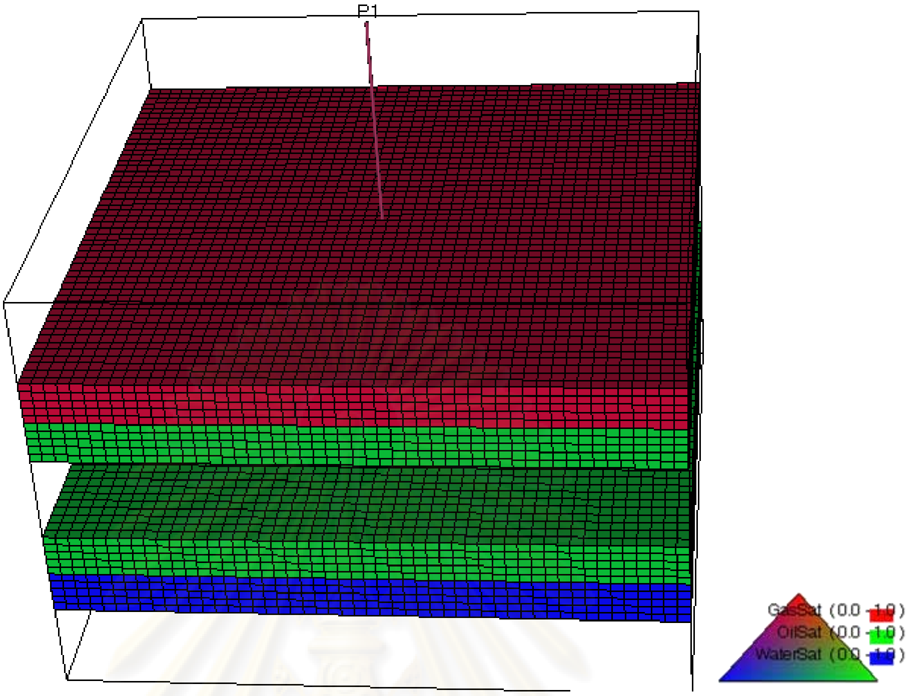

Figure 4.19: Initialized reservoir model for Case 11: G&O – O&W

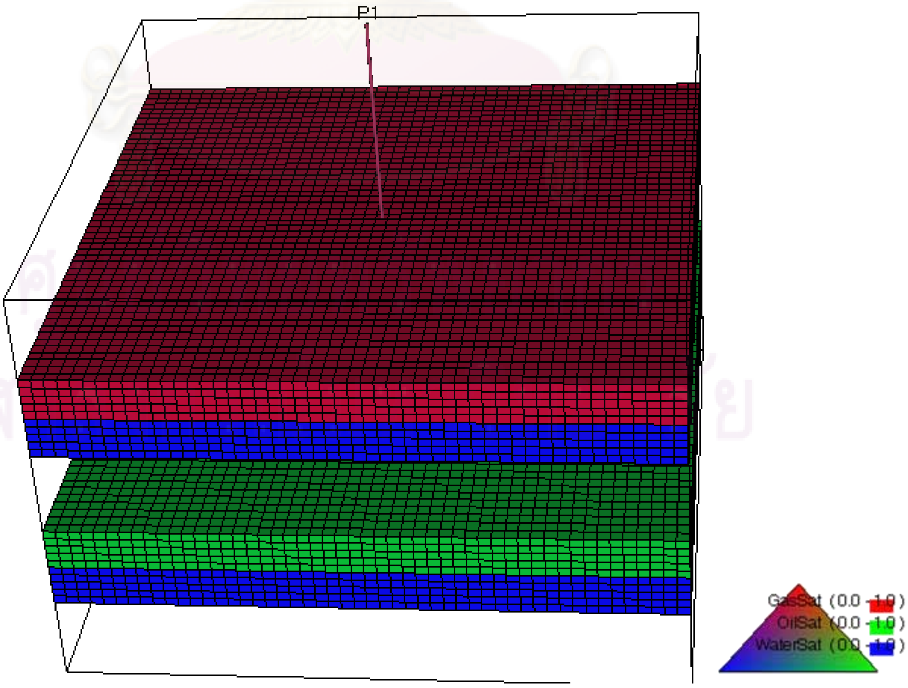

Figure 4.20: Initialized reservoir model for Case 12: G&W – O&W

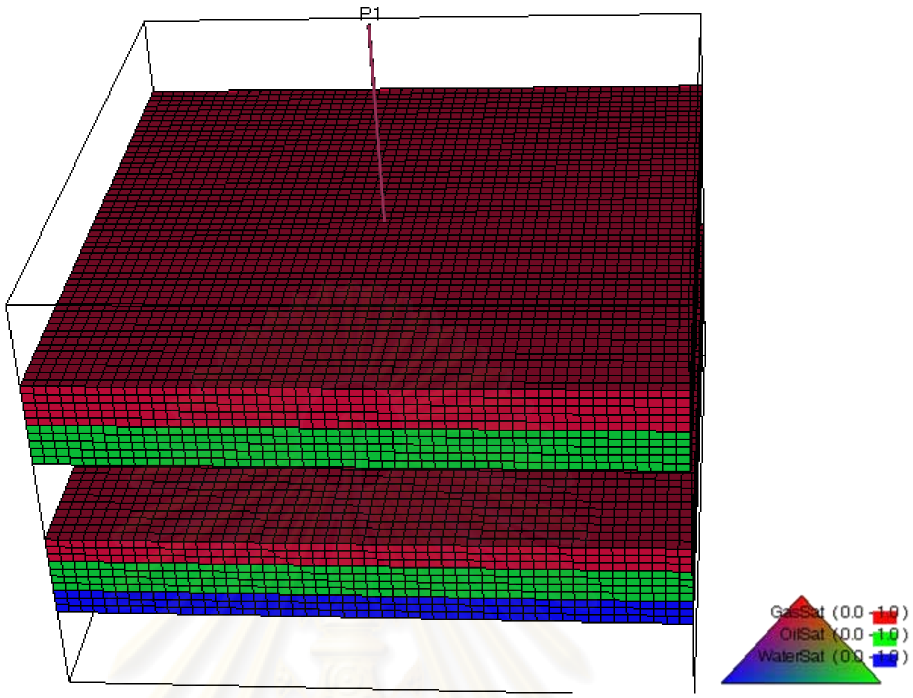

Figure 4.21: Initialized reservoir model for Case 13: G&O – G&O&W

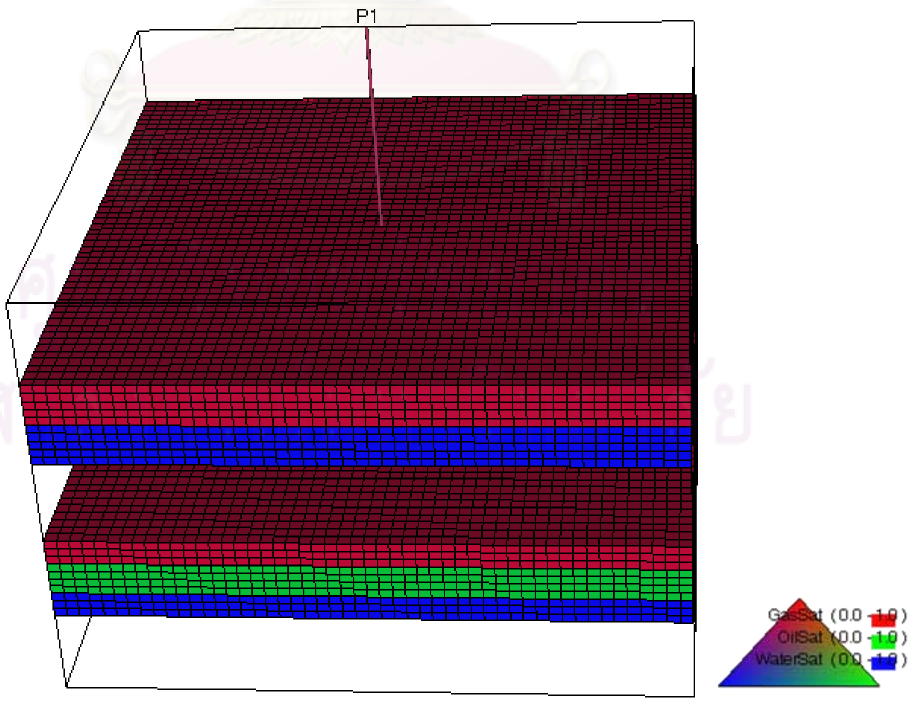

Figure 4.22: Initialized reservoir model for Case 14: G&W – G&O&W

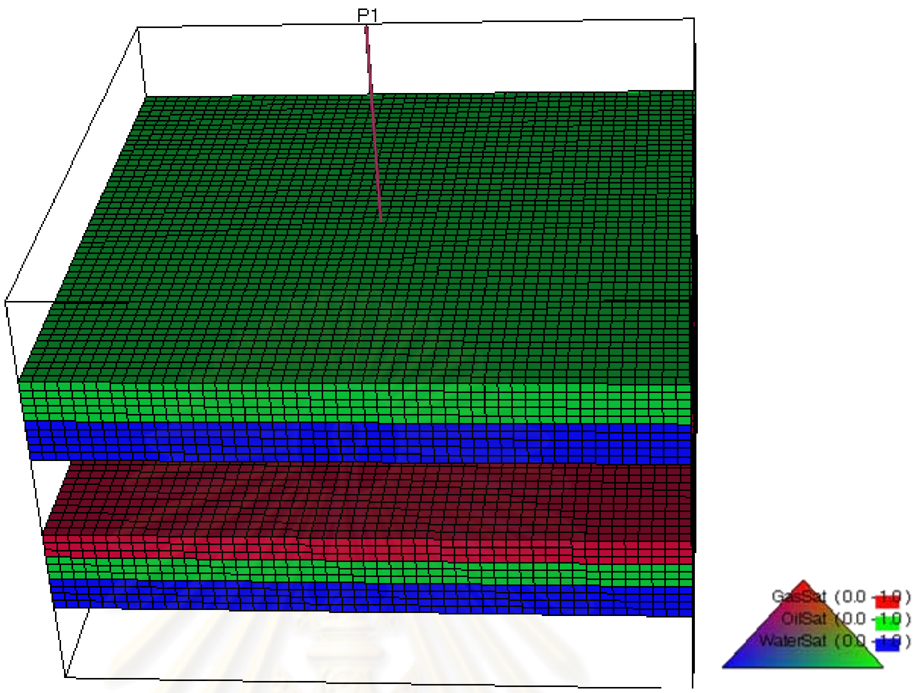

Figure 4.23: Initialized reservoir model for Case 15: O&W – G&O&W

4.2.4 REGIONS

The REGIONS section splits the computational grid blocks into regions for calculating fluid properties, saturation properties and initial conditions in the reservoir in each region. For this study, FIPNUM and EQUINUM were defined in order to calculate region production and initial conditions, respectively.

4.3 Simulation conditions

After all cases had been established, they were simulated as the reservoir was produced by natural depletion method. The tubing head pressure target of 200 psia was used for production well and VFP tables were generated via PROSPER. The maximum oil or gas production rate was used as the control variable to sustain a plateau production period at the beginning. The oil rate was varied case by case depending on OOIP while gas rate was set at 10,000 MSCF/D. The economic limits were defined at minimum gas rate of 500 MSCF/D and minimum oil rate was varied as shown in Table 4.9.

The perforation intervals applied to each fluid type in the layered reservoir are shown in Table 4.10.

Table 4.9: The maximum rate and economic limit for oil production

Case	Maximum oil production rate (STB/D)	Minimum oil production rate (STB/D)
Case 1: G – O	1,000	50
Case 2: G – G&O	500	25
Case 3: O – G&O	1,500	75
Case 4: O – O&W	1,500	75
Case 5: G – G&W	*	**
Case 6: G – O&W	500	25
Case 7: O – G&W	1,000	50
Case 8: G – G&O&W	300	15
Case 9: O – G&O&W	1,300	65
Case 10: G&O – G&W	500	25
Case 11: G&O – O&W	1,000	50
Case 12: G&W – O&W	500	25
Case 13: G&O – G&O&W	800	40
Case 14: G&W – G&O&W	300	15
Case 15: O&W – G&O&W	800	40

**Maximum gas rate was set at 10,000 MSCF/D*
***Minimum gas rate was set at 500 MSCF/D as an economic limit.*

Table 4.10: Perforation interval for different kinds of reservoir fluid

Reservoir fluid	Perforation interval
Single-phase gas	Well is perforated 100 ft full to base of gas sand.
Single-phase oil	Well is perforated 100 ft full to base of oil zone.
Two-phase gas and oil	Well is perforated 30 ft from the bottom of oil zone.
Two-phase gas and water	Well is perforated 30 ft from the top of gas zone.
Two-phase oil and water	Well is perforated 30 ft from the top of oil zone.
Three-phase gas, oil and water	Well is perforated 20 ft in the middle of oil zone

4.4 Production strategy

A study on production strategy for 15 cases was conducted in order to observe the impact of different production strategies for multilayer reservoirs and develop guideline for each case. Four different production strategies were considered here as defined as follows were considered.

Strategy 1: Commingled production

The fluids are produced from two layers simultaneously.

Strategy 2: Separate layer production

The fluid is produced from one layer at a time, starting with the bottom layer. When the production from the bottom layer reaches economics limit or stops producing, the reservoir is plugged and isolated. Then, we start producing from the top layer.

Strategy 3: Commingled production when bottom layer half depleted

The fluid is produced from one layer at a time, starting with the bottom layer. When the production rate decreases to half of the original rate, the upper layer is perforated. Then, the production comes from two layers simultaneously.

Strategy 4: Commingled production when top layer half depleted

The fluid is produced from one layer at a time, starting with the top layer. When the production rate decreases to half of the original rate, the lower layer is perforated. Then, the production comes from two layers simultaneously.

CHAPTER V

SIMULATION RESULTS AND ANALYSIS

When fifteen simulation cases representing different multilayer reservoirs which contain different kinds of fluid have been simulated, all results are generated and analyzed in this chapter. The production performances i.e. oil production rate, gas production rate and water production rate for different production strategies are observed to see the effects of each approach on cumulative production, recovery factor and abandonment time.

Cumulative production of each reservoir fluid, recovery factor and abandonment time achieved from each production strategy is visually summarized in the table form. The highlight cells are the most favorable out of all strategies comparing factor by factor. The main factors primarily concerned as criteria to select the best production strategy and develop the best guideline for each case are cumulative production and recovery factor of oil, gas and water. The best strategy should deliver maximum barrel of oil equivalent or BOE as well as deliver minimum water. When these factors obtained from different strategies are similar, then the abandonment time will be used as criteria.

At this point, the results obtained from simulation are presented and analyzed case by case. As well, possible reasons that support the best strategy in each case are described.

5.1 Case 1: G – O

In this case, the reservoir consists of 100 ft of gas zone at the top layer and 100 ft of oil zone at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a gas reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of gas sand. The bottom layer is an undersaturated oil reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of oil sand. A well schematic of Case 1 is shown in Figure 5.1.

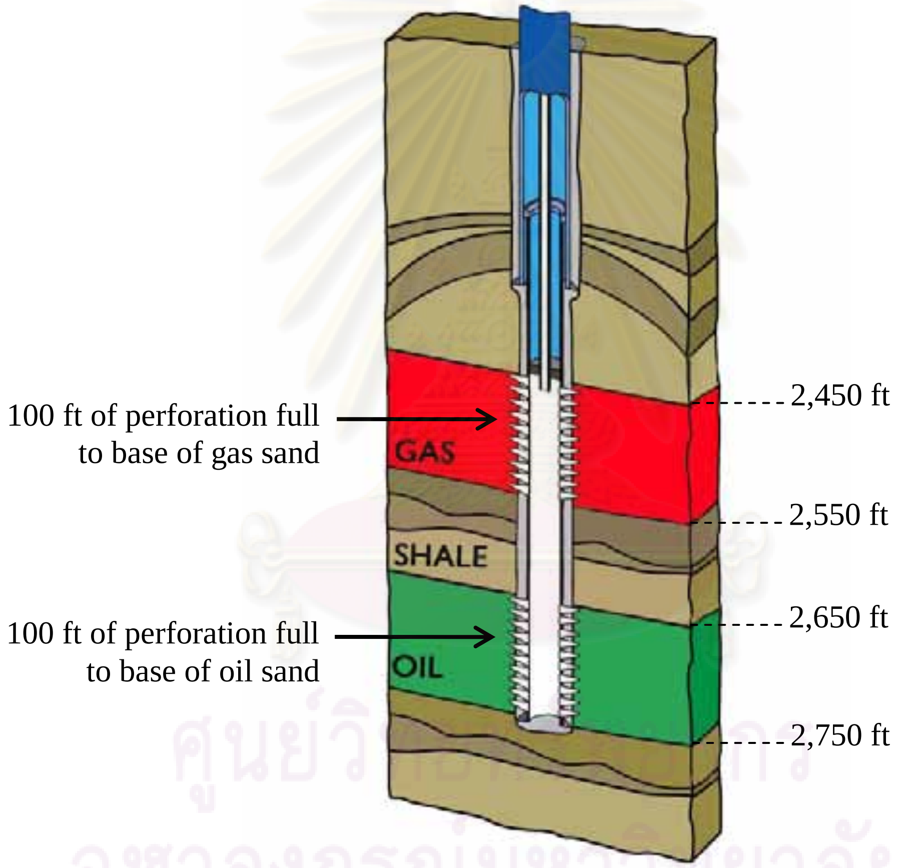

Figure 5.1: Well schematic for Case 1: G – O

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.2 and comparative results are summarized in Table 5.1.

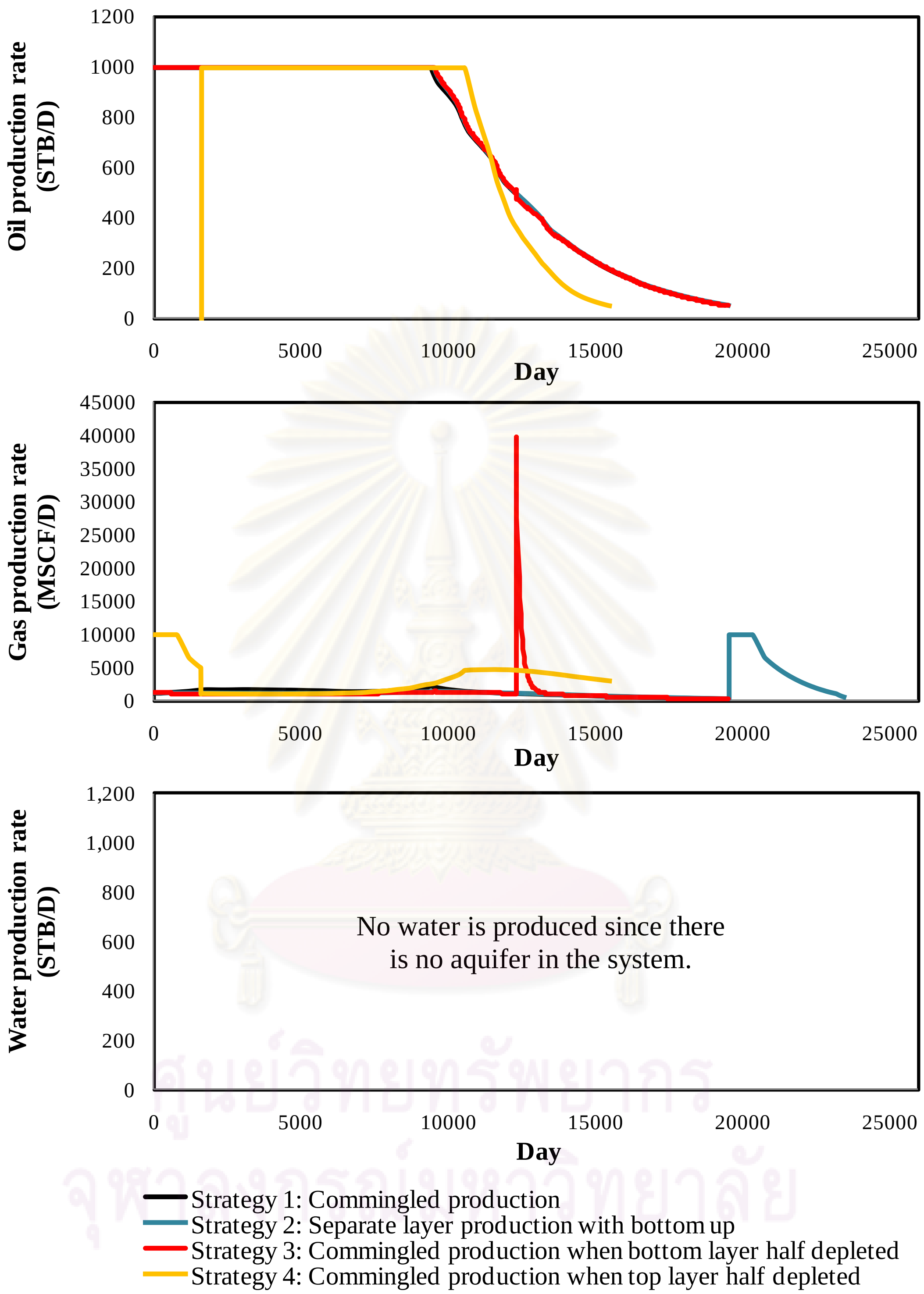

Figure 5.2: Production profiles of Case 1: G – O

Table 5.1: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 1: G - O

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	12,995	13,066	13,040	10,585
Gas (MMSCF)	23,031	37,313	23,032	48,326
Free gas (MMSCF)	10,871	25,093	10,829	39,163
Solution gas (MMSCF)	12,160	12,220	12,203	9,163
MBOE	16,965	19,499	17,011	18,917
Water (STB)	0	0	0	0
Oil recovery factor (%) *	30.04	30.21	30.15	24.47
Gas recovery factor (%) **	30.67	49.69	30.67	64.35
Abandonment time (day)	19,426	23,469	19,531	15,491

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.1.1 Oil production

For oil production comparison, cumulative production and recovery factor obtained from strategies 1, 2 and 3 are very similar as summarized in Table 5.1. This is because the wells start producing oil from the same OOIP at the very beginning and keep producing oil until the reservoir depletes at abandonment rate as shown in Figure 5.2. Thus, cumulative oil productions obtained from these 3 strategies are equal as shown in Figure 5.5B.

Strategy 2 delivers the highest cumulative oil production and oil recovery factor. The reason is that no crossflow takes place between the layers since oil from the bottom layer and gas from the top layer is produced one at a time.

Strategy 4 delivers the lowest cumulative oil production and oil recovery factor. The well starts producing gas from the top layer reservoir which creates a very large and rapid pressure drawdown at the top layer as shown in Figure 5.4A. After that, both layers are produced simultaneously. Since there is a large difference in reservoir pressure between the two layers, a lot of oil from the bottom layer flows into the top layer. This is the reason why a large quantity of oil remains in the top layer and cannot be produced to the surface. The negative oil rate and cumulative oil production of the layer can assure that crossflow takes place in the reservoir as clearly revealed in Figure 5.3 and 5.5A.

Strategies 1 and 3 do not deliver the best result for oil production since cross-flows occurs as shown in Figure 5.3 but cannot be obviously seen. The cause is that the pressure at the top layer which is occupied by gas depletes a lot faster than the bottom layer and hence oil from the bottom layer flows into the gas sand. However, the amount of oil that flows into the gas layer is not as much as strategy 4.

In summary, strategy 2 gives the highest ultimate production of oil as shown in Table 5.1 with the yellow highlight. However, strategy 1 which yields a little bit lower oil recovery may be more attractive since only one batch of perforation is needed while strategy 2 needs two perforation runs.

5.1.2 Gas production

For gas recovery, strategies 2 and 4 deliver excellent outcomes because gas from the top layer reservoir is produced separately. Producing gas without oil, the pressure drawdown is large and sharp as depicted in Figure 5.4A. In general, as the reservoir pressure drop is larger, a higher amount of gas is produced, due to a greater expansion of gas remaining in the reservoir. This mechanism that provides energy to move gas to the surface is called depletion-drive which is an efficient mechanism for a gas reservoir.

Importantly, strategy 4 can deliver the extra amount of gas as shown in Figure 5.6B due to the additional supporting pressure from crossflow which abruptly takes place after perforating the bottom layer. A lot of oil from the crossflow is a key reason since it supports energy to move extra amount of fluid out of the top layer reservoir. As we can see the increasing of reservoir pressure after crossflow takes place in Figure 5.4A. That is a reason why strategy 4 delivers the highest gas cumulative production and recovery factor.

Strategies 1 and 3 deliver the lowest cumulative gas production and recovery factor. This is because gas is produced in company with oil from the bottom layer. Since the reservoir pressure is better maintained due to production of oil as shown in Figure 5.4C, gas in the top layer will expand not as much. For this reason, a lower amount of gas is produced when compared to other strategies as shown in Figure

5.6A. Moreover, there is a small crossflow of gas into the top layer but cannot be clearly seen in Figure 5.3.

In summary, strategy 4 is the best approach to maximize the ultimate production of gas as shown in Table 5.1 with the green highlight.

5.1.3 Summary

Strategy 2 which is separate layer production delivers the highest production for oil while strategy 4 which is commingled production when top layer half depleted delivers the best recovery for gas. However, strategy 2 delivers the highest results in term of barrel of oil equivalent or BOE. Therefore, strategy 2 is the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.1 with the brown highlight.

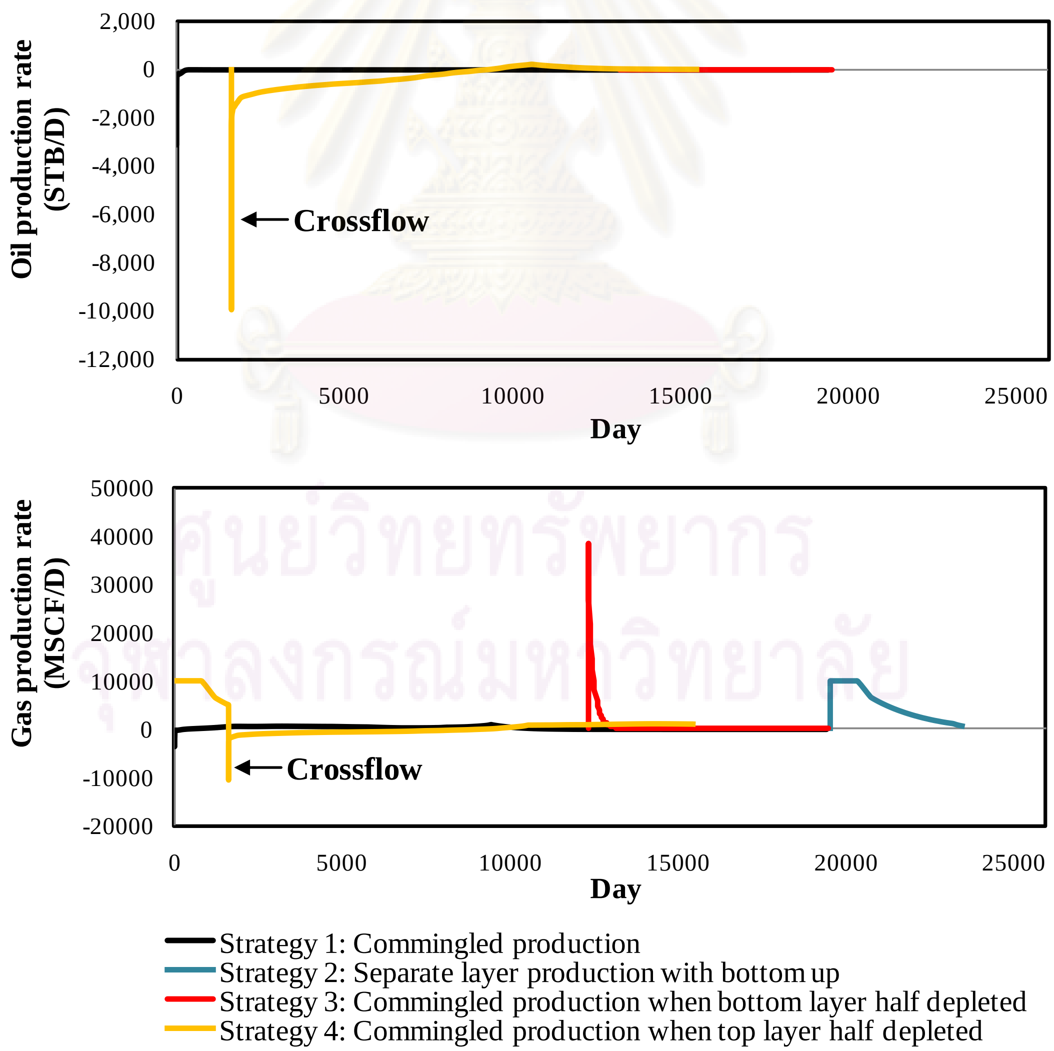

Figure 5.3: Production profiles of Case 1: G – O, at the top layer

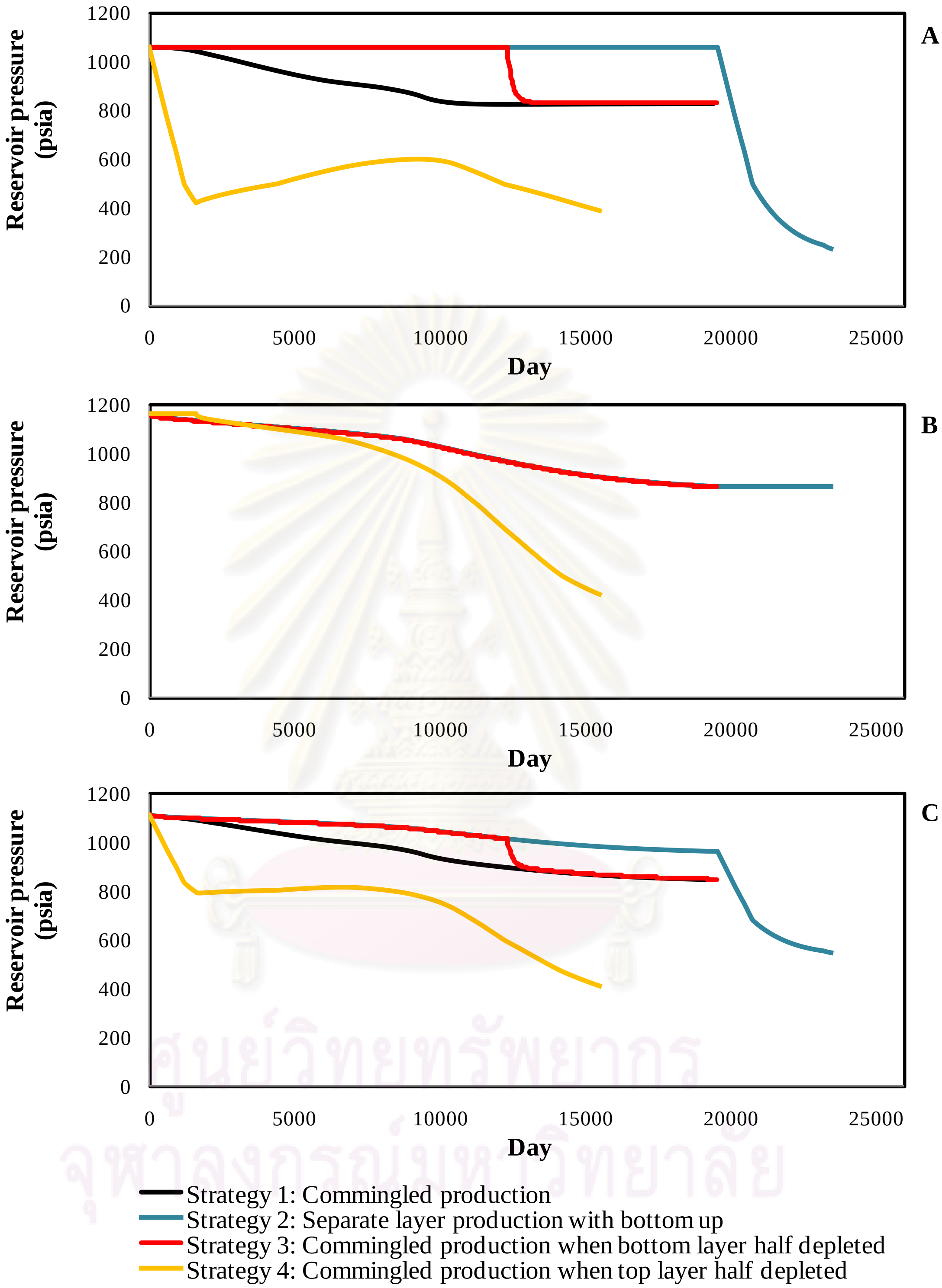

Figure 5.4: Reservoir pressure of Case 1: G – O at (A) the top layer, (B) the bottom layer and (C) both layers

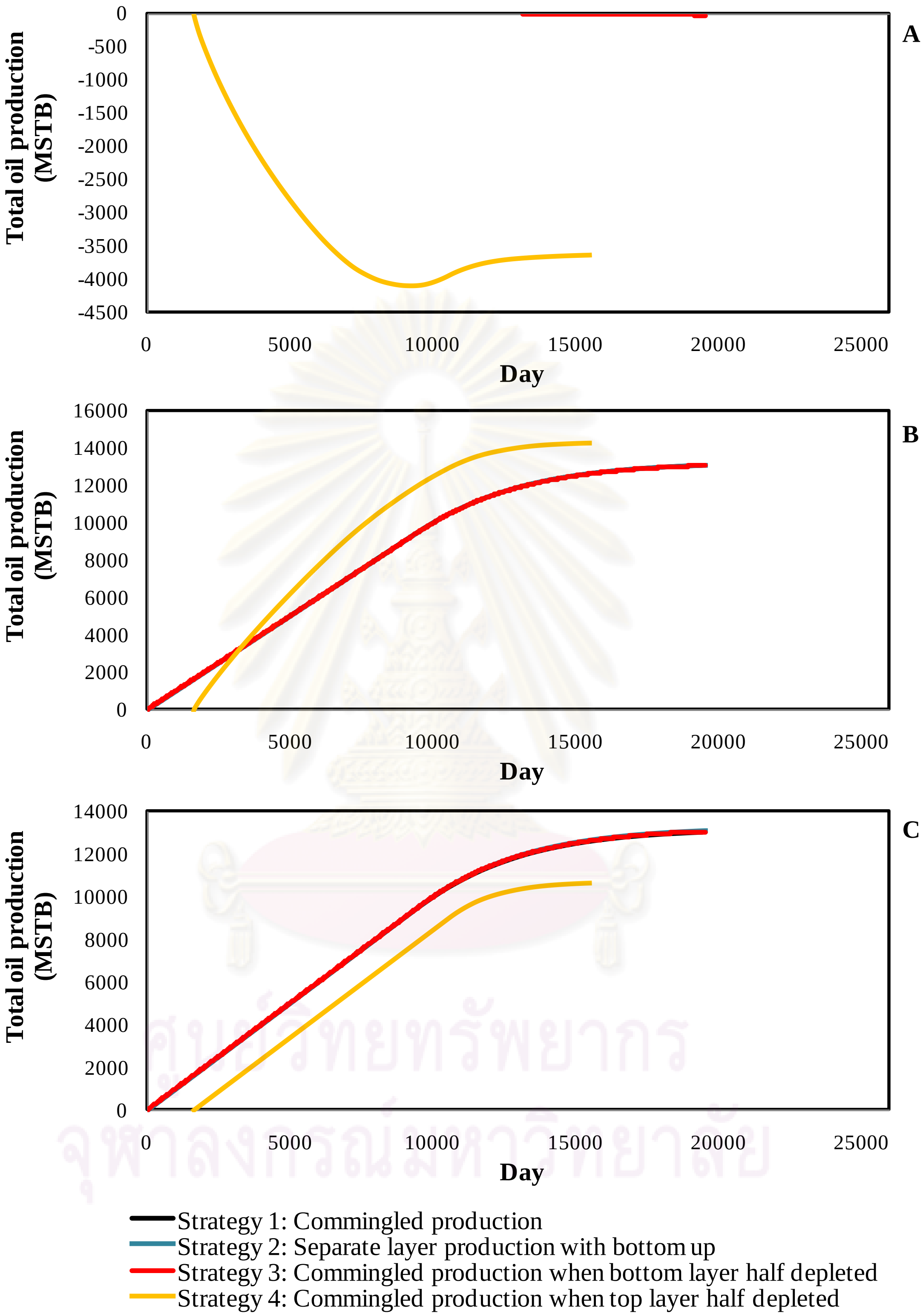

Figure 5.5: Total oil production of Case 1: G – O at (A) the top layer, (B) the bottom layer and (C) both layers

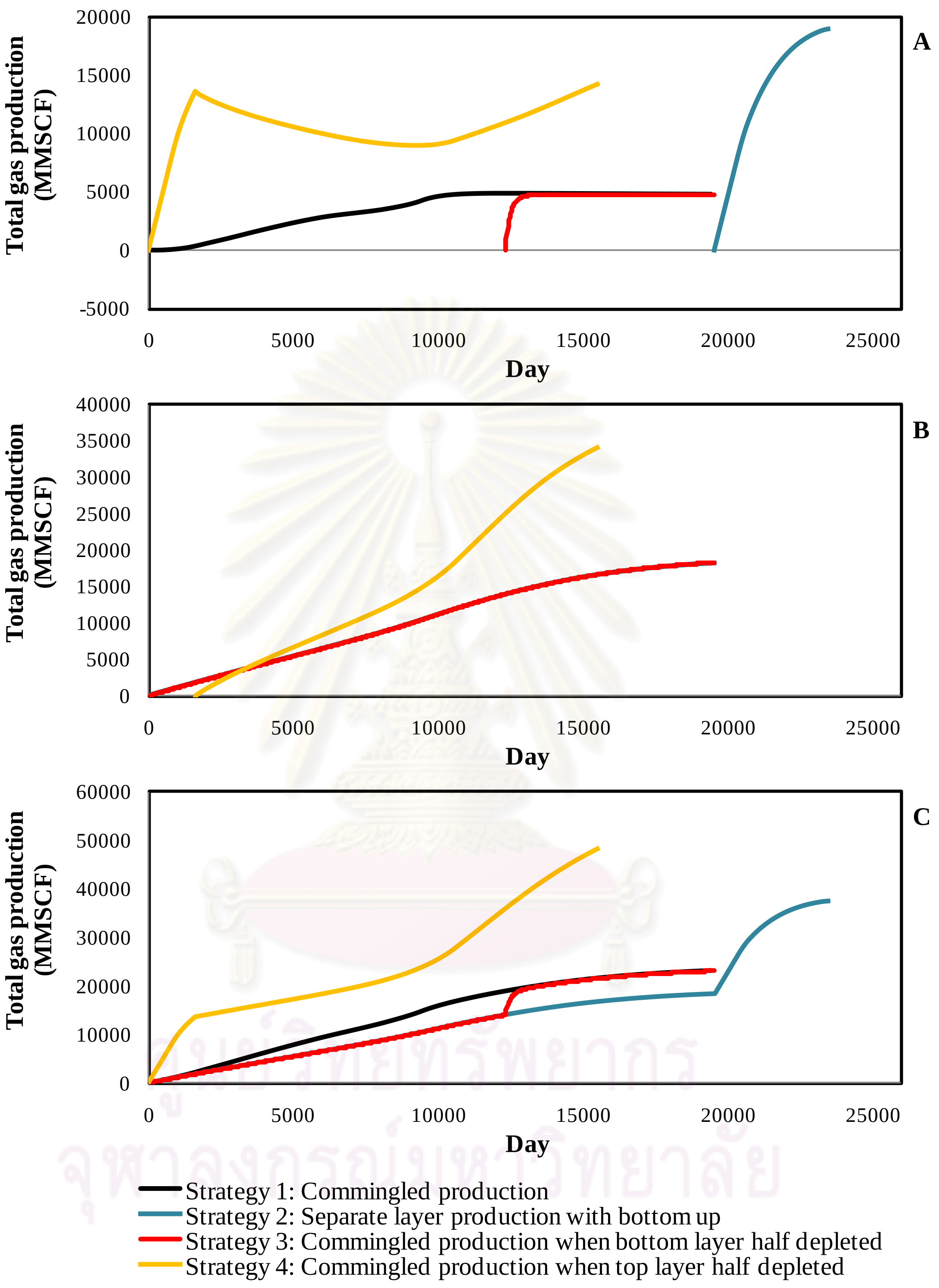

Figure 5.6: Total gas production of Case 1: G – O at (A) the top layer, (B) the bottom layer and (C) both layers

5.2 Case 2: G – G&O

In this case, the reservoir consists of 100 ft of gas zone at the top layer and 50 ft of gas and oil zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a gas reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of gas sand. The bottom layer is a saturated oil reservoir with a gas cap above. The reservoir is gas-cap-drive and is perforated 30 ft from the bottom of oil zone. A well schematic of Case 2 is shown in Figure 5.7.

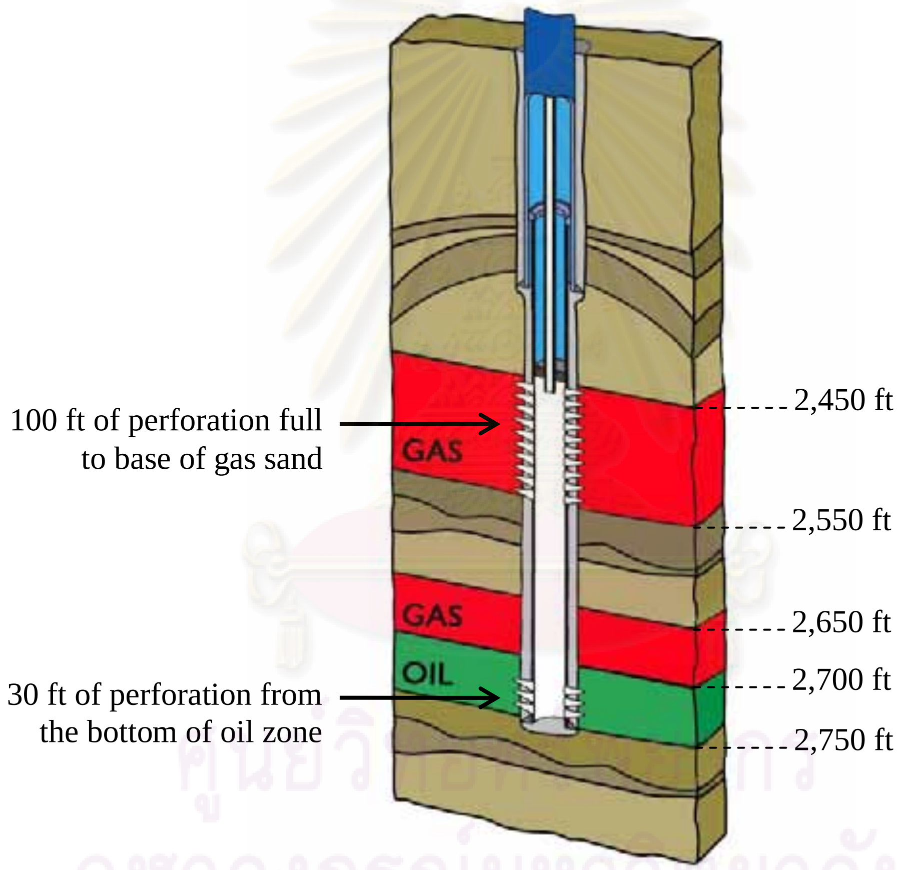

Figure 5.7: Well schematic for Case 2: G – G&O

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.8 and comparative results are summarized in Table 5.2.

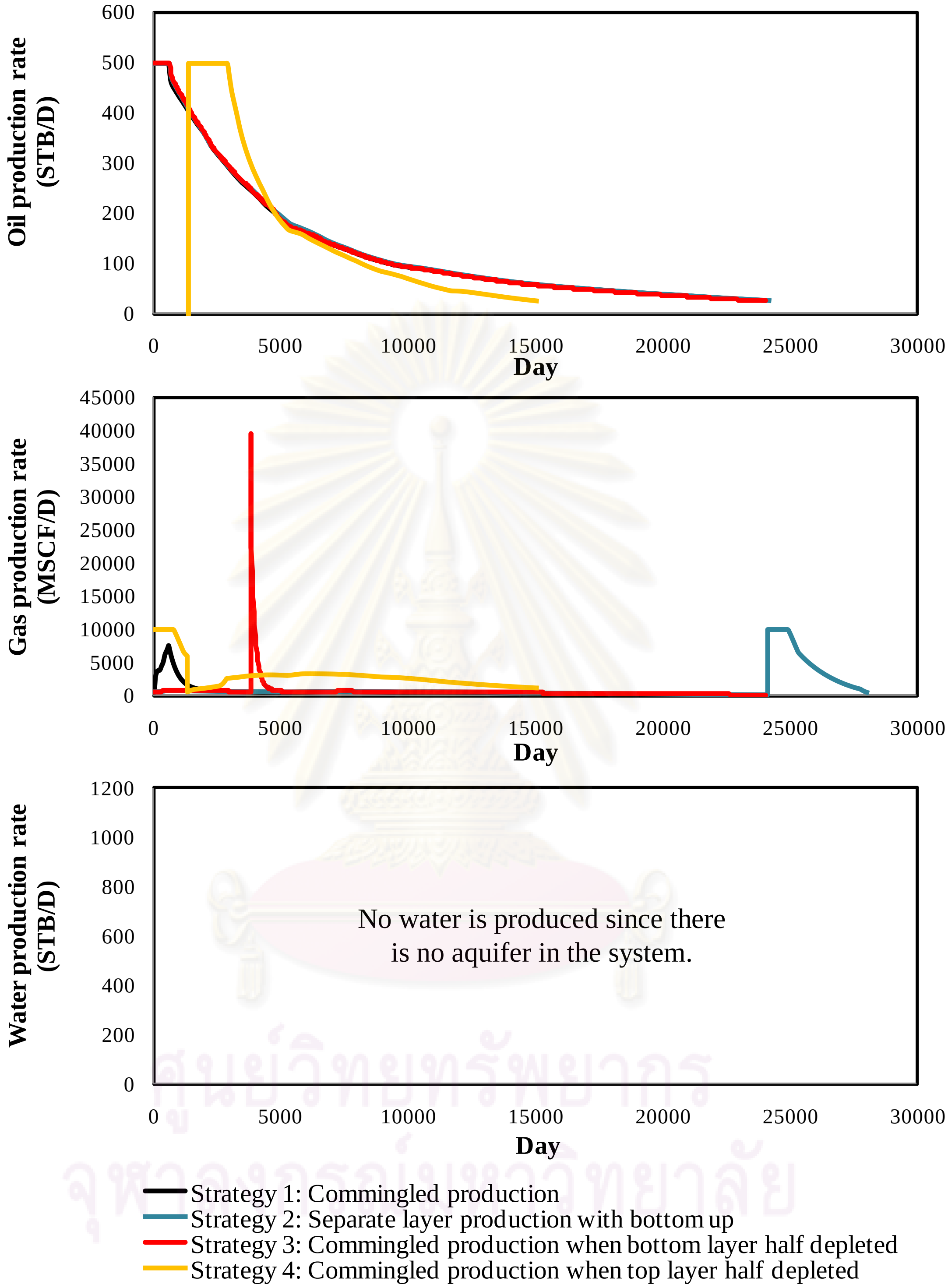

Figure 5.8: Production profiles of Case 2: G – G&O

Table 5.2: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 2: G – G&O

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	3,052	3,095	3,070	2,200
Gas (MMSCF)	15,751	30,069	15,753	44,641
Free gas (MMSCF)	12,850	27,139	12,840	42,912
Solution gas (MMSCF)	2,901	2,930	2,913	1,728
MBOE	5,768	8,279	5,786	9,896
Water (STB)	0	0	0	0
Oil recovery factor (%) *	14.12	14.32	14.21	10.18
Gas recovery factor (%) **	24.50	46.77	24.51	69.44
Abandonment time (day)	24,045	28,067	24,039	15,059

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.2.1 Oil production

For oil production comparison, cumulative production and recovery factor obtained from strategies 1, 2 and 3 are very similar as summarized in Table 5.2. This is because the wells start producing oil from the same OOIP at the very beginning and keep producing oil until the reservoir depletes at abandonment rate as shown in Figure 5.8. Moreover, Figure 5.12B indicates that strategies 1, 2 and 3 withdraw the same amount of oil from the bottom layer.

Strategy 2 delivers the highest cumulative oil production and oil recovery factor. The reason is that no crossflow takes place between the layers since each layer is produced one at a time.

Strategies 1 and 3 do not deliver the best result for oil production since cross-flows occurs as shown in Figure 5.9 but cannot be seen clearly. However, Figure 5.12A is evidence for crossflow as it shows a negative value of total oil production at the top layer. The negative value means that oil from the bottom layer flows in the top layer. However, the amount of oil that flows into the gas layer is not as much as strategy 4.

Strategy 4 delivers the lowest oil cumulative production and oil recovery factor. After both layers are produced simultaneously, there is a large difference in reservoir pressure between the two layers and a lot of oil from the bottom layer flows into the top layer reservoir. This is the reason why a large quantity of oil remains in the top layer and cannot be produced to the surface. The negative oil rate of the top layer can assure that crossflow takes place in the reservoir as clearly revealed in Figure 5.9 and confirmed by negative total production in Figure 5.12A. On top of that, to get the desired oil rate of 500 STB/D, a large quantity of oil from the bottom layer must be produced in order to compensate the oil many lost to the top layer from the crossflow.

In summary, strategy 2 is gives the highest ultimate production of oil as shown in Table 5.2 with the yellow highlight.

5.2.2 Gas production

For gas recovery, strategies 2 and 4 deliver excellent outcomes at the top layer as shown in Figure 5.13A because gas from the top layer reservoir is produced separately. The pressure drawdown is large and sharp as depicted in Figure 5.11A. The significant difference of gas recovery between these two strategies comes from the bottom layer as shown in Figure 5.13B. Strategy 4 can deliver gas better than strategy 2 since gas at the bottom layer flows with very high rate as shown in Figure 5.10 due to the crossflow compensation as described before in the oil case.

Strategies 1 and 3 deliver poor results for gas recovery. This is because gas is produced in company with oil from the bottom layer. Since the reservoir pressure is better maintained due to production of oil as shown in Figure 5.11C, gas in the reservoir expands not as much. For this reason, a lower amount of gas is produced when compared to other strategies. Moreover, there is a small crossflow of gas into the top layer but cannot be clearly seen in Figure 5.9.

In summary, strategy 4 is the best approach to maximize the ultimate production of gas as shown in Table 5.2 with the green highlight.

5.1.3 Summary

Strategy 2 which is separate layer production delivers the highest production for oil while strategy 4 which is commingled production when top layer half depleted delivers the best recovery for gas. However, strategy 4 delivers the highest results in term of barrel of oil equivalent or BOE. Therefore, strategy 4 is the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.2 with the brown highlight.

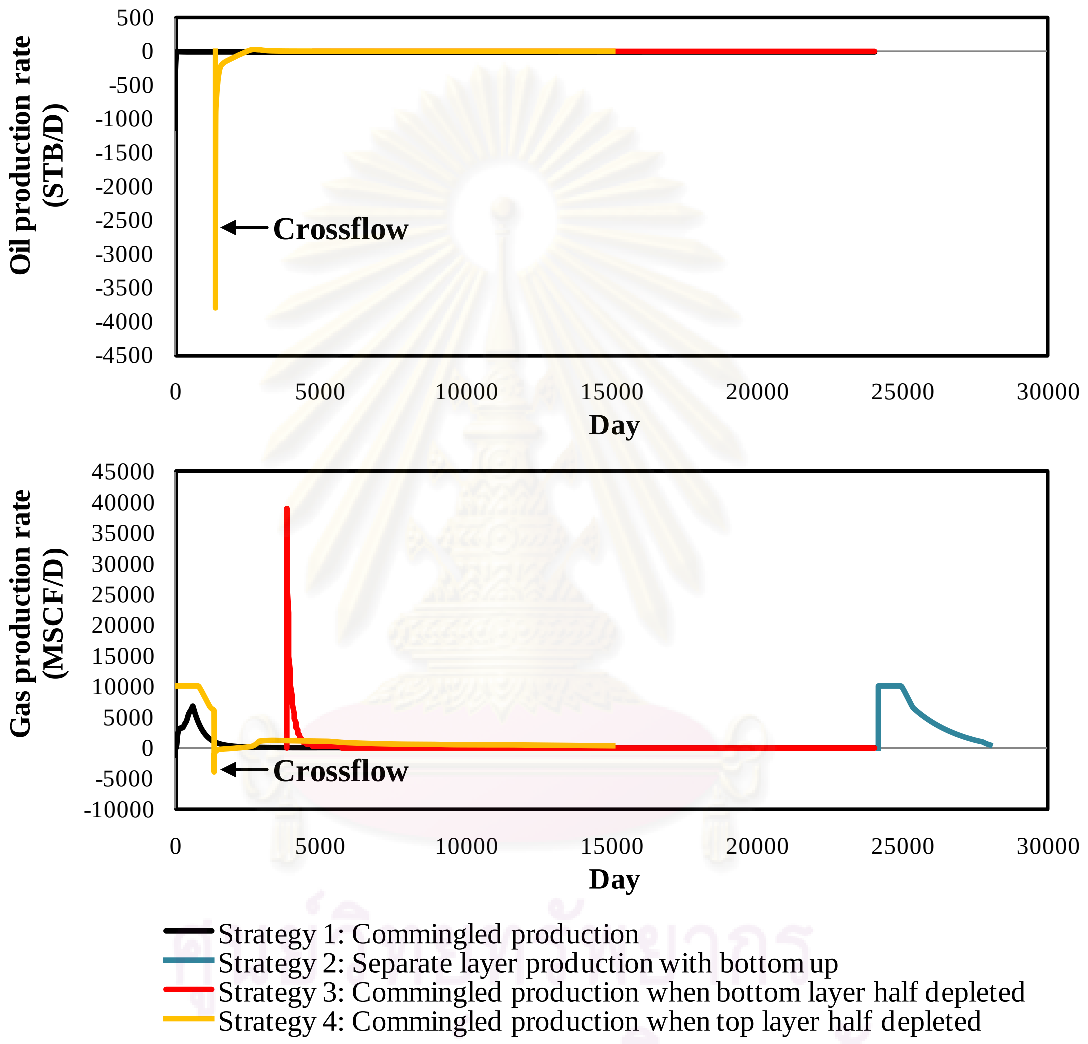

Figure 5.9: Production profiles of Case 2: G – G&O, at the top layer

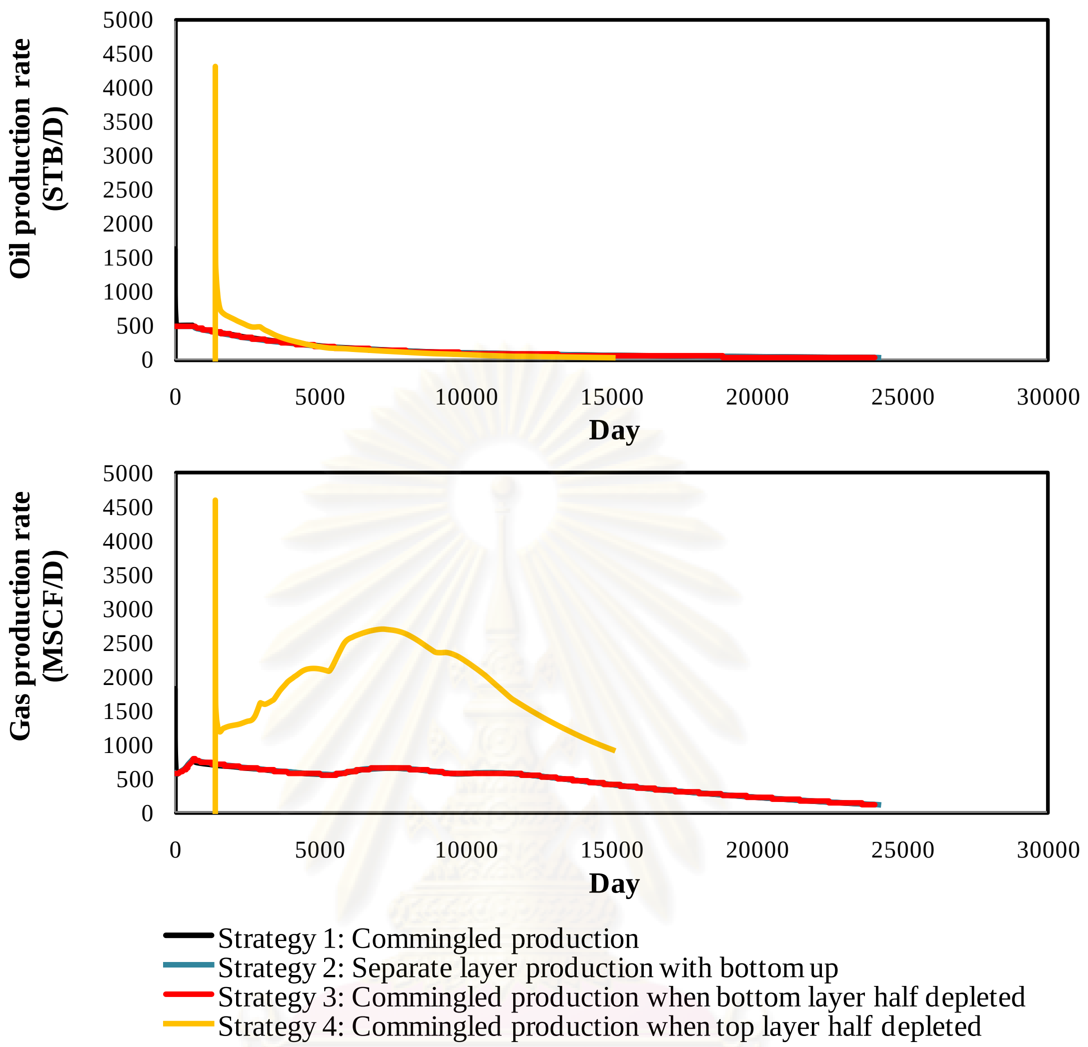

Figure 5.10: Production profiles of Case 2: G – G&O, at the bottom layer

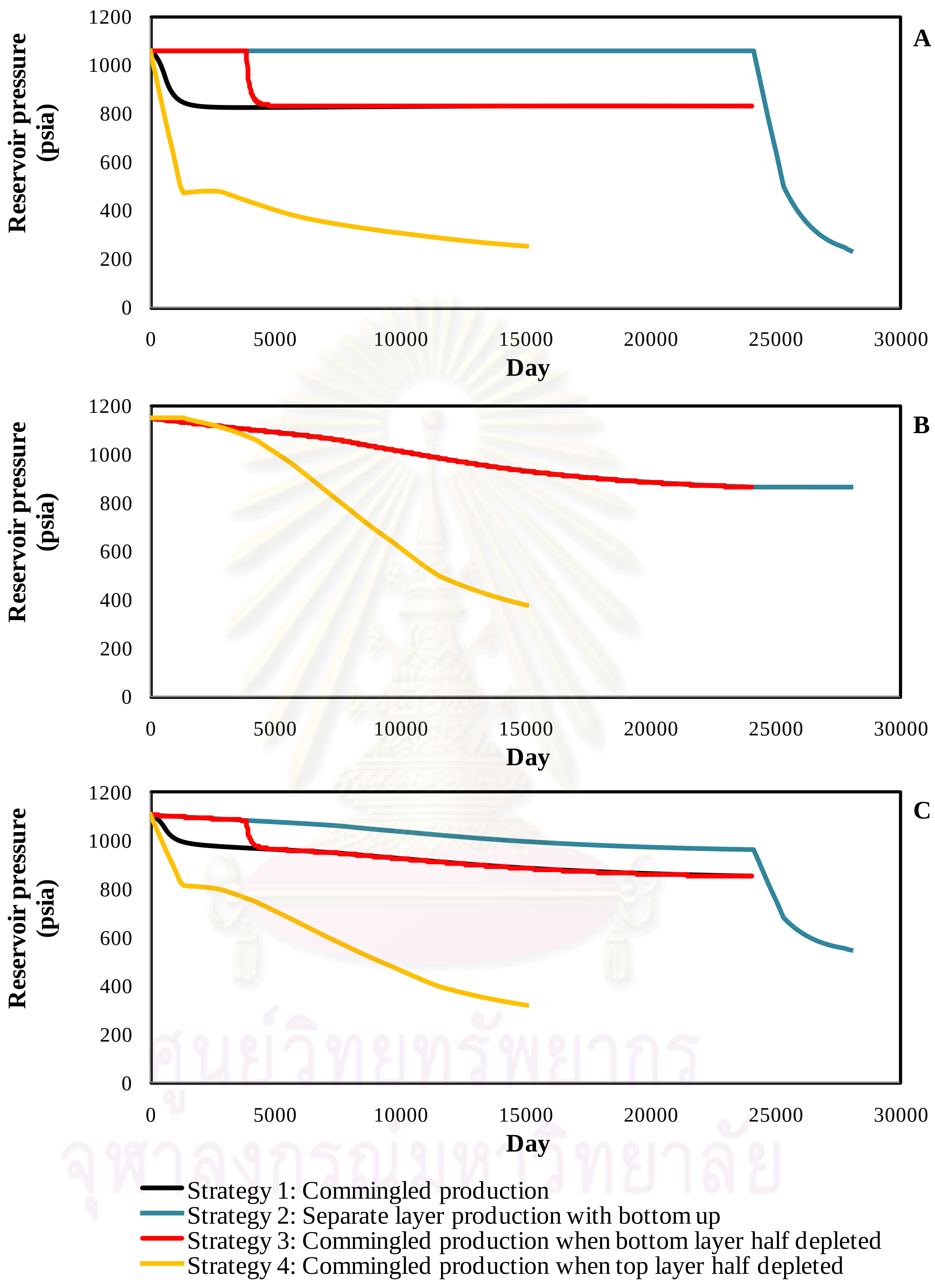

Figure 5.11: Reservoir pressure of Case 2: G – G&O at (A) the top layer, (B) the bottom layer and (C) both layers

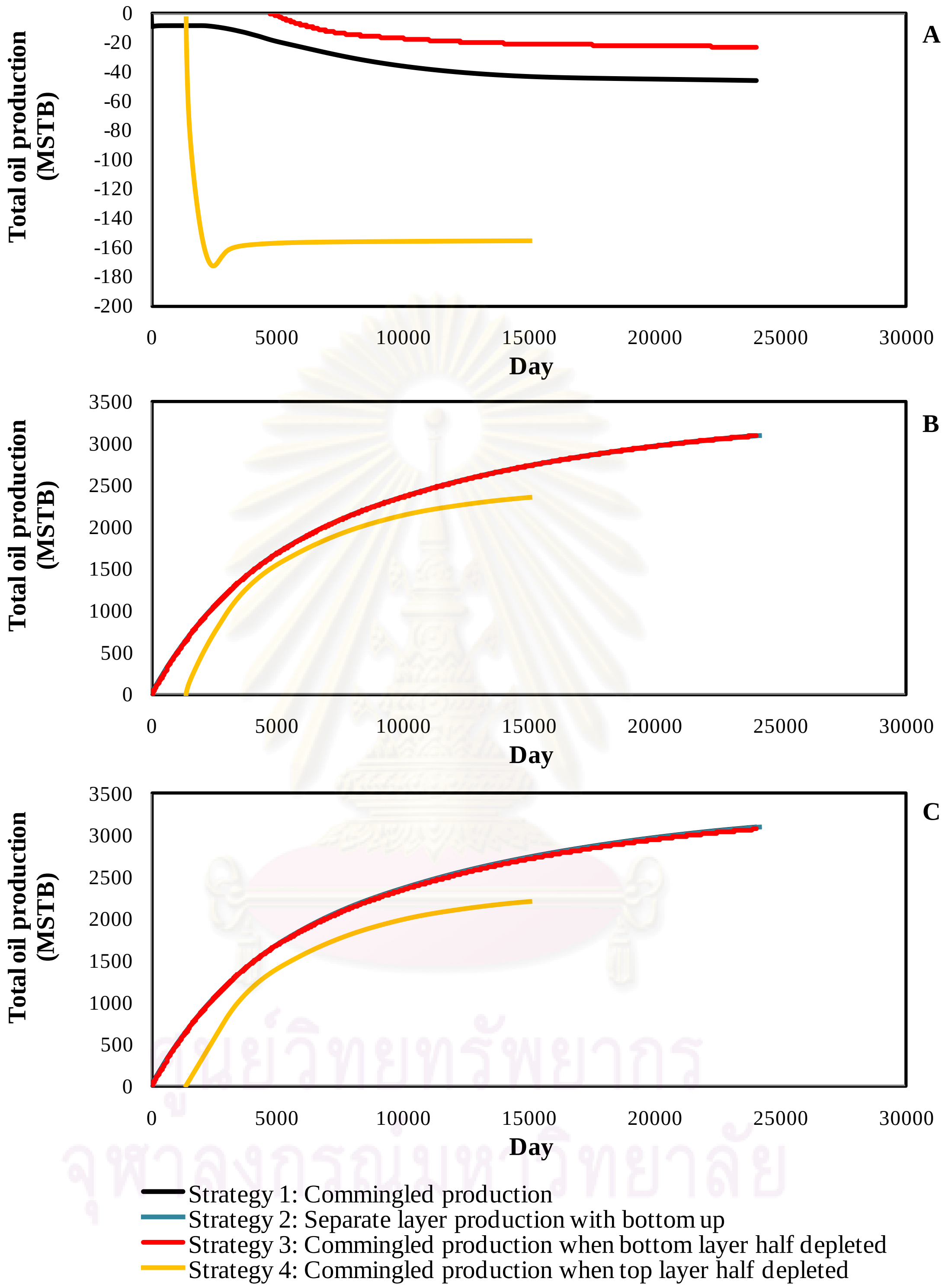

Figure 5.12: Total oil production of Case 2: G – G&O at (A) the top layer, (B) the bottom layer and (C) both layers

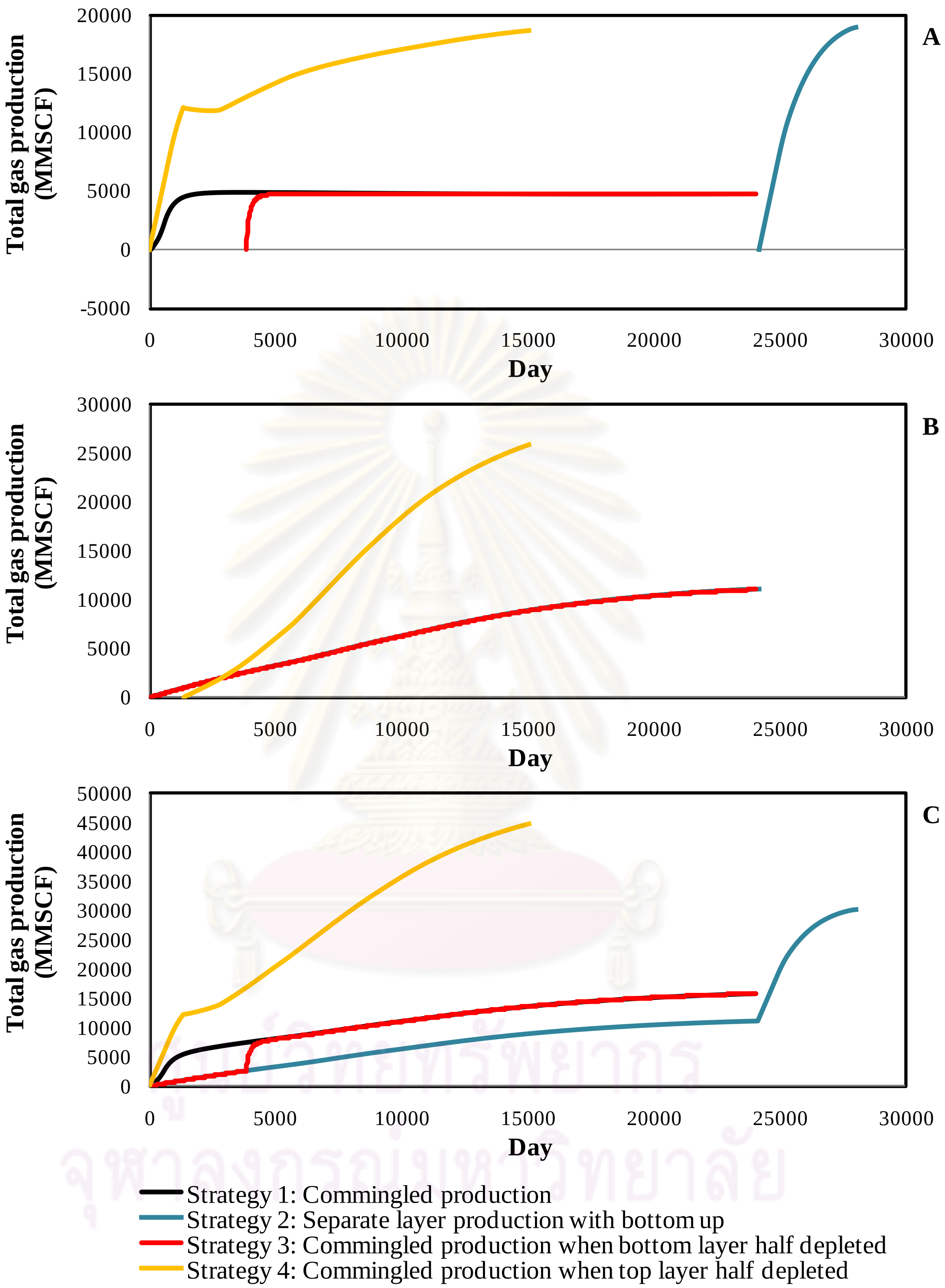

Figure 5.13: Total gas production of Case 2: G – G&O at (A) the top layer, (B) the bottom layer and (C) both layers

5.3 Case 3: O – G&O

In this case, the reservoir consists of 100 ft of oil zone at the top layer and 50 ft of gas and oil zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is an undersaturated oil reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of oil sand. The bottom layer is a saturated oil reservoir with a gas cap above. The reservoir is gas-cap-drive and is perforated 30 ft from the bottom of oil zone. A well schematic of Case 3 is shown in Figure 5.14.

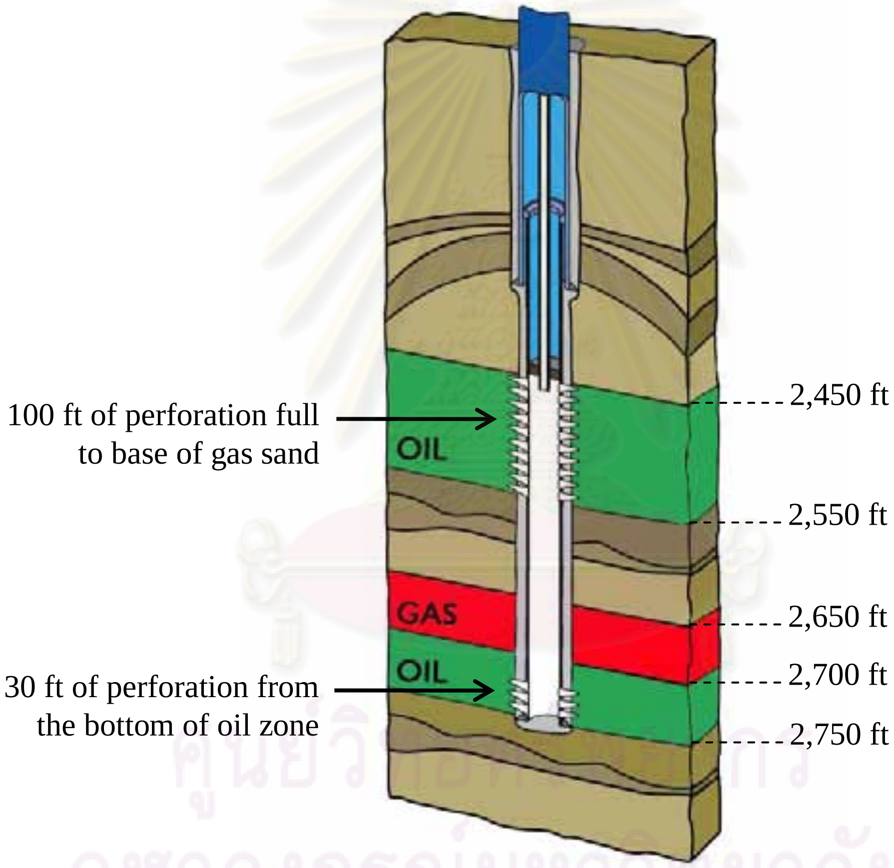

Figure 5.14: Well schematic for Case 3: O – G&O

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.15 and comparative results are summarized in Table 5.3.

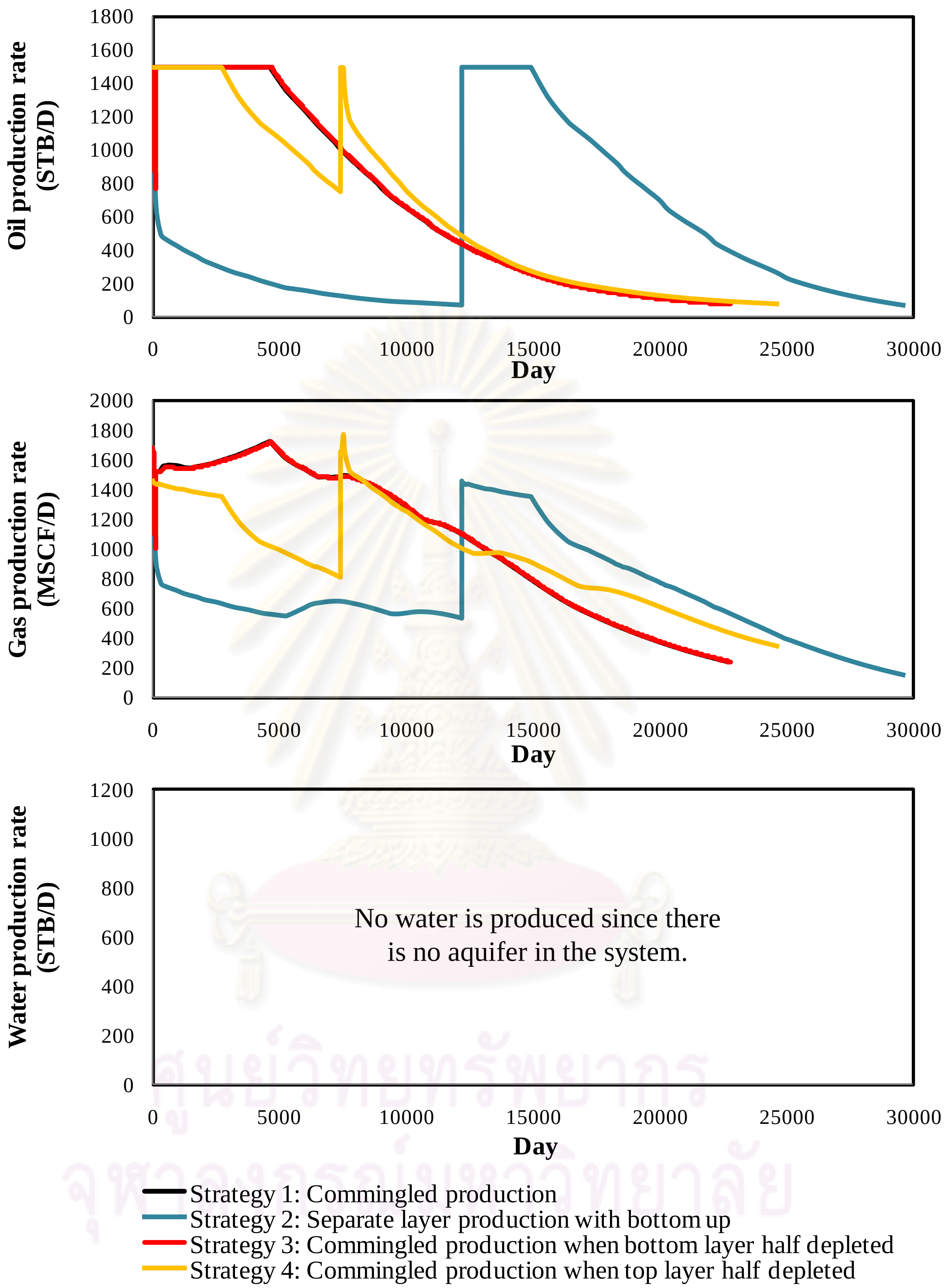

Figure 5.15: Production profiles of Case 3: O – G&O

Table 5.3: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 3: O – G&O

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	15,735	14,801	15,734	15,462
Gas (MMSCF)	24,209	20,579	24,209	23,183
Free gas (MMSCF)	10,801	8,077	10,808	10,179
Solution gas (MMSCF)	13,408	12,502	13,401	13,004
MBOE	19,909	18,349	19,908	19,459
Water (STB)	0	0	0	0
Oil recovery factor (%) *	23.40	22.01	23.40	23.00
Gas recovery factor (%) **	29.21	24.83	29.21	27.97
Abandonment time (day)	22,765	29,616	22,788	24,646

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.3.1 Oil production

The oil performances obtained from strategies 1 and 3 seem to be identical as shown in Figure 5.15. The cumulative oil production and recovery factor obtained from different production strategies are not much different as shown in Table 5.3. Figure 5.18A shows that total oil production from the top layer is not much different among 4 strategies. However, more focus will be given to the bottom layer performance which is obviously different as graphically shown in Figure 5.18B due to difference in a pressure drop as shown in Figure 5.17B.

Strategies 1 and 3 deliver the highest cumulative oil production and recovery factor. The reason is that they produce saturated oil reservoir at the bottom layer and undersaturated oil reservoir at the top layer simultaneously. In order to acquire the plateau producing rate of 1,500 STB/D, the oil rate is contributed from both layers. As a result, the oil producing rate from the bottom layer is not too high. Generally, lower producing rate will permit a certain amount of free gas in the oil zone to migrate to the gas cap, and hence prevent the evolved gas to flow into the well. As a result of preventing the flow of gas in the oil zone, the ultimate oil recovery will increase.

Although strategy 4 produces gas-cap-drive reservoir at the bottom layer and depletion-drive reservoir at the top layer simultaneously. But its outcomes are not as good as strategies 1 and 3. The reason is that crossflow takes place between the two layers as depicted in Figure 5.16. However, the amount of oil that flows into the top layer is not much since it occurs for only five days of reservoir's life.

Strategy 2 delivers the lowest cumulative oil production and recovery factor as shown in Table 5.3. This is because saturated oil reservoir at the bottom layer and undersaturated oil reservoir at the top layer is produced one at a time. As the oil production rate is contributed from only one layer, thus the oil rate at the bottom layer must be high. We have already discussed before that the saturated oil reservoir with gas-cap-drive mechanism is rate sensitive, as higher production rate usually results in decreased oil recovery. In theory, the producing gas-oil ratio from the affected wells will increase to high values as shown in Figure 5.20.

To sum up, strategies 1 and 3 are excellent ways to maximize the ultimate production of oil as shown in Table 5.3 with the yellow highlight.

5.3.2 Gas production

For gas production comparison, strategies 1, 3 and 4 deliver almost the same cumulative production and recovery factor of gas as shown in Table 5.3. In addition, the gas performances obtained from strategies 1 and 3 seem to be identical as shown in Figure 5.15, with the same number of cumulative gas production and recovery factor as shown in Table 5.3. Table 5.3 reveals that the results obtained from strategy 4 are slightly poorer since there is a small crossflow of gas into the top layer as shown in Figure 5.16.

Strategy 2 delivers the lowest cumulative gas production and recovery factor as shown in Table 5.3. This is because it can produce a smaller amount of gas from the gas-cap-drive reservoir at the bottom layer as graphically depicted in Figure 5.19B. Since the gas-cap-drive reservoir which is located at the lower formation is developed first, before moving on to the upper reservoir. However, it is not possible to fully deplete the lower formation in practice. What happens is that when the oil flow rate drops, the well is deemed sub-commercial and the production moves on to the overlying formation. And hence, there is a certain amount of gas that can be recovered but still remains in the reservoir.

In summary, strategies 1 and 3 are excellent approaches to maximize the ultimate production of gas as shown in Table 5.3 with the green highlight.

5.3.3 Summary

In term of barrel of oil equivalent or BOE, strategies 1 and 3 are favored strategies as shown in Table 5.3 with the brown highlight. Looking to the economics life of the reservoir, strategy 1 is more worthwhile compared with strategy 3 because its abandonment time is shorter as shown in Table 5.3 with the pink highlight. Thus, strategy 1 which is a commingled production is the most excellent strategy for this kind of multilayer reservoirs.

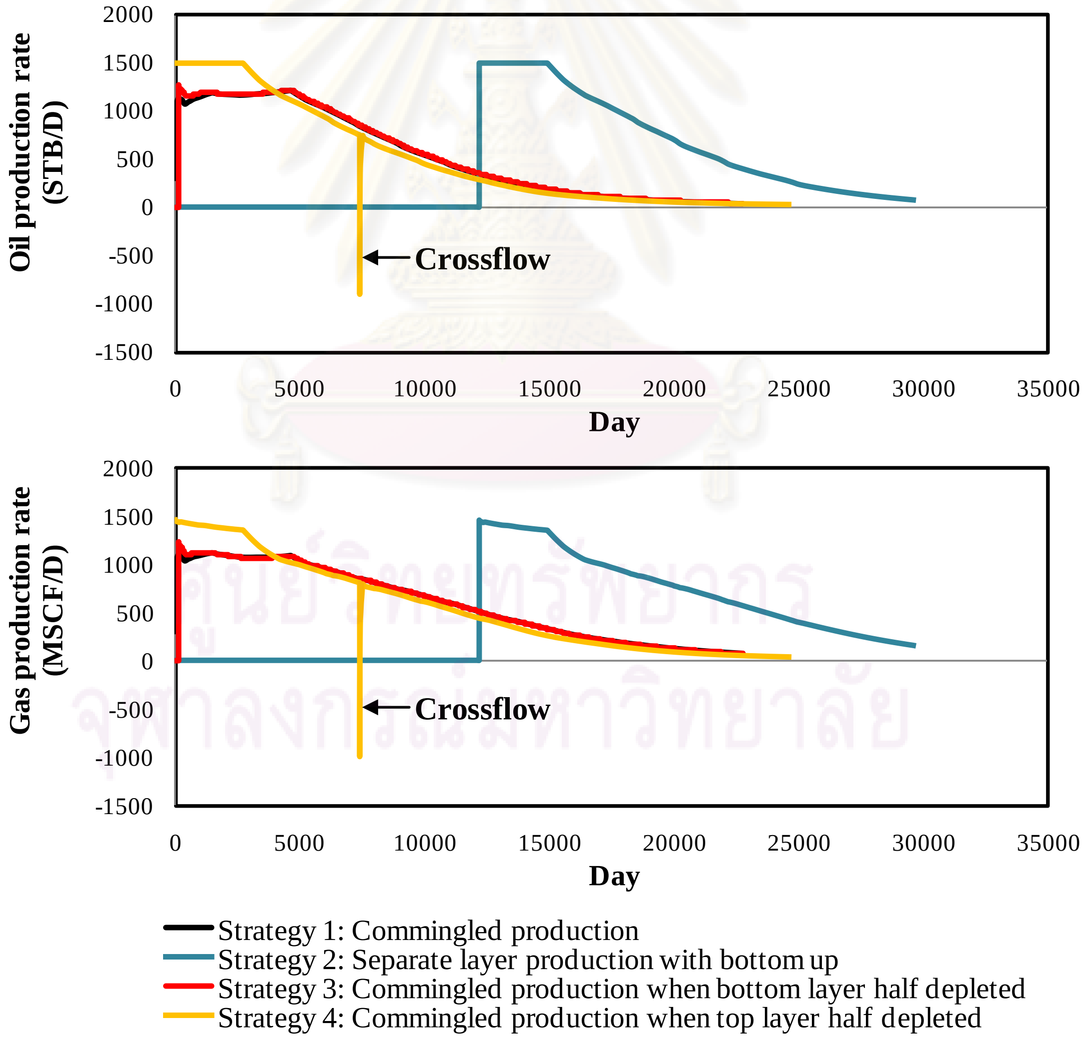

Figure 5.16: Production profiles of Case 3: O – G&O, at the top layer

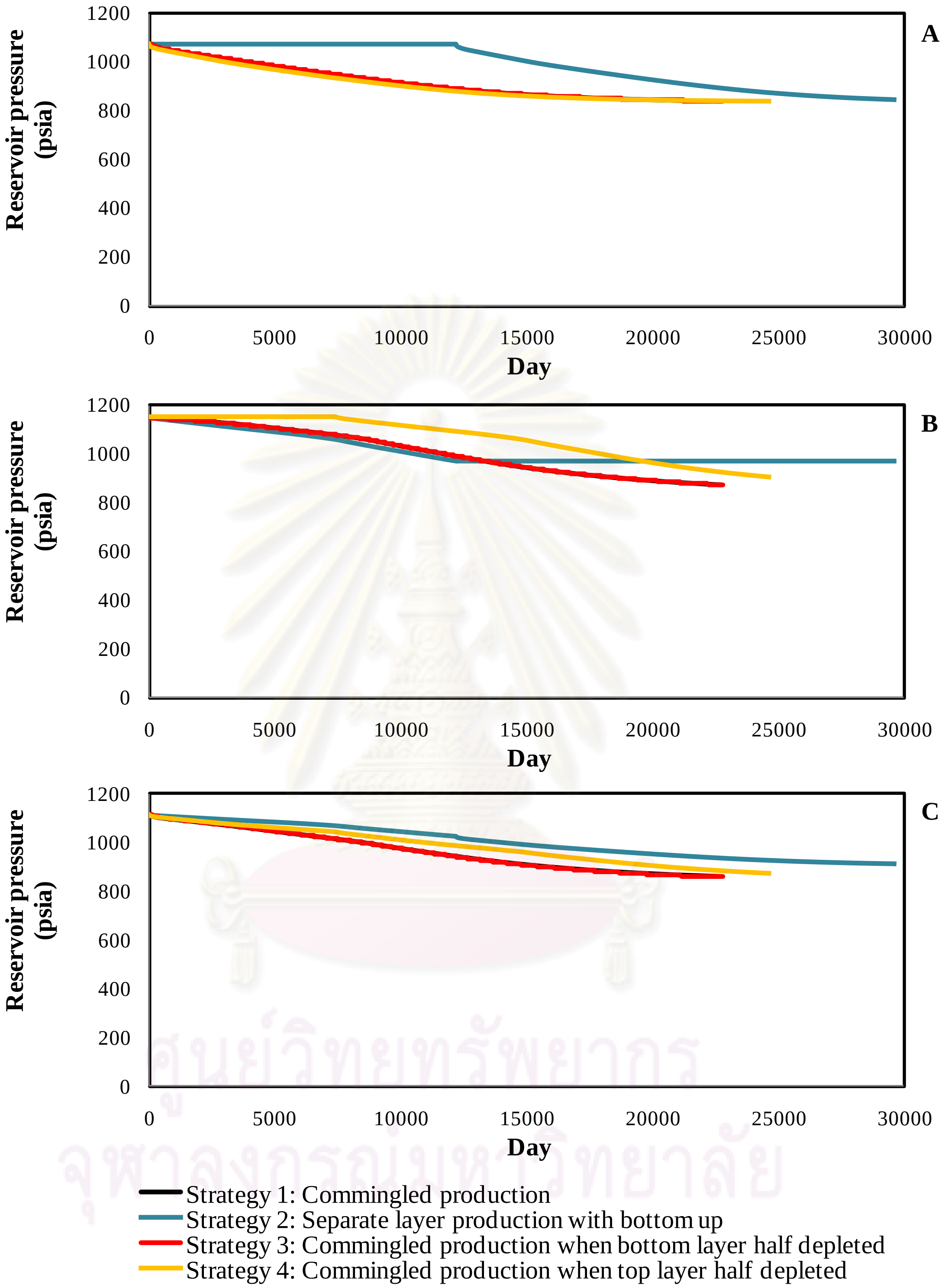

Figure 5.17: Reservoir pressure of Case 3: O – G&O at (A) the top layer, (B) the bottom layer and (C) both layers

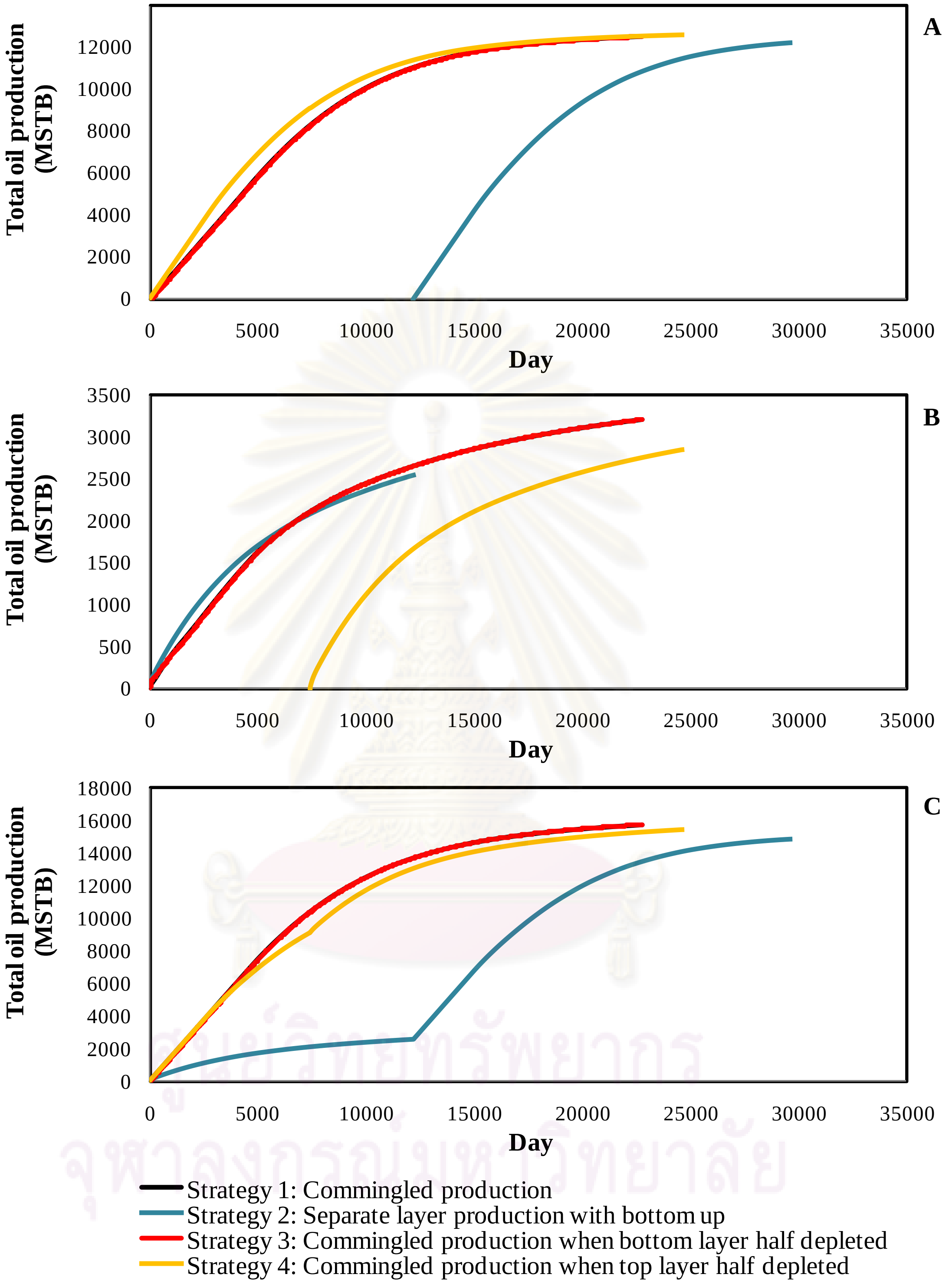

Figure 5.18: Total oil production of Case 3: O – G&O at (A) the top layer, (B) the bottom layer and (C) both layers

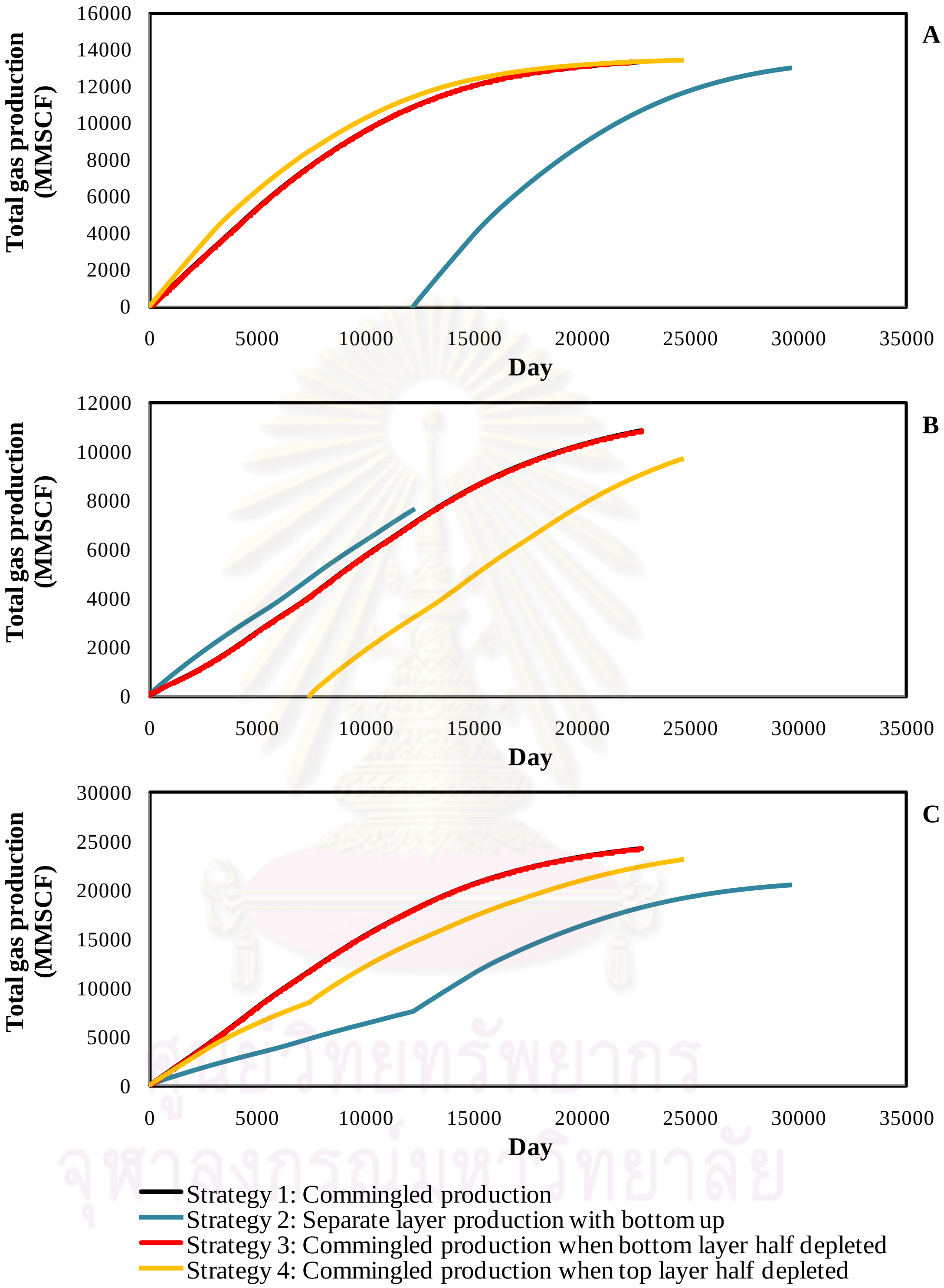

Figure 5.19: Total gas production of Case 3: O – G&O at (A) the top layer, (B) the bottom layer and (C) both layers

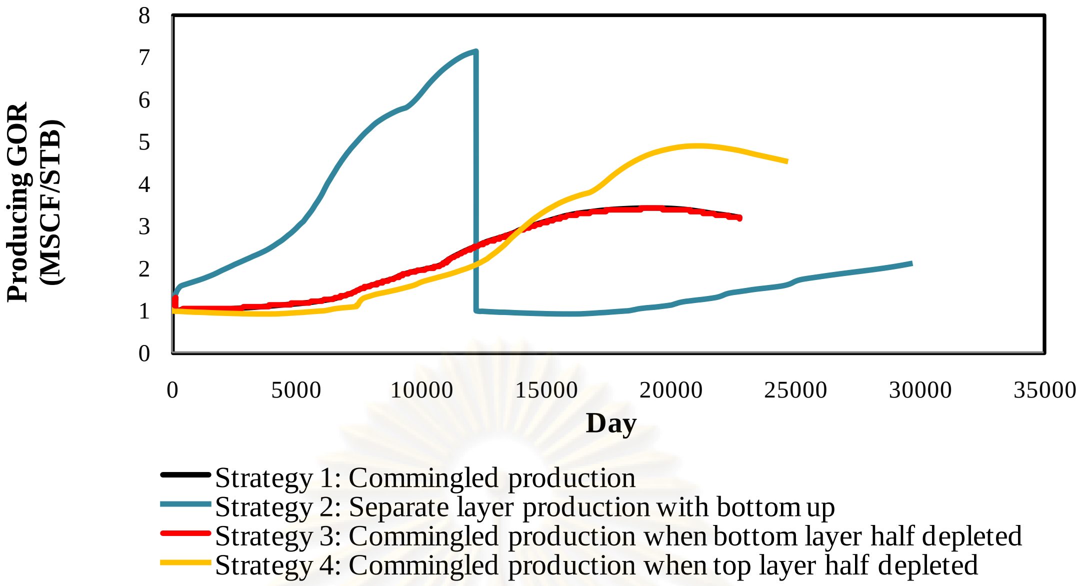

Figure 5.20: Producing GOR of Case 3: O – G/O

5.4 Case 4: O – O&W

In this case, the reservoir consists of 100 ft of oil zone at the top layer and 50 ft of oil and water zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is an undersaturated oil reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of oil sand. The bottom layer is an undersaturated oil reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of oil zone. A well schematic of Case 4 is shown in Figure 5.21.

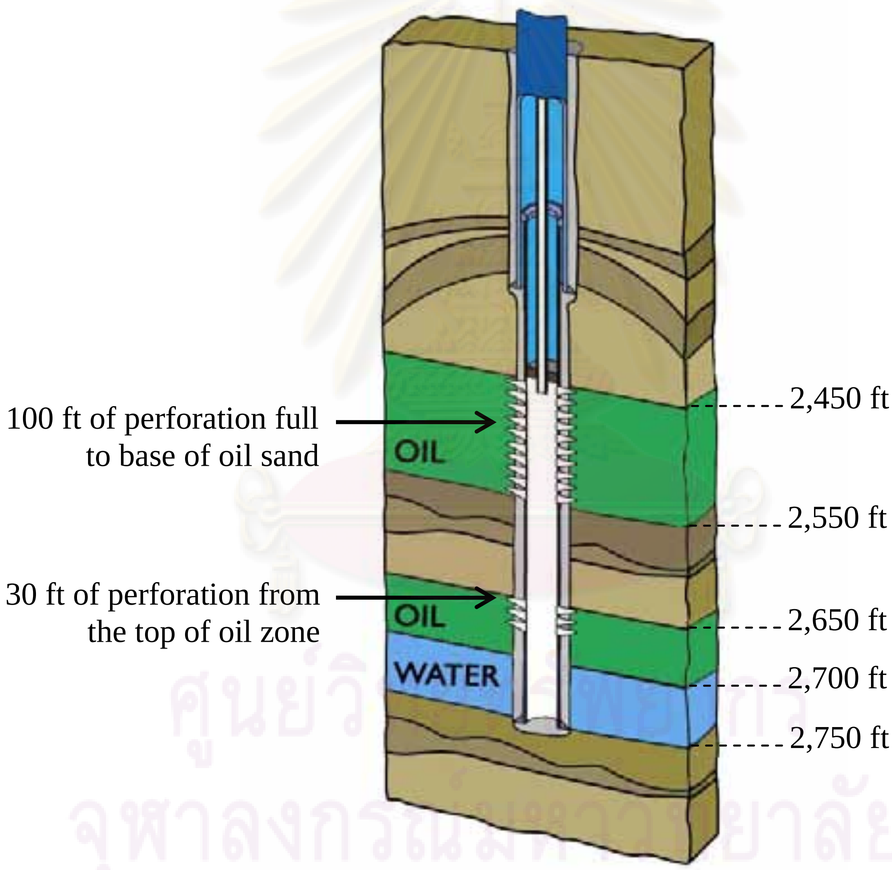

Figure 5.21: Well schematic for Case 4: O – O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.22 and comparative results are summarized in Table 5.4.

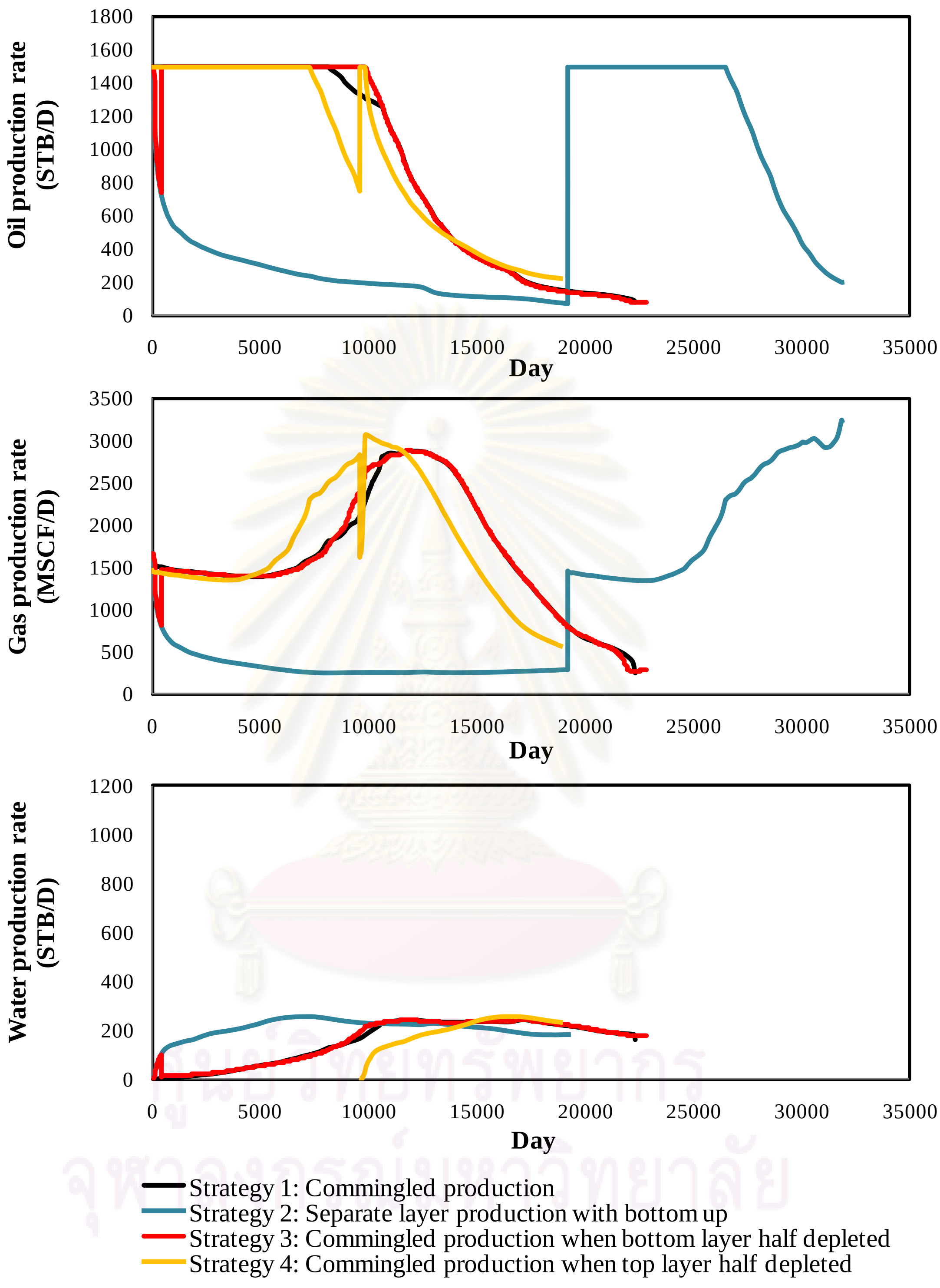

Figure 5.22: Production profiles of Case 4: O – O&W

Table 5.4: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 4: O – O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	20,016	19,598	20,031	18,519
Gas (MMSCF)	37,143	32,255	37,228	33,659
Free gas (MMSCF)	21,707	17,701	21,906	20,009
Solution gas (MMSCF)	15,436	14,554	15,322	13,650
MBOE	26,420	25,159	26,449	24,322
Water (STB)	3,403	3,947	3,540	1,865
Oil recovery factor (%) *	29.76	29.14	29.79	27.54
Gas recovery factor (%) **	53.80	46.72	53.92	48.75
Abandonment time (day)	22,370	31,928	22,826	18,932

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.4.1 Oil production

Table 5.4 reveals that strategies 1 and 3 deliver good results for cumulative production and recovery factor of oil. Figure 5.25A reveals that oil cumulative productions from the top layer reservoir obtained from all strategies are equivalent, while Figure 5.25B shows significant differences of oil production from the bottom layer which is a water-drive oil reservoir.

Strategies 1 and 3 deliver the best outcomes for oil recovery because the reservoir produces fluids until depletion by the abandonment rate of 50 STB/D as shown in Figure 5.22.

Table 5.4 shows that strategy 3 is slightly better than strategy 1 because at the beginning of production, strategy 3 produces oil from a water-drive reservoir at the bottom layer separately. During this period, the reservoir can take more advantage from water-drive mechanism which is the best one to maximize the oil recovery. For strategy 1, water-drive reservoir is produced together with depletion-drive reservoir from the beginning to the end, resulting in slight decrease in oil recovery.

Strategies 2 and 4 deliver lower oil recoveries because the well dies before the reservoir depletes by the abandonment rate. The reason is that water flows into the wellbore rapidly, as shown in Figure 5.27 that the trend of water cut is very steep.

For strategy 2, the oil producing rate is contributed from one layer at a time. In order to achieve a desired oil production rate, fluids at the bottom layer will be individually produced with a higher rate, and hence the water rate at the bottom layer is high.

For strategy 4, most of the oil production rate at late time is contributed by the bottom layer since it has higher pressure and amount of hydrocarbon in place since the top layer is partially depleted. To produce at high oil production rate, a high drawdown is needed. This causes the water rate to be high as well. Moreover, another reason for low oil recovery is a small crossflow of oil into the top layer as shown in Figure 5.23.

To sum up, strategy 1 is the best way to maximize the ultimate production of oil as shown in Table 5.4 with the yellow highlight.

5.4.2 Gas production

Figure 5.22 illustrates gas performances obtained from different production strategies. Figure 5.26A reveals that gas cumulative productions from the top layer reservoir obtained from all strategies are almost the same, but there are differences in productions from the water-drive oil reservoir at the bottom layer as shown in Figure 5.26B. Since all of the producing gas comes from the oil which is the solution gas liberated from the saturated oil and free gas from the secondary gas cap, thus the reasons supporting the performance of gas production are related to the oil production.

Table 5.4 reveals that strategies 1 and 3 deliver good results for cumulative production and recovery factor of gas. The reason is practically the same as the oil case as mentioned before that the reservoir produces fluids until the economic limit.

Strategies 2 and 4 deliver poorer outcomes due to the same explanation as described in the oil case, which is early well abandonment. Even though strategy 4 causes the crossflow between the two layers as shown in Figure 5.23, it can produce gas better than strategy 2 as confirmed by the higher producing gas-oil ratio in Figure 5.28. This is because a large pressure drawdown at the top layer (shown in Figure

5.24A) results in a large expansion of gas in the secondary gas caps that supplies energy for the reservoir. Therefore, an enormous amount of free gas is produced from the top layer.

In summary, strategy 3 is the best way to maximize the ultimate production of gas as shown in Table 5.4 with the green highlight.

5.4.3 Summary

Strategy 3 is the best way for oil and gas production, and also in term of BOE as shown in Table 5.4 with the brown highlight. Thus, strategy 3 which is a commingled production when bottom layer is half depleted is the most excellent strategy for this kind of multilayer reservoirs.

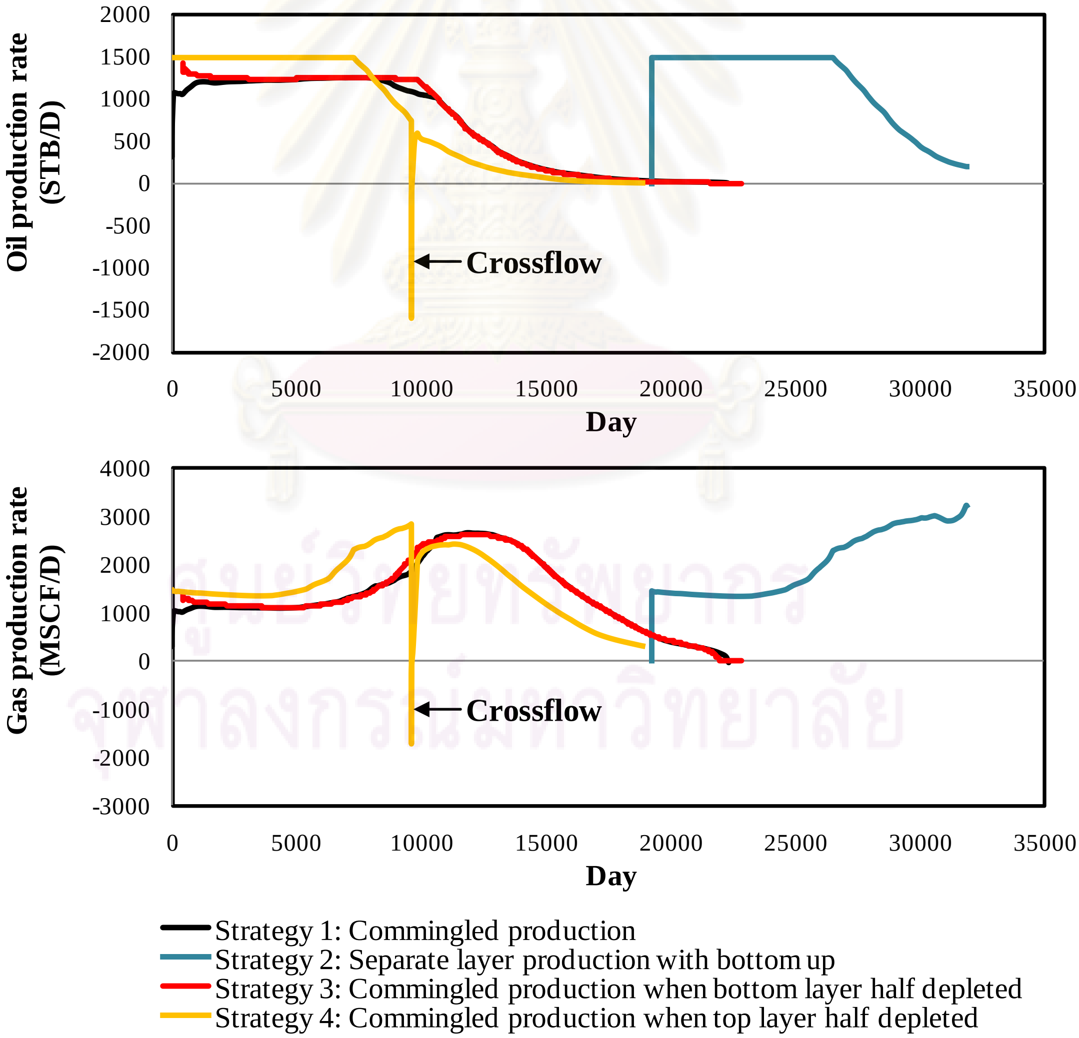

Figure 5.23: Production profiles of Case 4: O – O&W, at the top layer

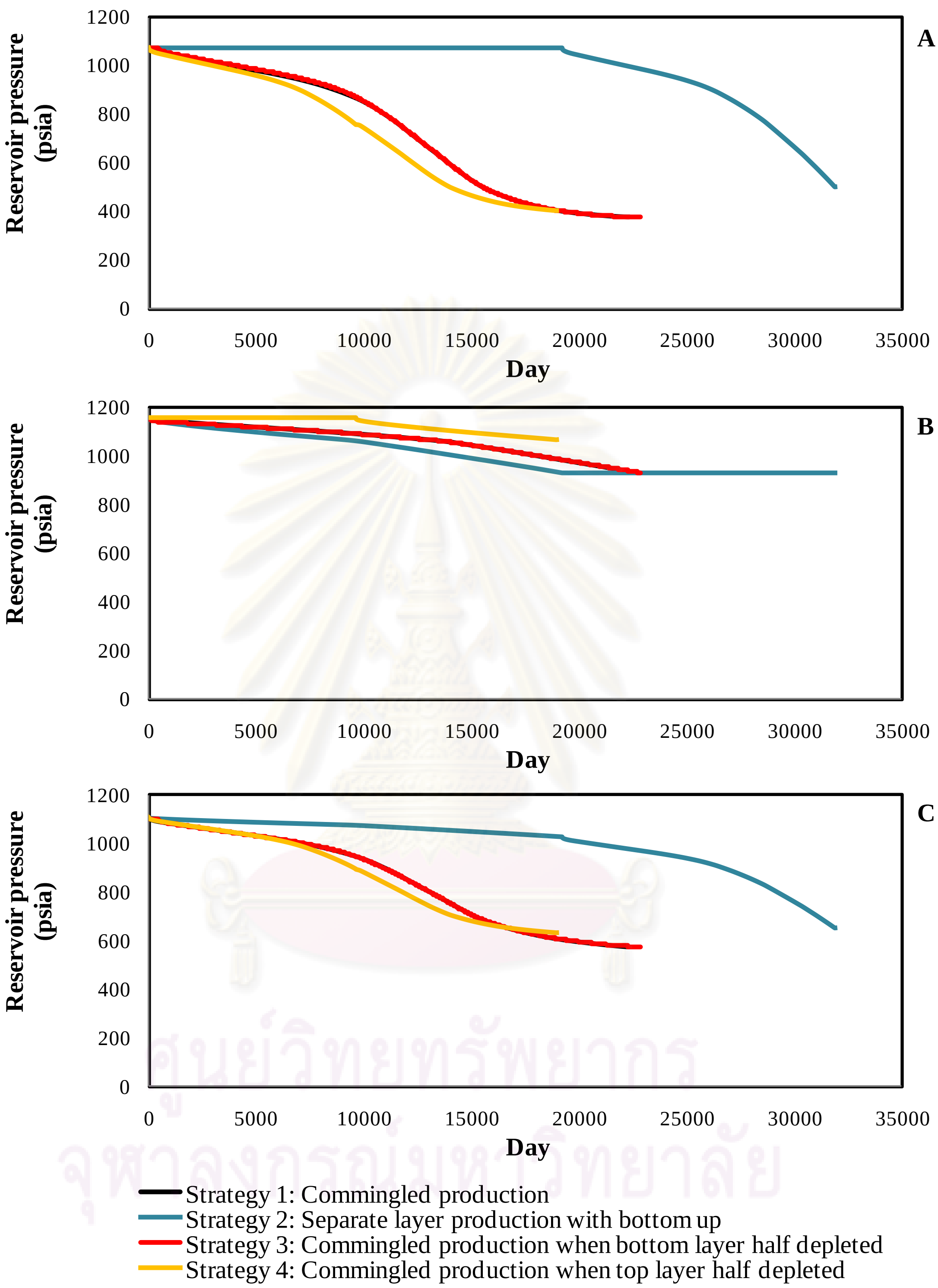

Figure 5.24: Reservoir pressure of Case 4: O – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

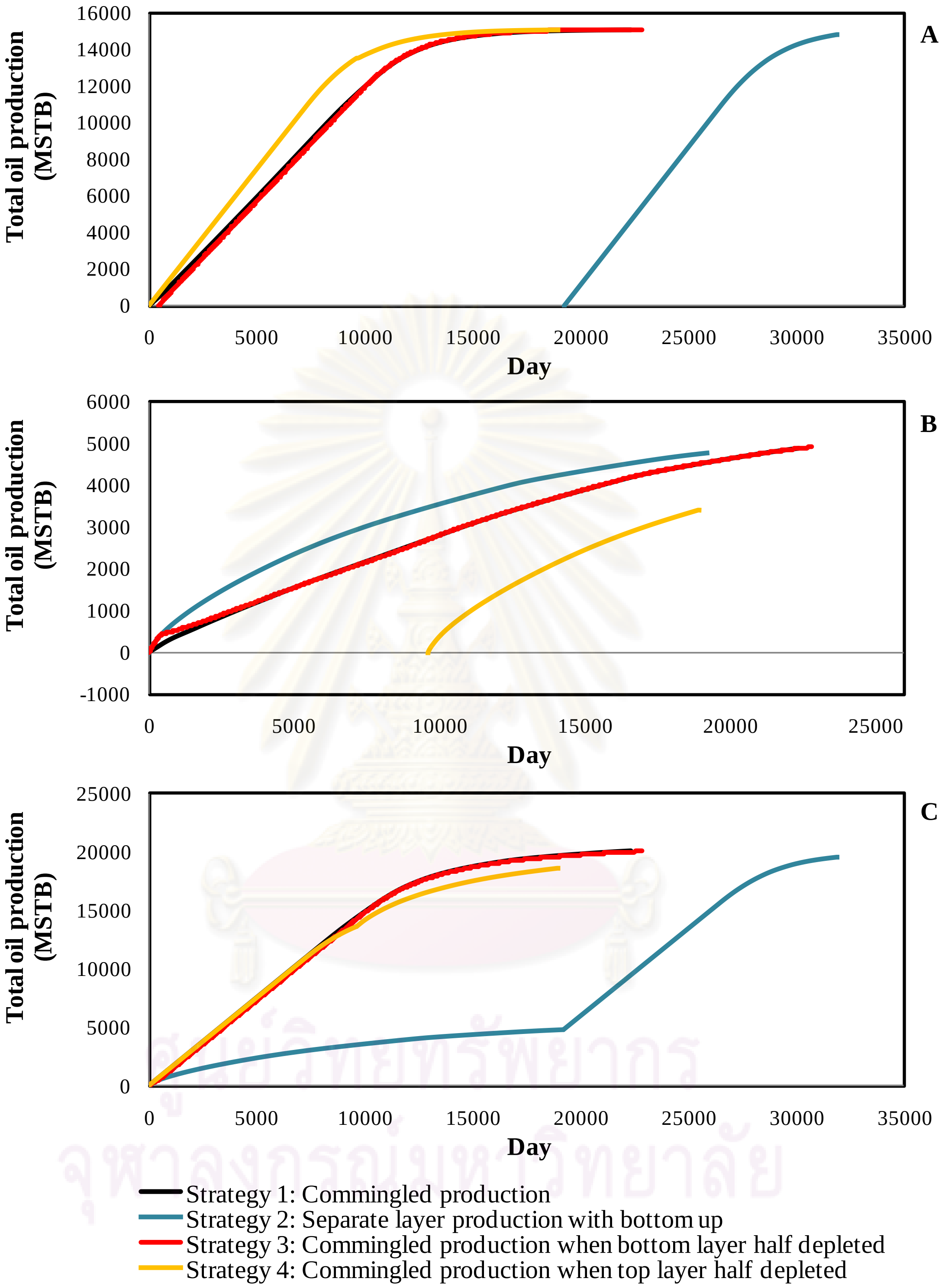

Figure 5.25: Total oil production of Case 4: O – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

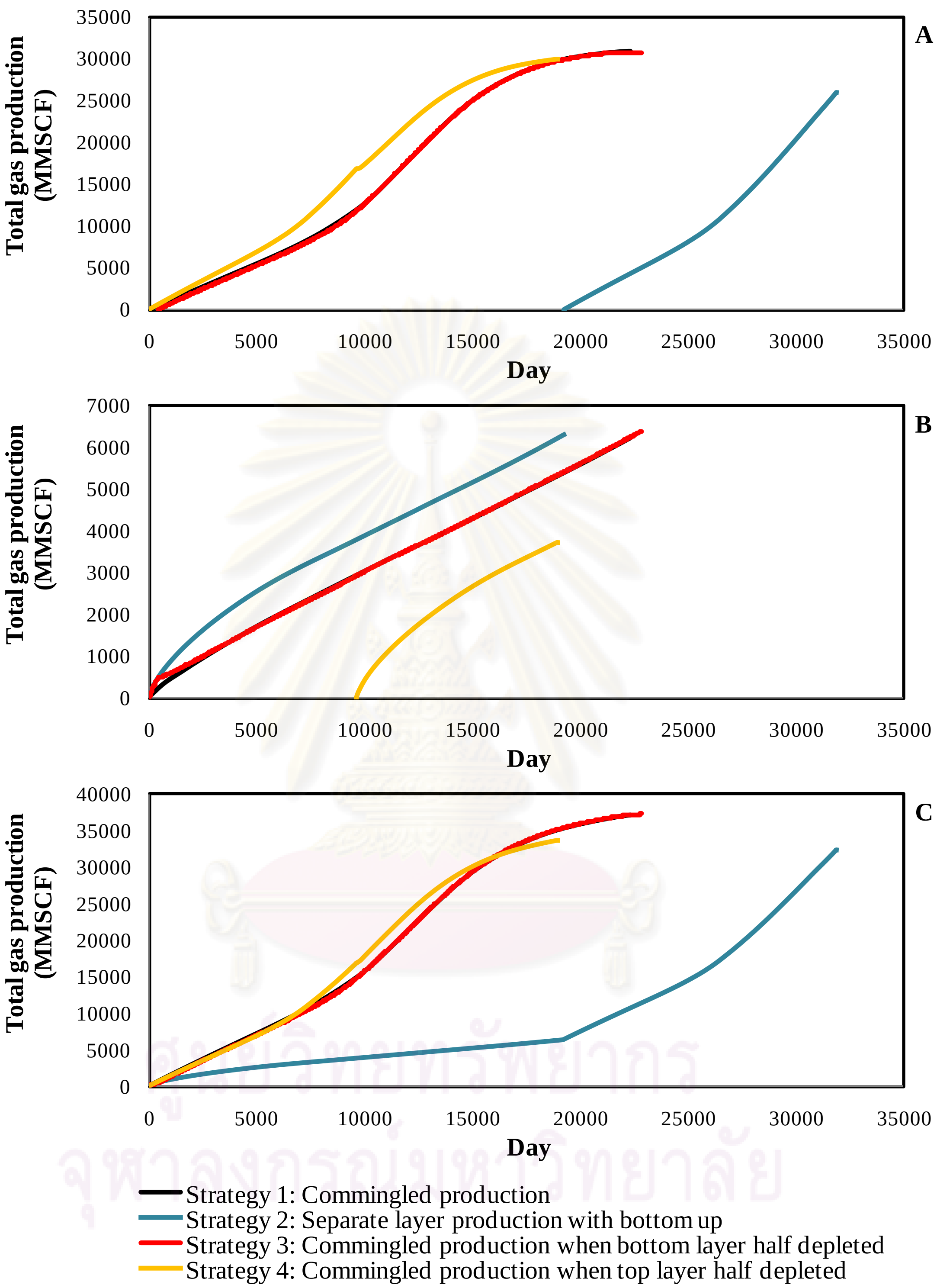

Figure 5.26: Total gas production of Case 4: O – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

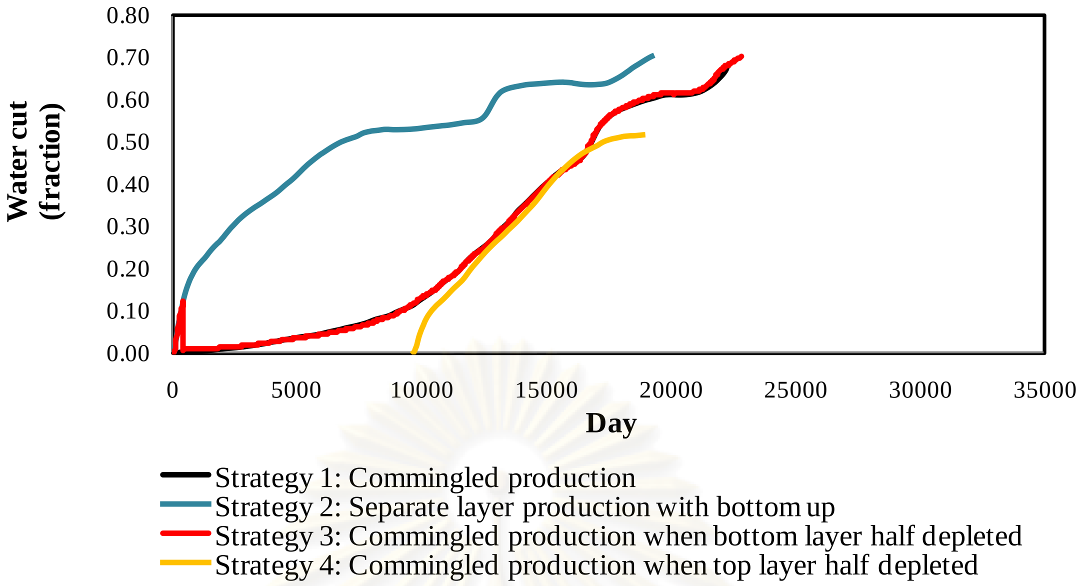

Figure 5.27: Water Cut of Case 4: O – O&W

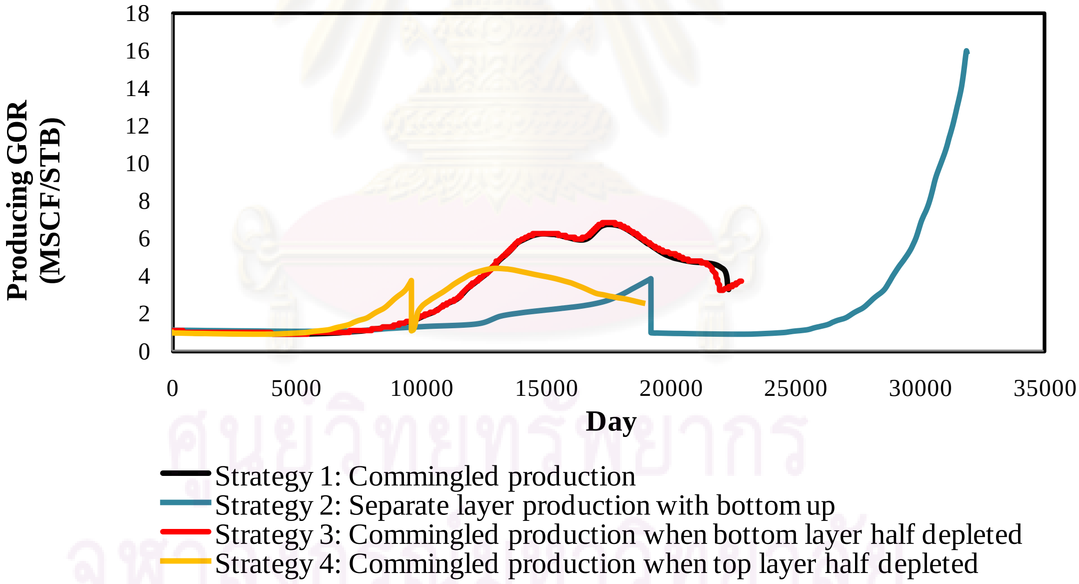

Figure 5.28: Producing GOR of Case 4: O – O&W

5.5 Case 5: G – G&W

In this case, the reservoir consists of 100 ft of gas zone at the top layer and 50 ft of gas and water zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layr. The top layer is a gas reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of gas sand. The bottom layer is a gas reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of gas zone. A well schematic of Case 5 is shown in Figure 5.29.

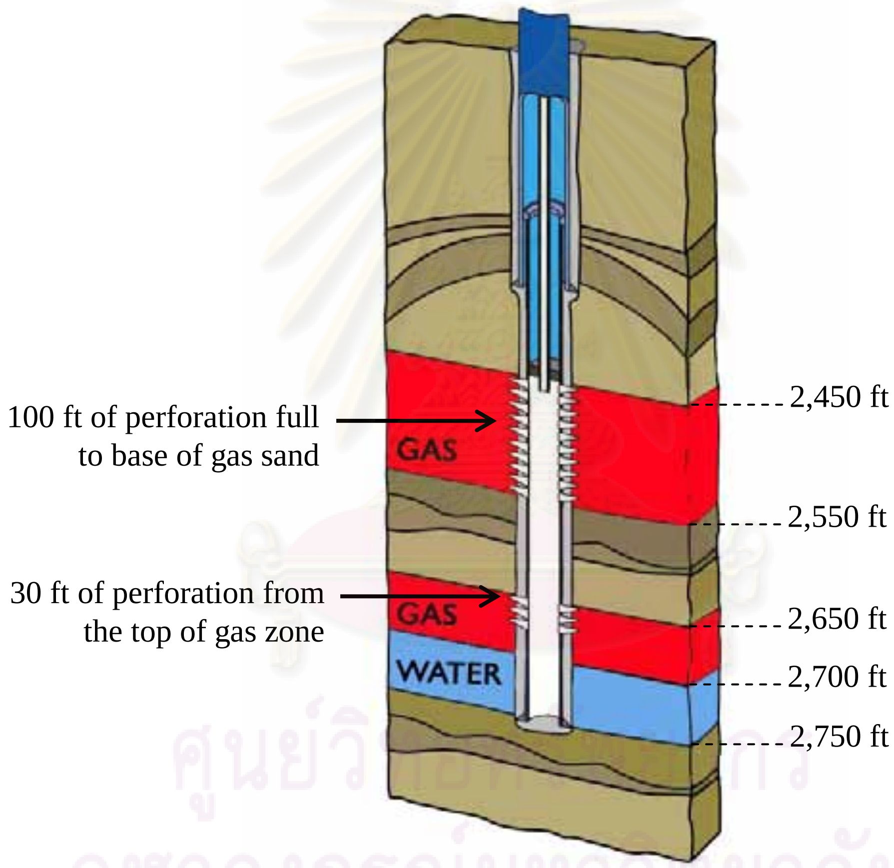

Figure 5.29: Well schematic for Case 5: G – G&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.30 and comparative results are summarized in Table 5.5.

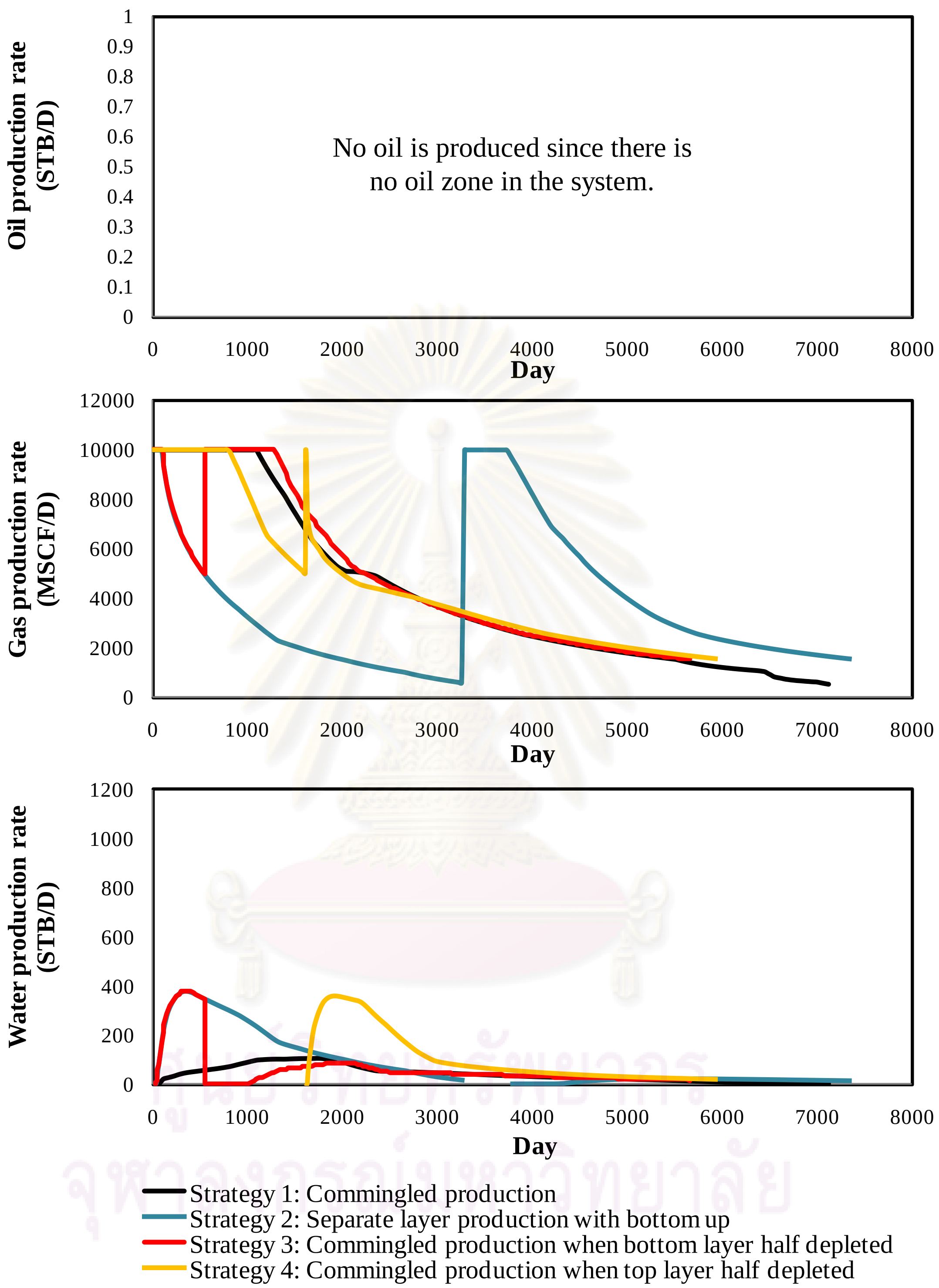

Figure 5.30: Production profiles of Case 5: G – G&W

Table 5.5: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 5: G – G&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Gas (MMSCF)	29,400	28,144	27,411	27,229
Water (MSTB)	288	524	358	463
Gas recovery factor **	74.17	71.00	69.15	68.69
Abandonment time (day)	7,121	7,181	5,690	5,964

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.5.1 Gas production

Figure 5.30 reveals that all production strategies give totally different gas and water production profiles. Figure 5.33A shows that strategies 1 and 3 can recover gas from the depletion-drive reservoir at the top layer equally, but Figure 5.33B shows difference of total gas production from the water-drive reservoir at the bottom layer. Strategy 1 recovers more gas from the water-drive reservoir than other strategies because the reservoir is produced in a commingled fashion with depletion-drive reservoir at the top layer. Generally, the depletion-drive mechanism is the best for gas reservoir. Therefore, gas production from the depletion-drive reservoir induces a larger pressure drop at the bottom layer as shown in Figure 5.32B. In general, as the reservoir pressure drops larger, the higher amount of gas will be produced, due to greater expansion of gas remaining in the reservoir.

Strategies 3 and 4 deliver lower cumulative production and recovery factor of gas as shown in Table 5.5. This is due to the fact that the well dies before the reservoir depletes by the abandonment rate. The reason is that water flows into the wellbore rapidly, as shown in Figure 5.34 with a high water rate. The reason that the water cut earlier high and consequence earlier reach economic limit is the high water flow rate.

Another reason for low gas recovery is that the crossflow takes place between the layers. The configuration of strategy 3 generates the crossflow of gas into the bottom layer as illustrated in Figure 5.31B while the configuration of strategy 4 generates the crossflow of gas into the top layer as illustrated in Figure 5.31A. Therefore, there is a certain amount of gas remaining in the reservoir.

In summary, strategy 1 is the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.5 with the green highlight.

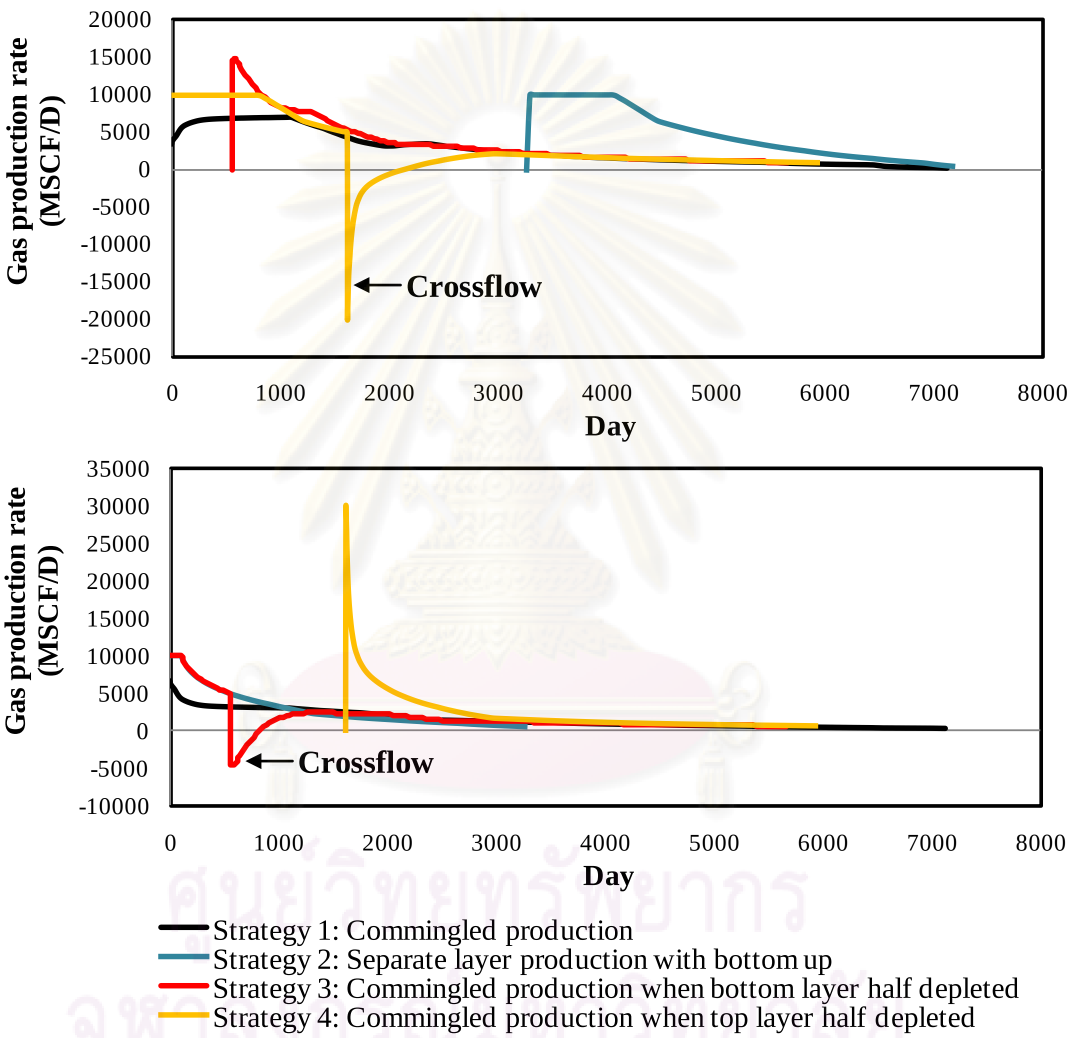

Figure 5.31: Gas profiles by layer of Case 5: G – G&W at (A) the top layer and (B) the bottom layer

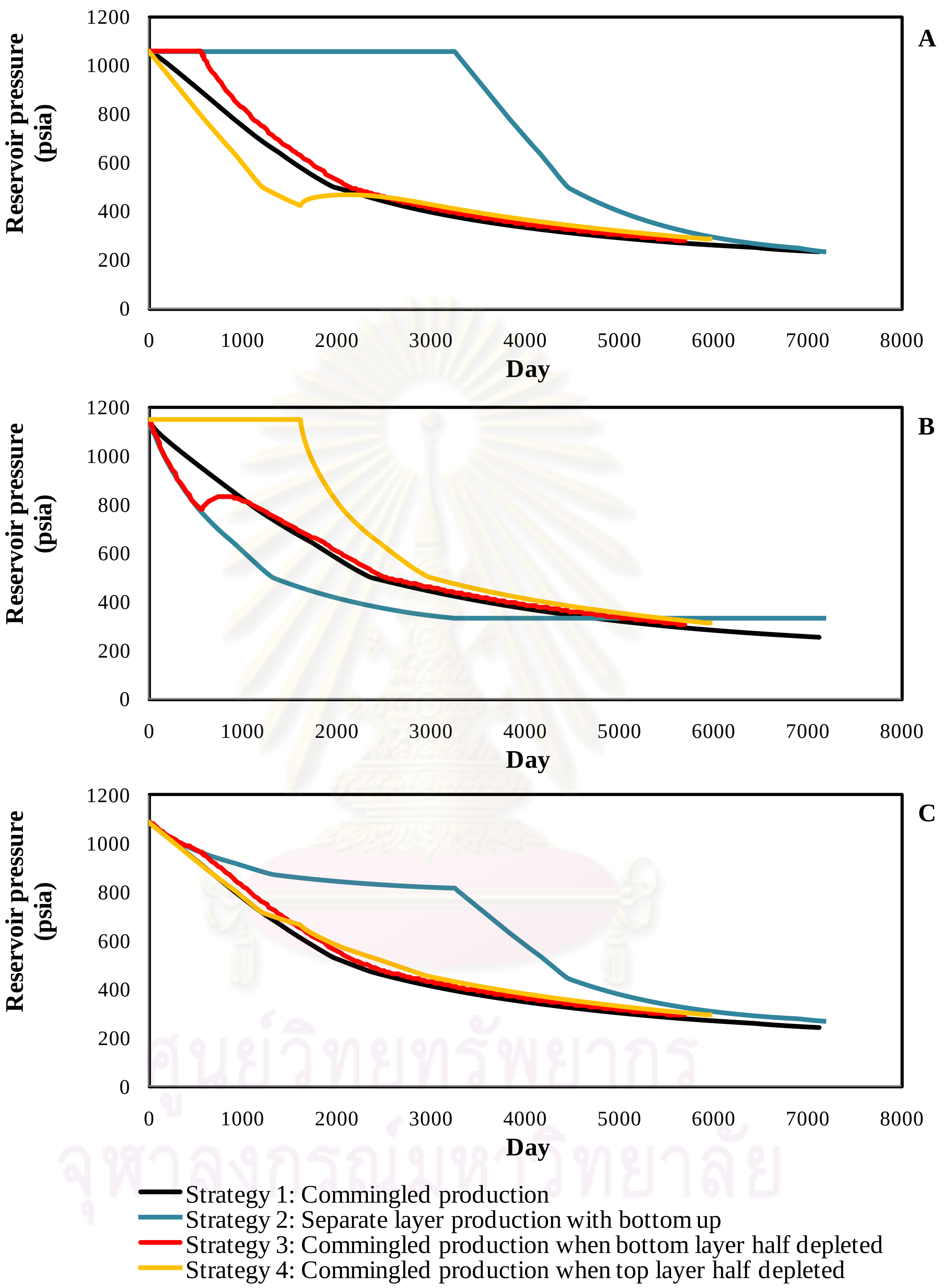

Figure 5.32: Reservoir pressure of Case 5: G – G&W at (A) the top layer, (B) the bottom layer and (C) both layers

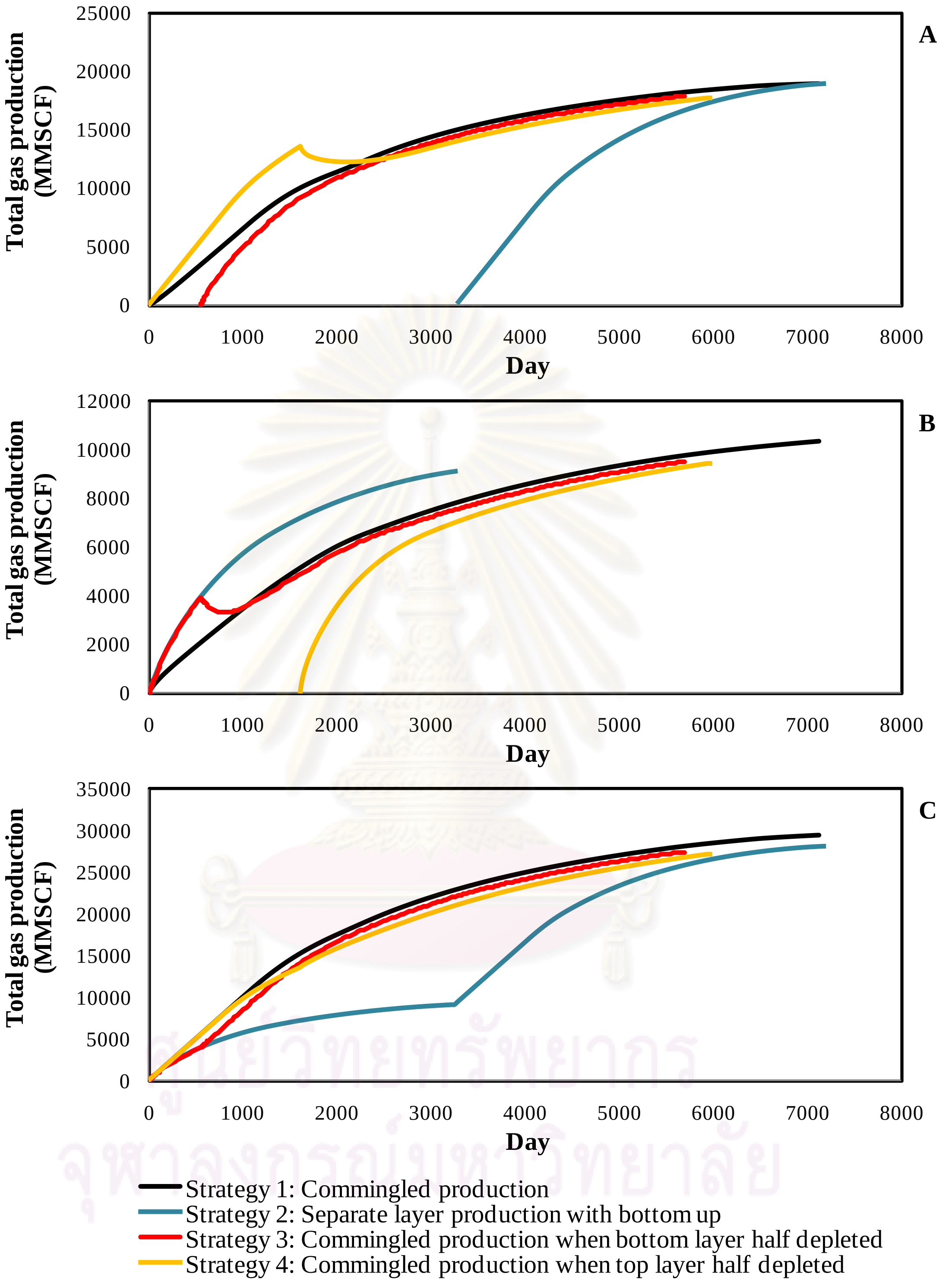

Figure 5.33: Total gas production Case 5: G – G&W at (A) the top layer, (B) the bottom layer and (C) both layers

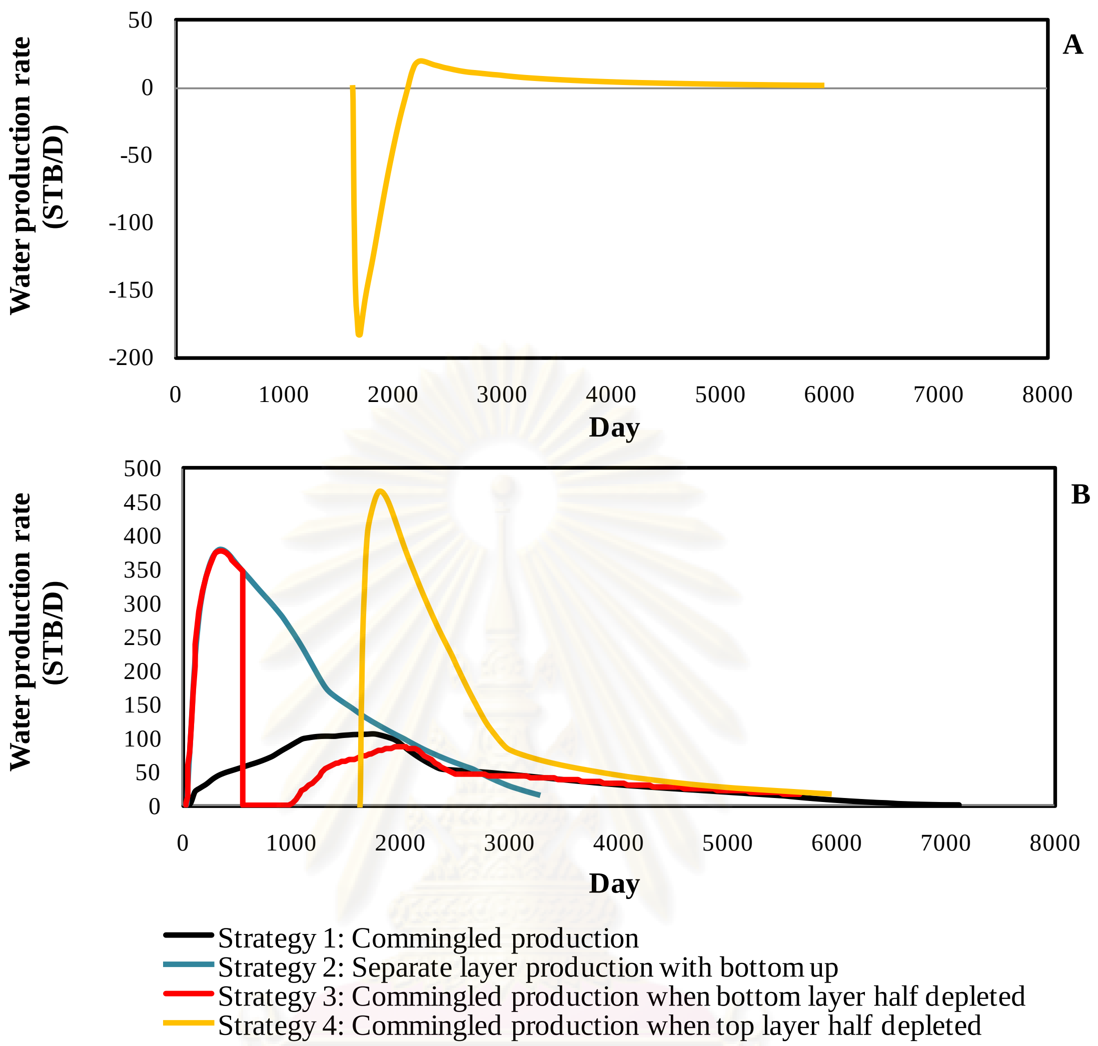

Figure 5.34: Water profiles by layer of Case 5: G – G&W at (A) the top layer and (B) the bottom layer

5.6 Case 6: G – O&W

In this case, the reservoir consists of 100 ft of gas zone at the top layer and 50 ft of oil and water zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a gas reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of gas sand. The bottom layer is an undersaturated oil reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of oil zone. A well schematic of Case 6 is shown in Figure 5.35.

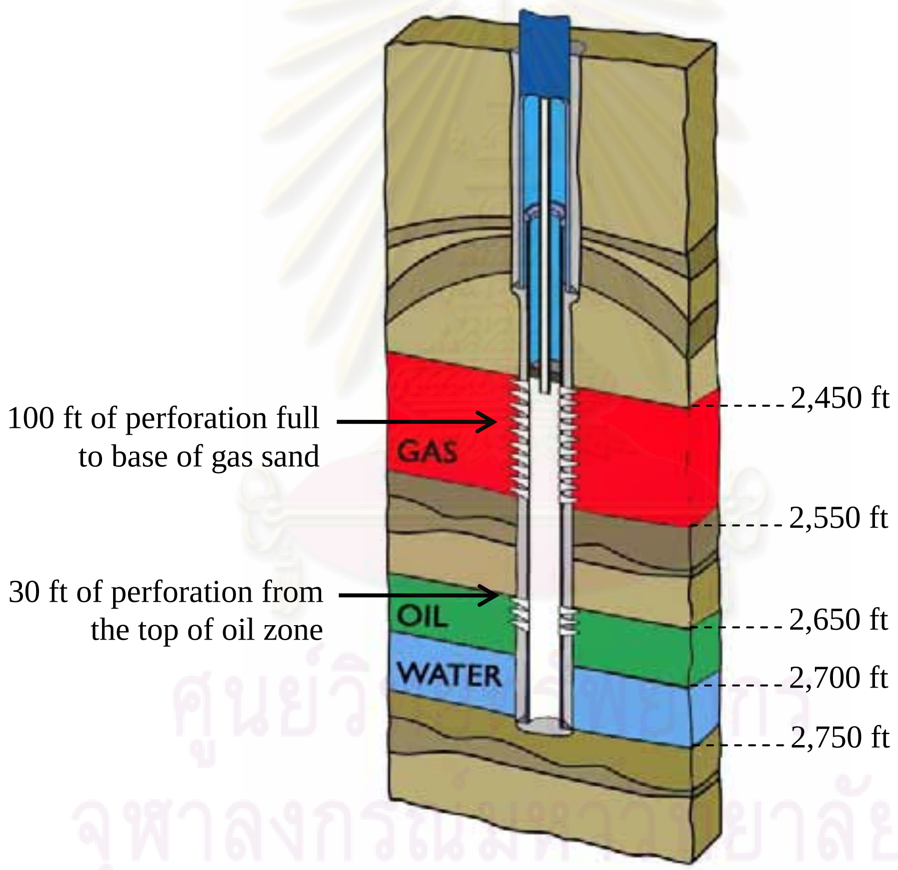

Figure 5.35: Well schematic for Case 6: G – O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.36 and comparative results are summarized in Table 5.5.

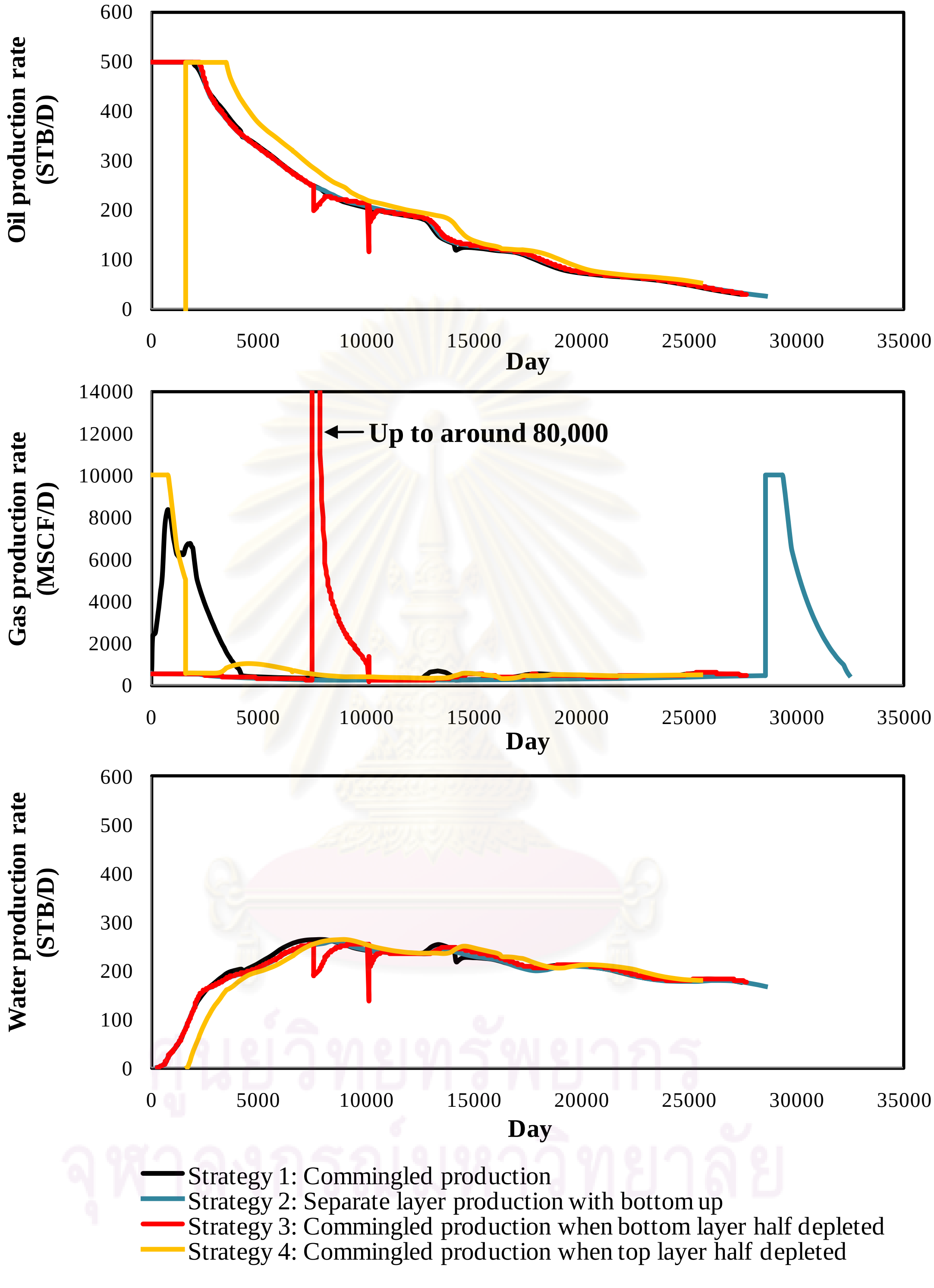

Figure 5.36: Production profiles of Case 6: G – O&W

Table 5.6: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 6: G – O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	5,247	5,301	5,266	4,933
Gas (MMSCF)	27,129	28,898	27,167	25,435
Free gas (MMSCF)	22,696	24,422	22,700	21,238
Solution gas (MMSCF)	4,433	4,476	4,466	4,197
MBOE	9,924	10,283	9,950	9,319
Water (STB)	5,562	5,697	5,535	5,063
Oil recovery factor (%) *	24.27	24.52	24.36	22.82
Gas recovery factor (%) **	53.79	57.30	53.86	50.43
Abandonment time (day)	27,514	32,507	27,728	25,567

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.6.1 Oil production

Figure 5.36 illustrates the oil production performances obtained from different production strategies. Figure 5.39B indicates that strategies 1, 2 and 3 deliver the same amount of total oil production, and strategy 4 delivers the minimum amount. Moreover, the figure also indicates that the oil is withdrawn from the bottom layer only which is a water-drive oil reservoir.

As shown in Table 5.6, strategies 1, 2 and 3 deliver similar cumulative oil production. However, strategy 2 yields slightly higher oil production than other strategies since it is strategy that permits the well to produce the fluid until reservoir depletes by economics limit. In other strategies, the well dies because of liquid load up. Moreover, no crossflow takes place between the layers since each layer is produced one at a time.

Strategy 4 delivers the lowest oil cumulative production and oil recovery factor. The well starts producing gas from the top layer reservoir which makes a very large and rapid pressure drawdown at the top layer as shown in Figure 5.38A. After that, both layers are produced simultaneously. Since there is a large difference in reservoir pressure between the two layers, a lot of oil from the bottom layer flows into the top layer. This is the reason why a large quantity of oil remains in the top layer and cannot be produced to the surface. The negative oil rate can assure that crossflow takes place in the reservoir as clearly revealed in Figure 5.37. Moreover, the well dies before the reservoir depletes by the abandonment rate due to water loading.

Strategies 1 and 3 do not deliver the best result for oil production since cross-flows occurs as shown in Figure 5.37 but cannot be clearly seen. The cause is that the pressure at the top layer which is occupied by gas depletes a lot faster than the bottom layer. Hence, oil from the bottom layer flows into the gas sand. However, Figure 5.39A indicates that the amount of oil that flows into the gas layer is not as much as strategy 4.

In summary, strategy 2 provides the highest ultimate production of oil as shown in Table 5.1 with the yellow highlight.

5.6.2 Gas production

Figure 5.36 illustrates the gas performances obtained from different production strategies. Figure 5.40B indicates that the performance of gas production at the bottom layer reservoir obtained from each strategy is consistent with the oil case since all producing gas is solution gas liberated from the oil. Therefore, more focus will be given to the top layer which is depletion-drive gas reservoir. Figure 5.40A indicates that strategy 2 gives very outstanding performance for gas production. The clarification is that the top layer maximizes the benefit of depletion-drive mechanism since it is produced without any oil or gas from the bottom layer.

Even though strategy 4 produces gas from the top layer separately at the beginning of production, but it delivers the lowest gas production from the top layer reservoir since crossflow takes place between the two layers as shown in Figure 5.37. Moreover, the well dies before the reservoir depletes by the abandonment rate due to water loading.

Strategies 1 and 2 do not deliver the best result for gas production since cross-flows occurs as shown in Figure 5.37 but cannot be clearly seen. The cause is the same as the oil case as described before.

To sum up, strategy 2 is the best approach to maximize the ultimate production of gas as shown in Table 5.6 with the green highlight.

5.6.3 Summary

Strategy 2 which is separate layer production delivers the best outcomes for both oil and gas production. In term of barrel of oil equivalent or BOE, it is still the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.6 with the brown highlight.

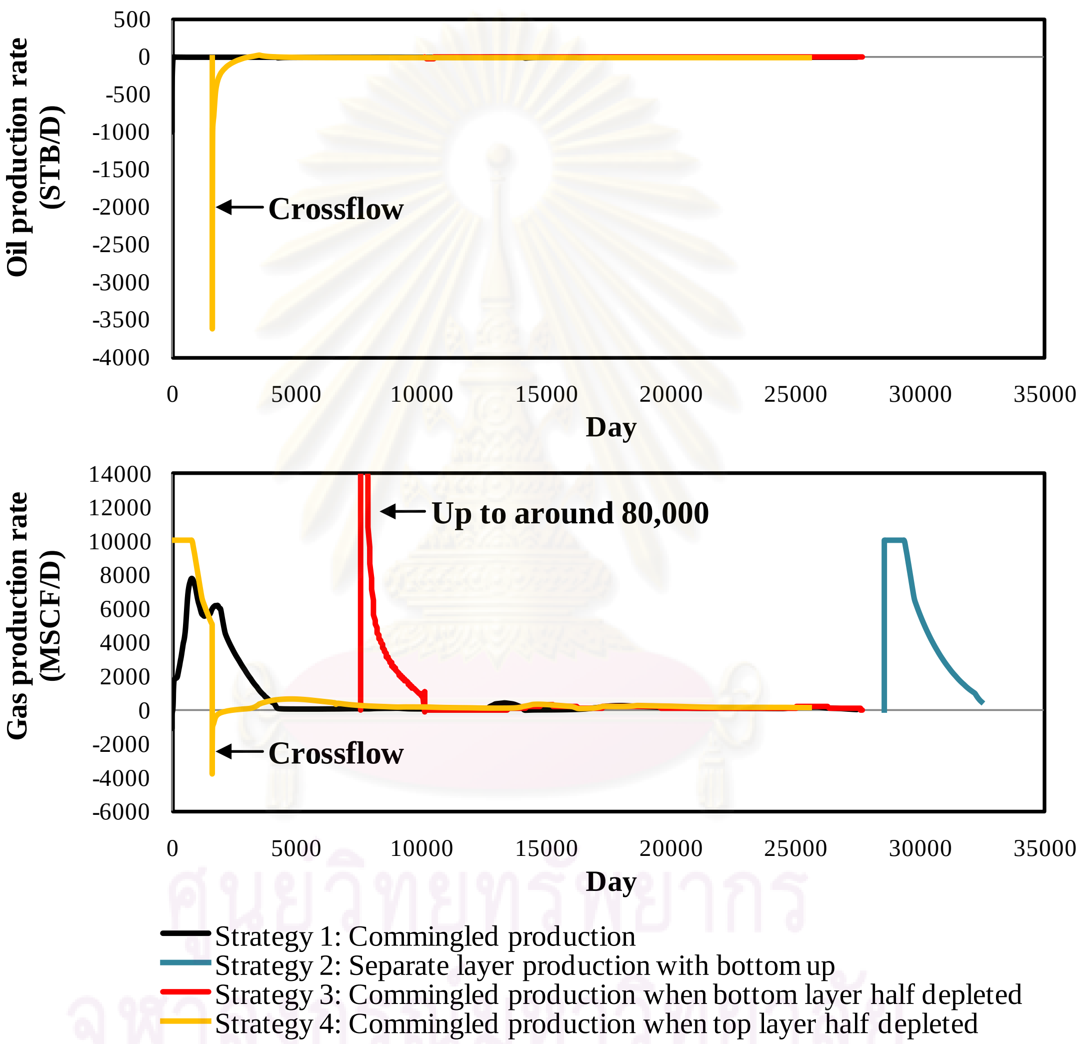

Figure 5.37: Production profiles of Case 6: G – O&W, at the top layer

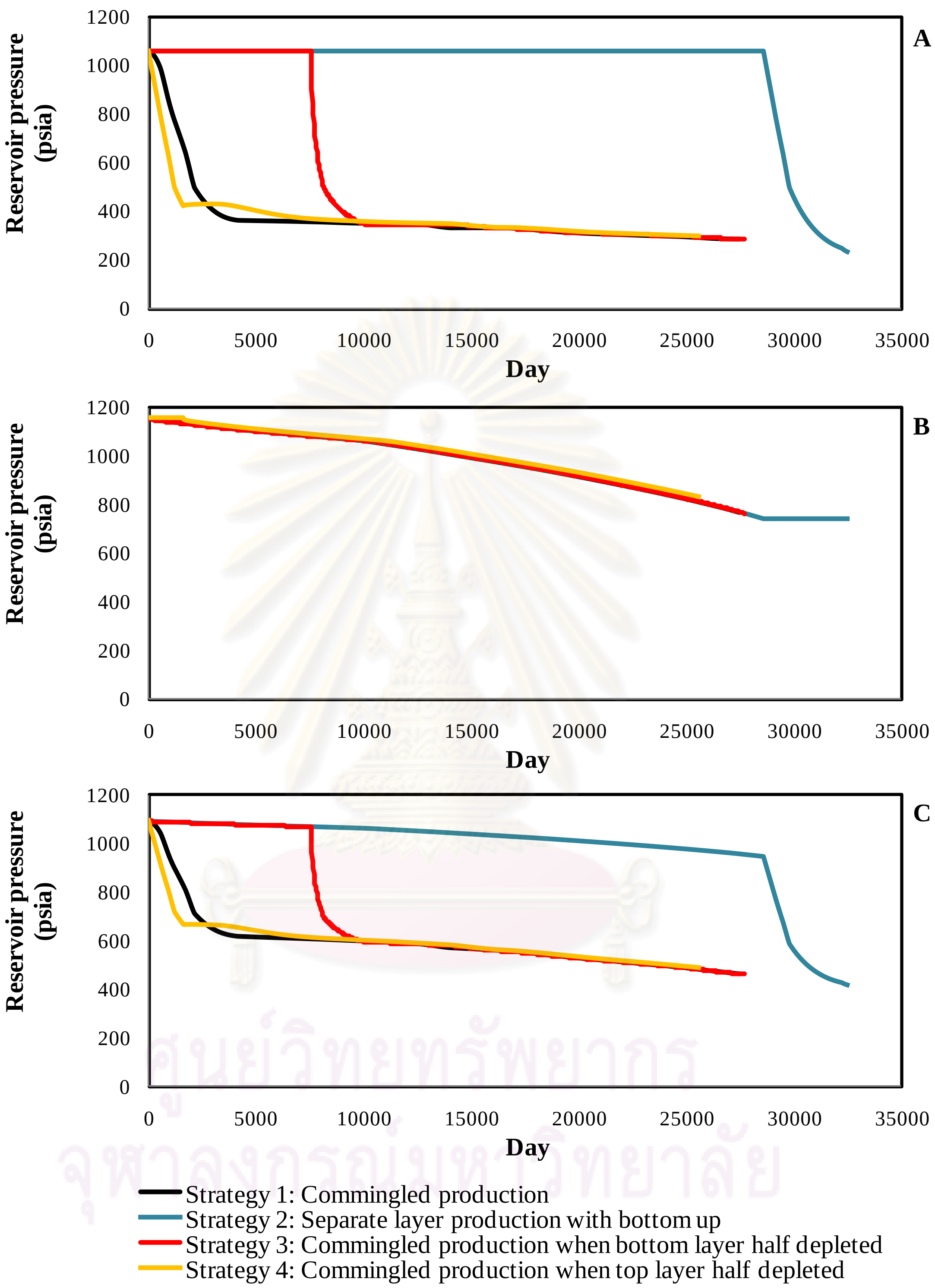

Figure 5.38: Reservoir pressure of Case 6: G – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

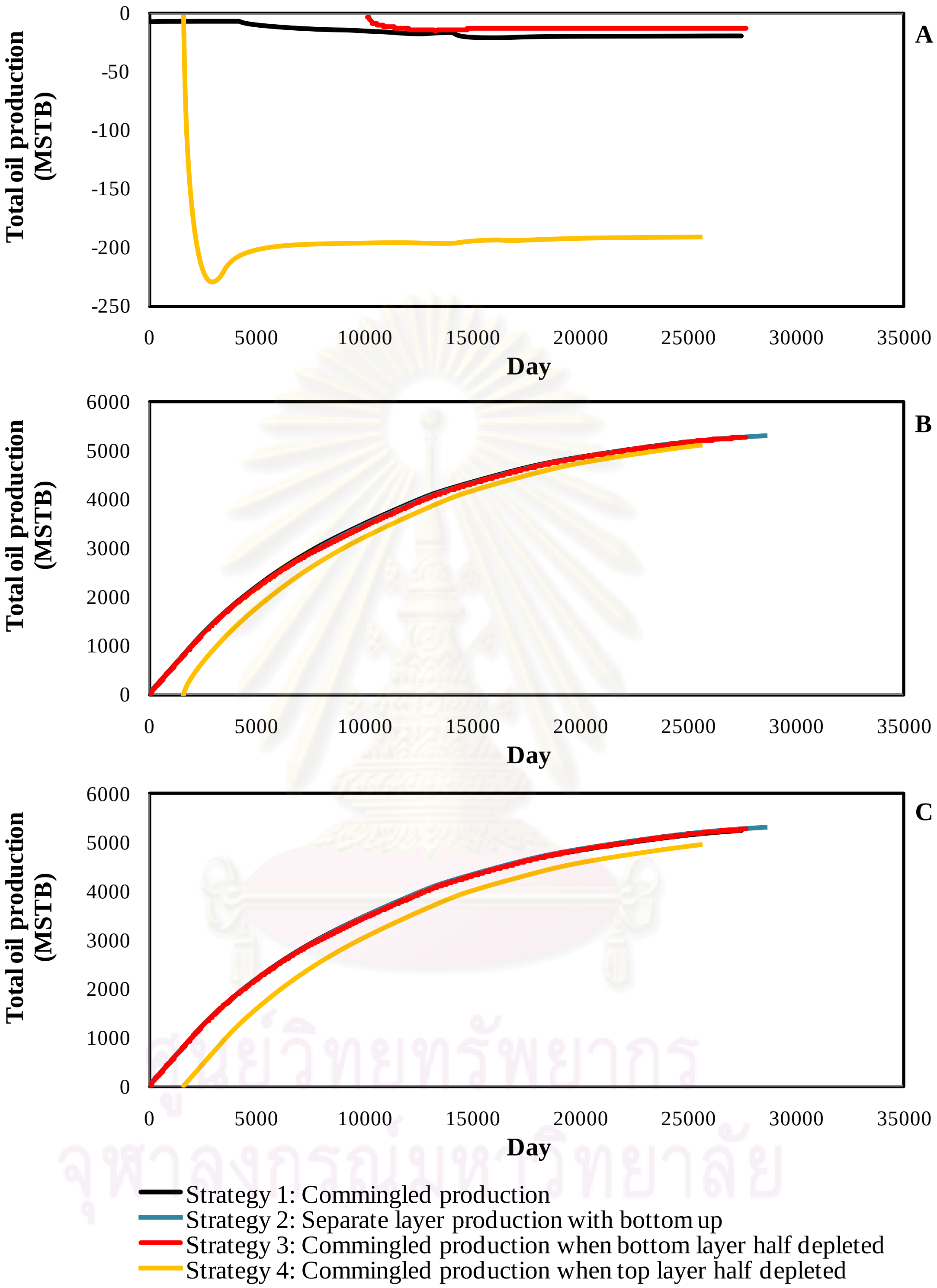

Figure 5.39: Total oil production of Case 6: G – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

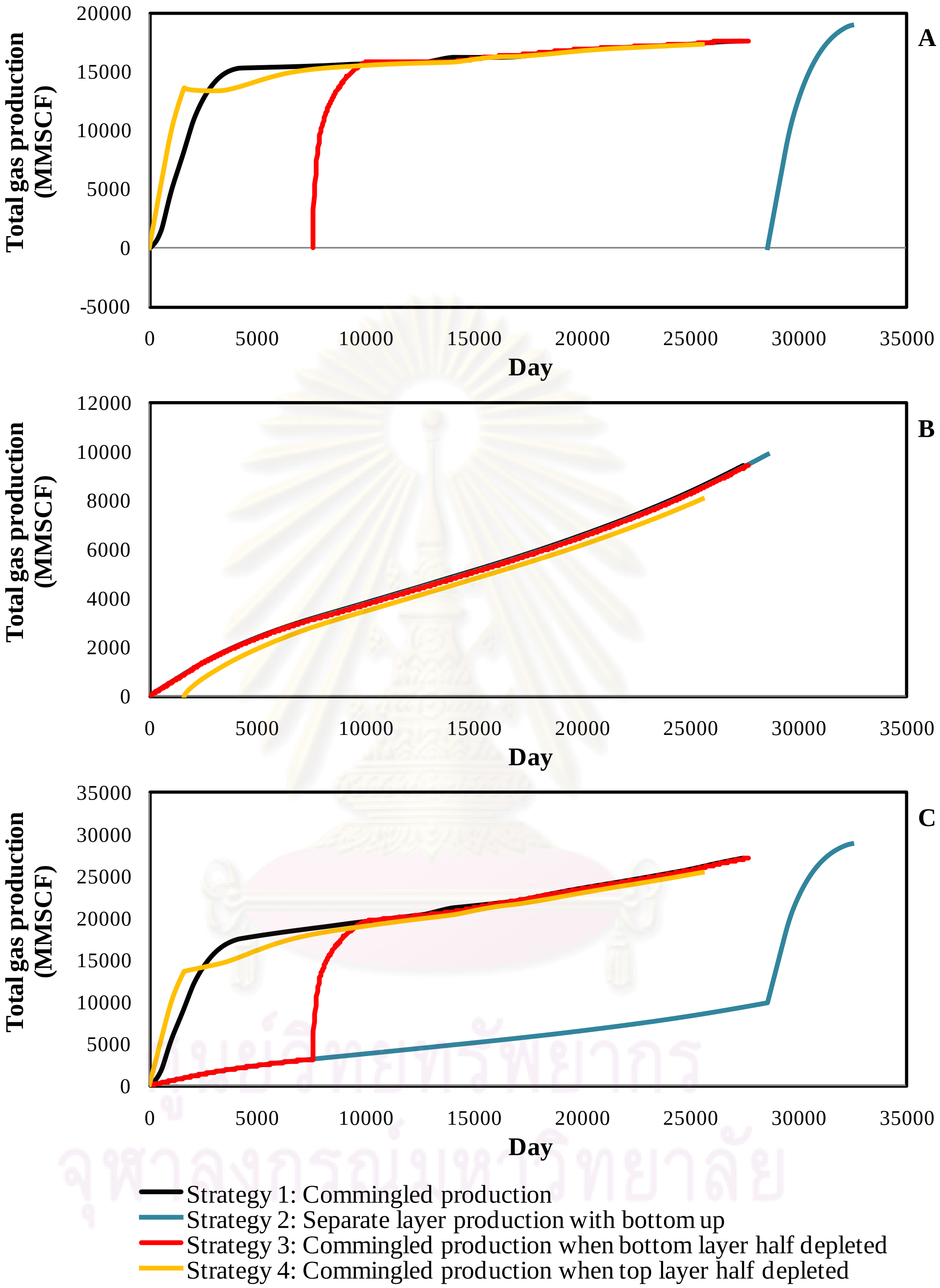

Figure 5.40: Total gas production of Case 6: G – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

5.7 Case 7: O – G&W

In this case, the reservoir consists of 100 ft of oil zone at the top layer and 50 ft of gas and water zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is an undersaturated oil reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of oil sand. The bottom layer is a gas reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of gas zone. A well schematic of Case 7 is shown in Figure 5.41.

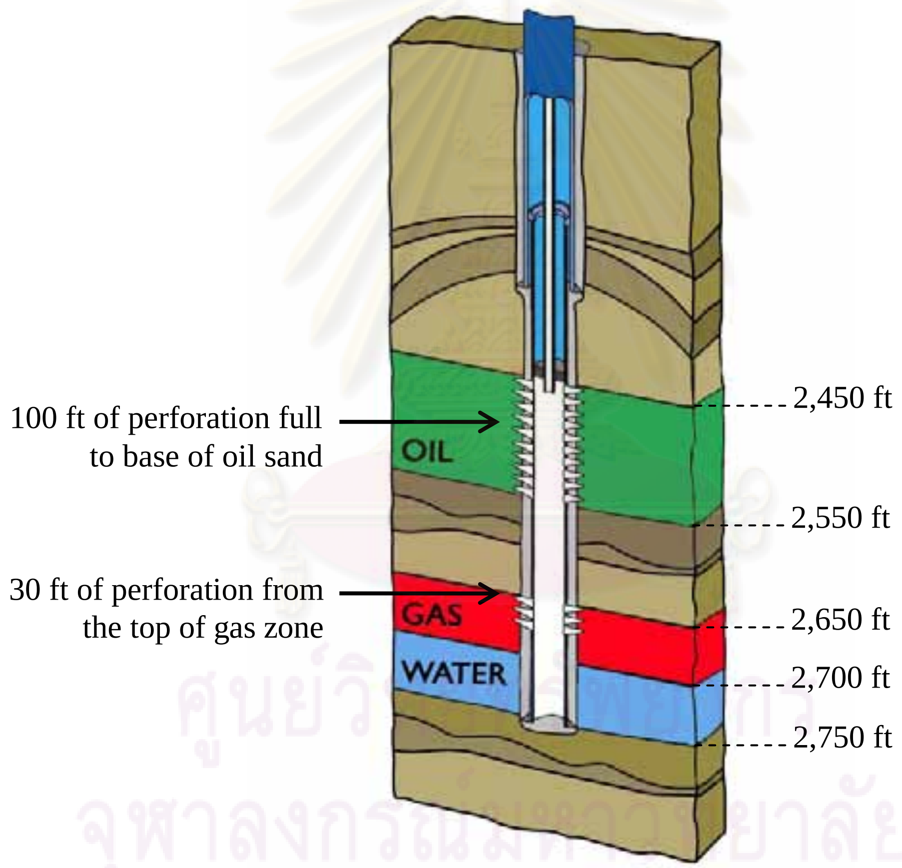

Figure 5.41: Well schematic for Case 7: O – G&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.42 and comparative results are summarized in Table 5.7.

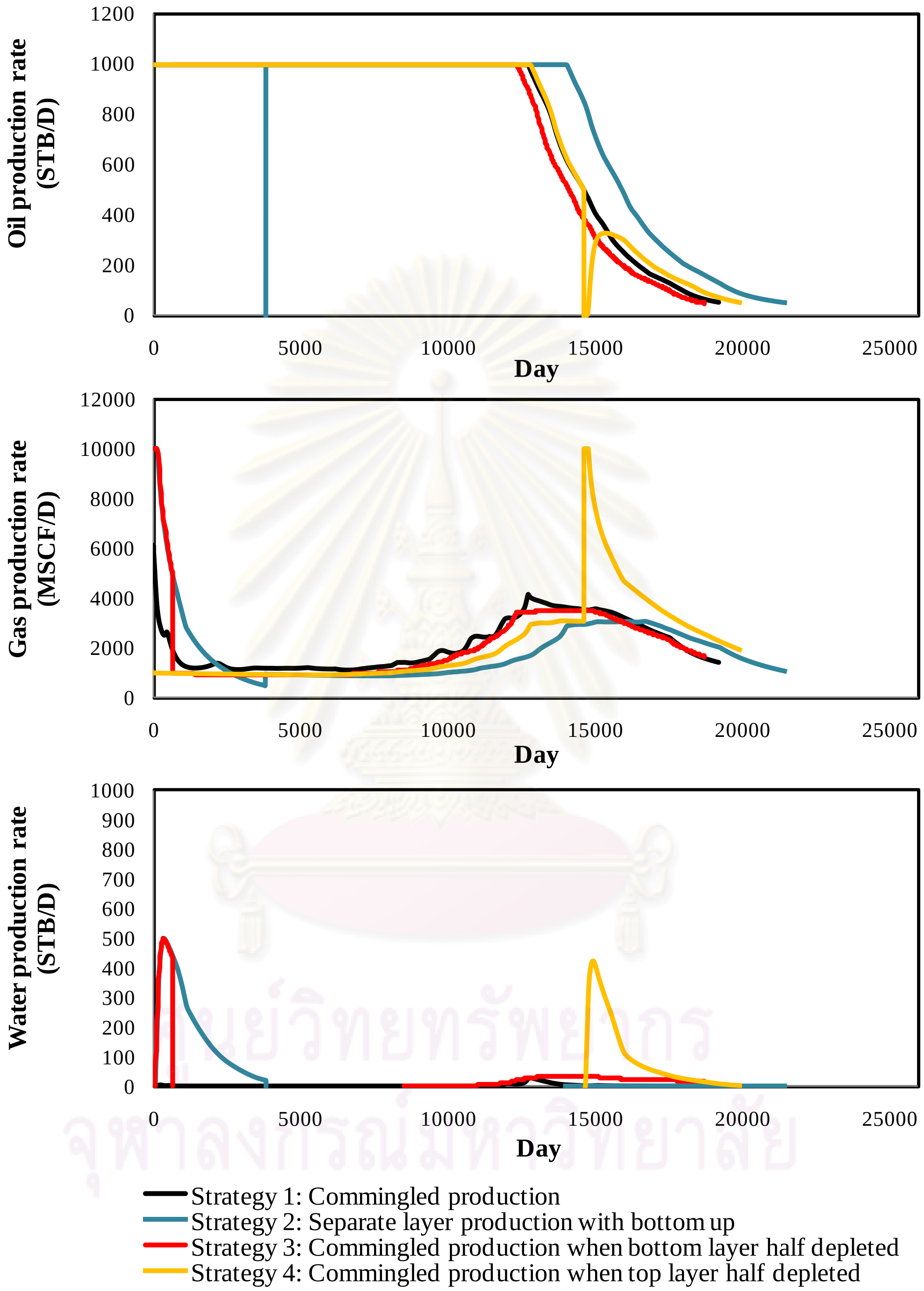

Figure 5.42: Production profiles of Case 6: G – O&W

Table 5.7: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 7: O – G&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	15,040	12,677	13,910	15,084
Gas (MMSCF)	40,479	39,921	38,277	41,482
Free gas (MMSCF)	29,362	30,805	28,146	30,349
Solution gas (MMSCF)	11,117	9,115	10,131	11,133
MBOE	22,019	19,560	20,510	22,236
Water (STB)	31	691	431	497
Oil recovery factor (%) *	32.96	27.78	30.49	33.06
Gas recovery factor (%) **	69.49	68.53	65.71	71.21
Abandonment time (day)	19,237	21,457	18,748	19,935

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.7.1 Oil production

Figure 5.42 illustrates the oil performances obtained from different production strategies. Figure 5.46A indicates that all strategies deliver the same amount of total oil production. Figure 5.46B indicates that the oil is withdrawn from the top layer only which is a depletion-drive oil reservoir. Moreover, the figure also reveals that a curtain amount of oil flows back in the opposite direction into the bottom layer for strategies 2 and 3. This crossflow is also identified in Figure 5.44. All of this explains why strategies 2 and 3 do not obtain the maximum oil recovery as summarized in Table 5.7.

Strategies 1 and 4 deliver excellent outcomes for oil recovery since no crossflow of oil takes place between the two layers. This is because the pressure difference between the layers of these strategies is not as much since the gas reservoir is not produced separately. Strategy 4 delivers slightly better results than strategy 1 because there is some water from the bottom layer flowing into the top layer as shown in Figure 5.43. This water may provide extra energy to deliver the oil out of the reservoir.

To sum up, strategy 4 gives the highest ultimate production of oil as shown in Table 5.7 with the yellow highlight. However, the oil recovery in strategy 1 is only slightly lower than that in strategy 4.

5.7.2 Gas production

Figure 5.42 illustrates gas performances for different production strategies. Figure 5.44A indicates that the performances of gas production at the top layer reservoir are consistent with the oil case since all gas produced from the top layer is solution gas liberated from the oil. Therefore, more focus will be given to the bottom layer which is water-drive gas reservoir. Figure 5.47B indicates that strategies 2 and 3 give poorer performance than others. This is because the crossflow takes place between the two layers. Gas flows into the bottom layer as shown in Figure 5.44 since there is a large differential pressure between the layers when the top layer commences producing.

Regarding the crossflow of oil as explained before, there is some oil from the top layer flowing into the bottom layer for strategies 2 and 3. This amount of oil helps sustain the reservoir pressure at the bottom layer as shown in Figure 5.45B with the increasing trend of pressure after crossflow occurs. As a result, the remaining gas in the bottom layer reservoir expands not much, and hence the gas recovery decreases.

Strategy 4 delivers better results than strategy 1 because the pressure drawdown at the bottom layer is higher. This is due to the fact that the gas reservoir is produced separately for a certain duration.

To sum up, strategy 4 is the best approach to maximize the ultimate production of gas as shown in Table 5.7 with the green highlight.

5.7.3 Summary

Strategy 4 which is commingled production when the top layer is half depleted delivers the best outcomes for both oil and gas production. In term of barrel of oil equivalent or BOE, it is still the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.7 with the brown highlight.

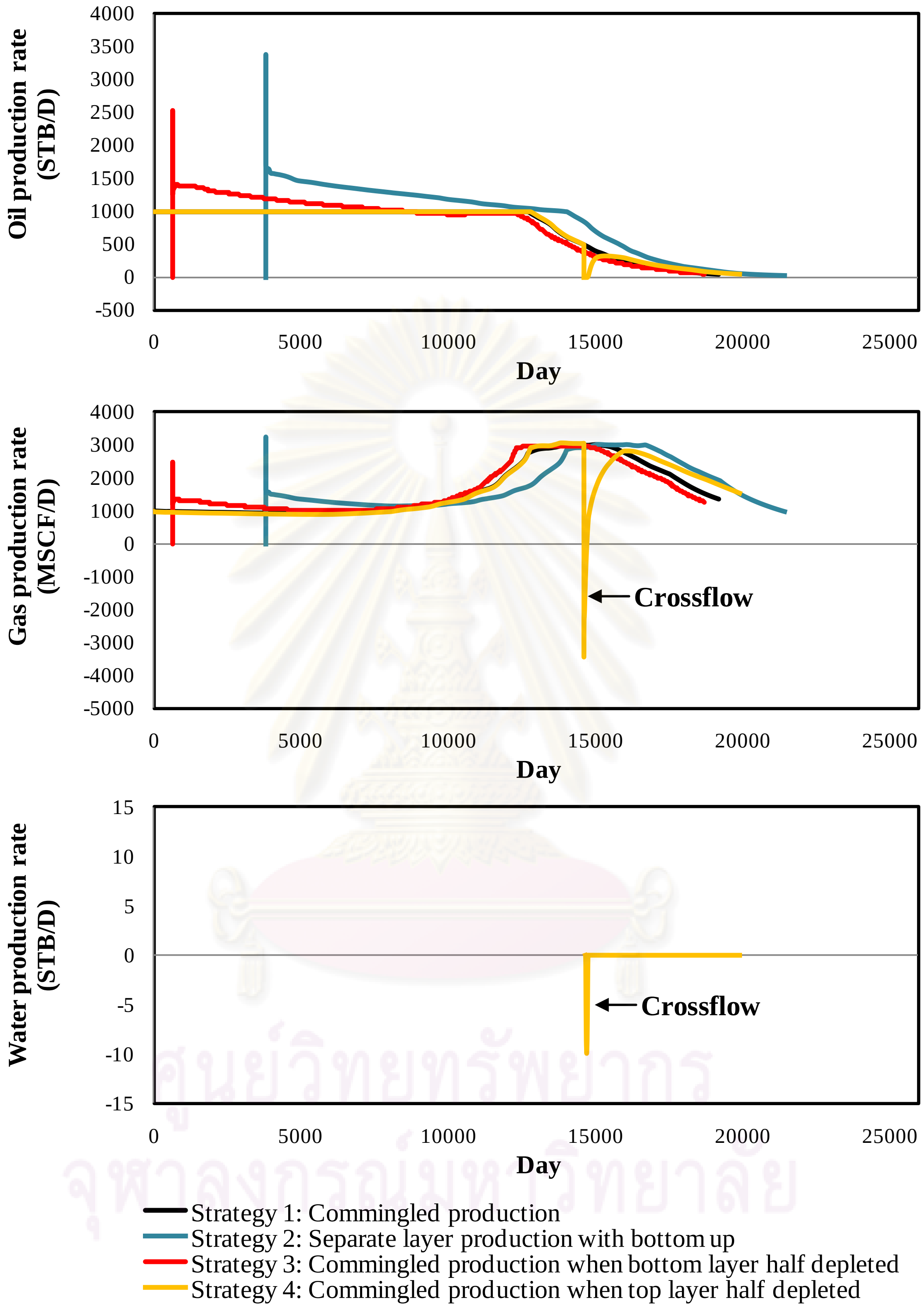

Figure 5.43: Production profiles of Case 7: O – G&W, at the top layer

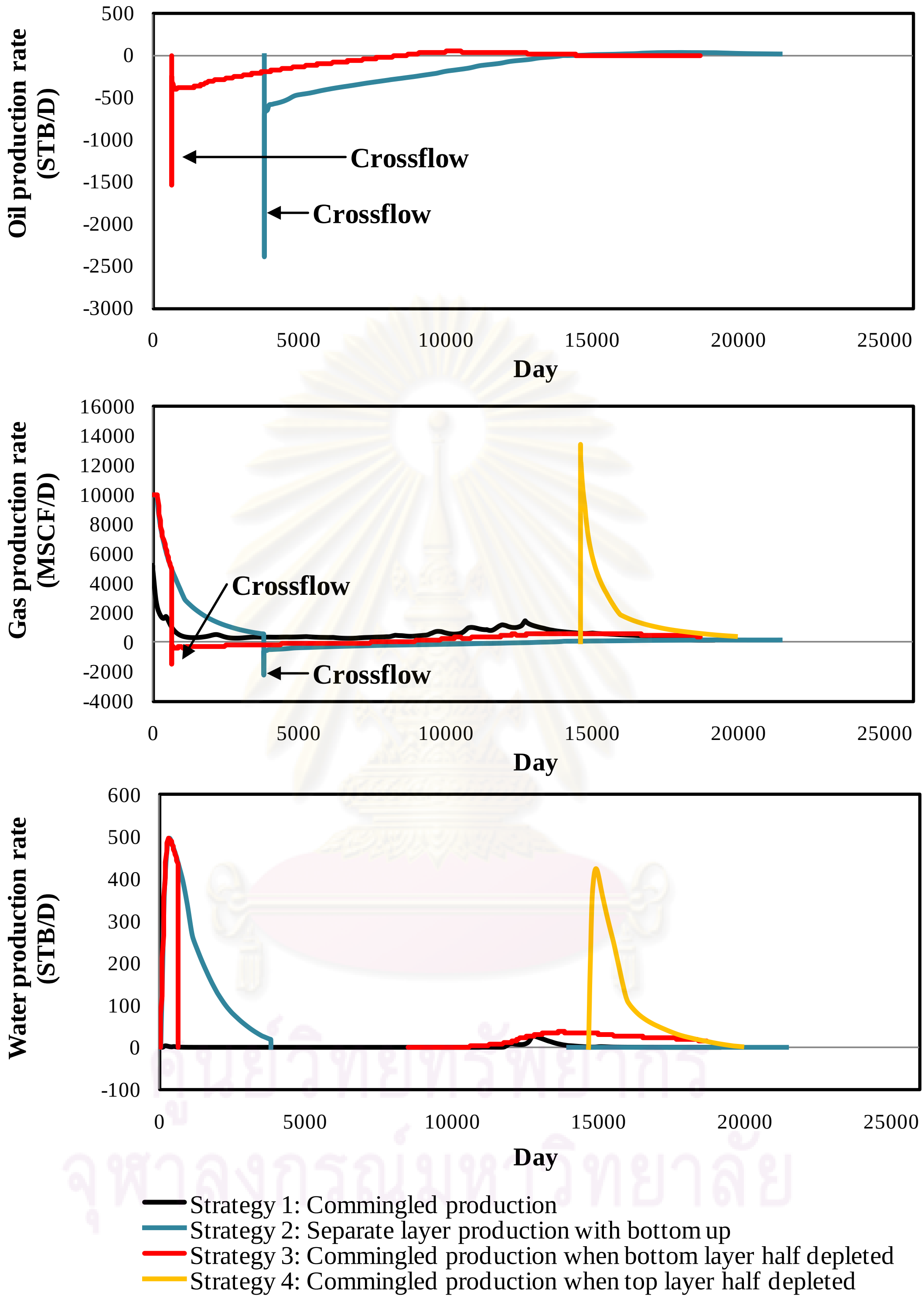

Figure 5.44: Production profiles of Case 7: O – G&W, at the bottom layer

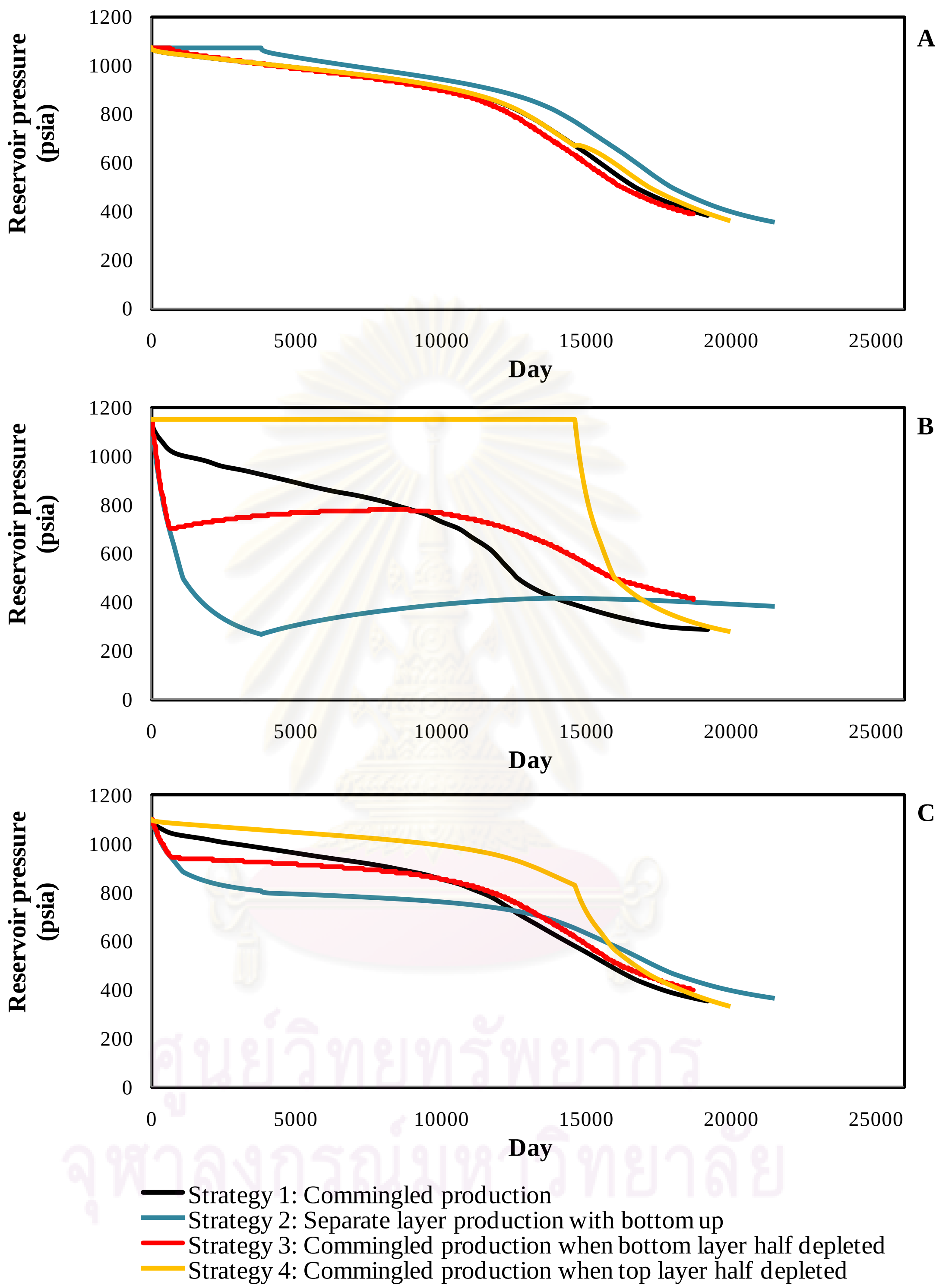

Figure 5.45: Reservoir pressure of Case 7: O – G&W at (A) the top layer, (B) the bottom layer and (C) both layers

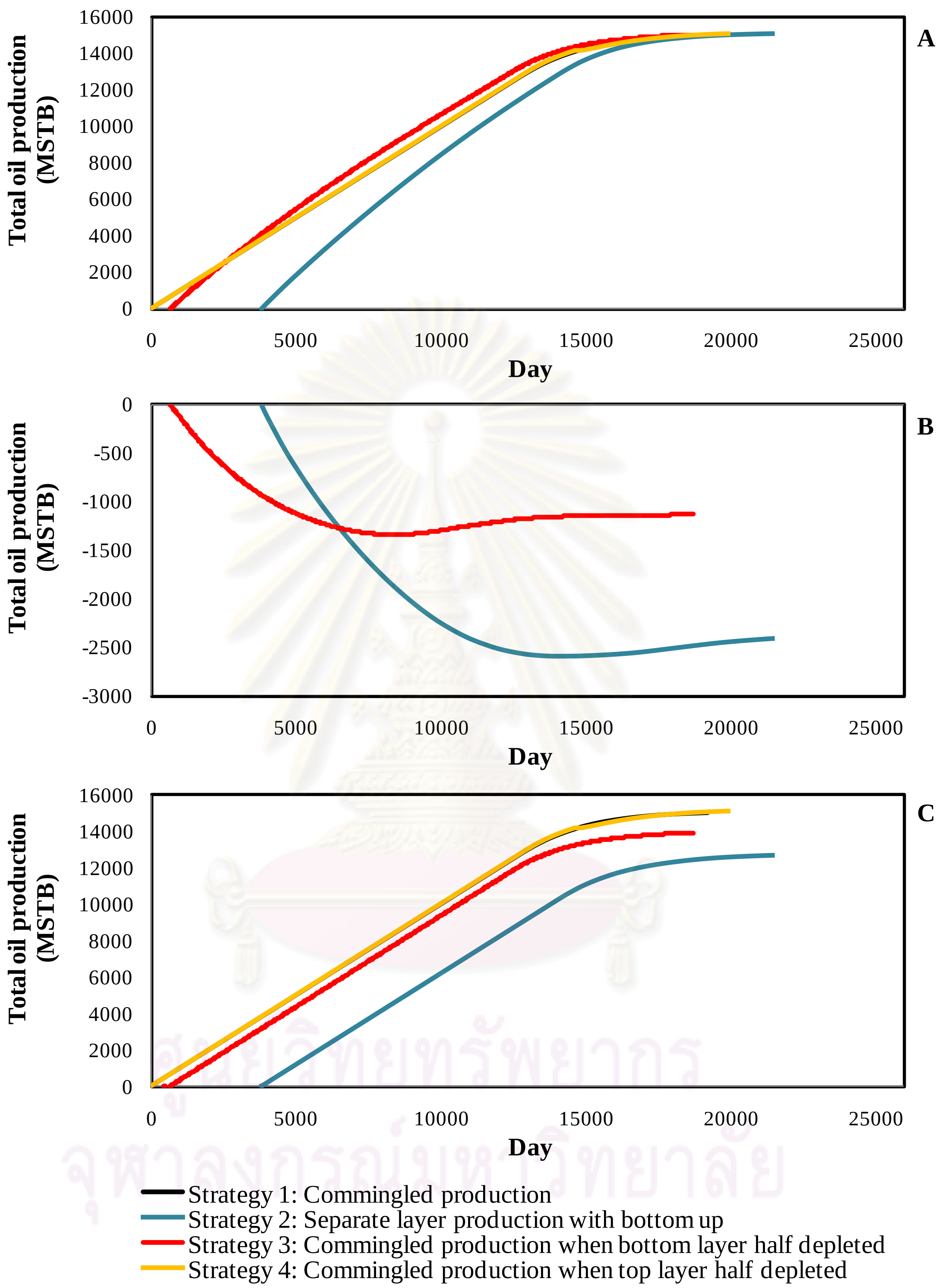

Figure 5.46: Total oil production of Case 7: O – G&W at (A) the top layer, (B) the bottom layer and (C) both layers

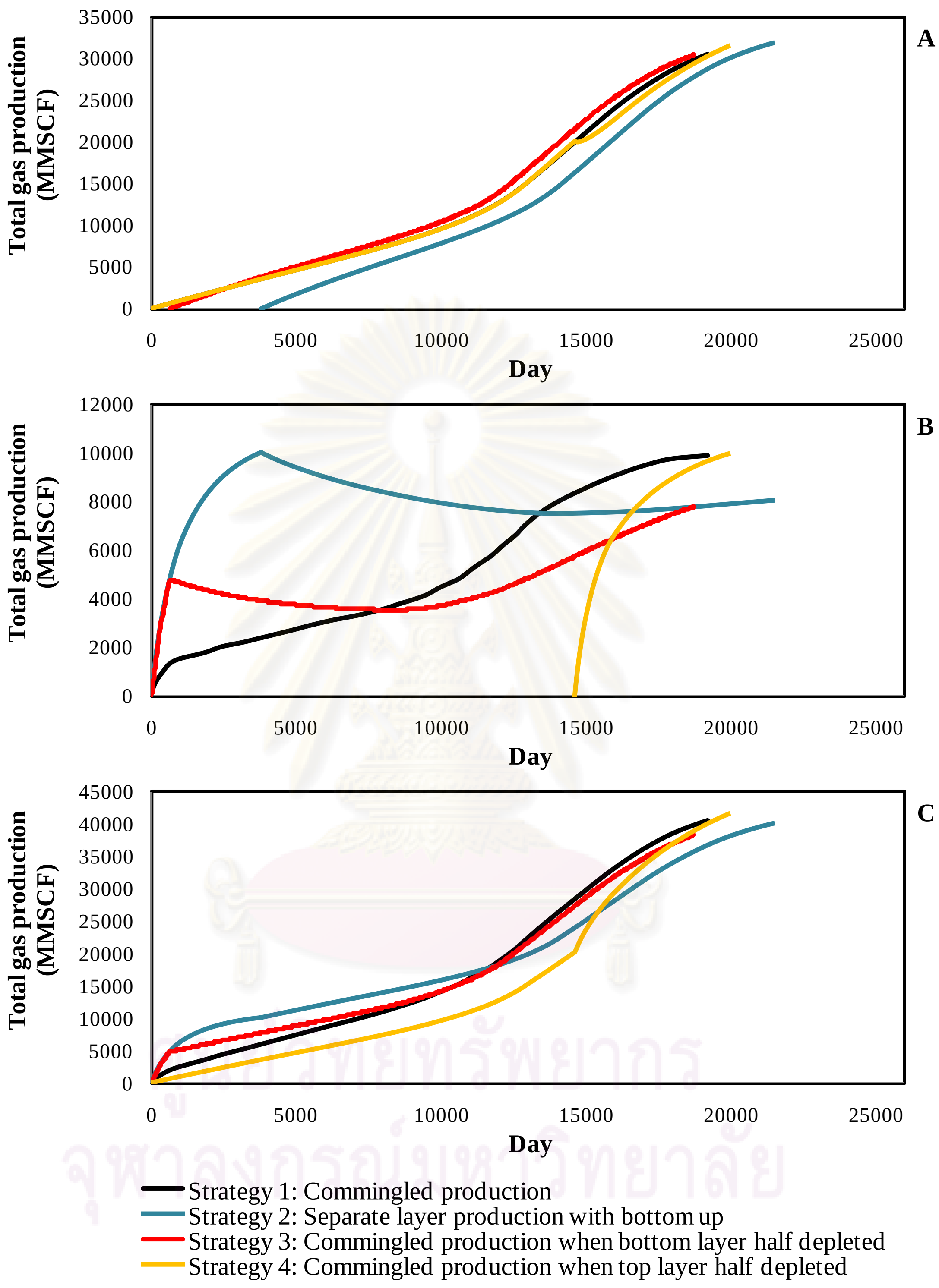

Figure 5.47: Total gas production of Case 7: O – G&W at (A) the top layer, (B) the bottom layer and (C) both layers

5.8 Case 8: G – G&O&W

In this case, the reservoir consists of 100 ft of gas zone at the top layer and 30 ft, 40 ft and 30 ft of gas, oil and water zone, respectively at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a gas reservoir with depletion-drive. The reservoir is perforated 100 ft full to base of gas sand. The bottom layer is a saturated oil reservoir with a gas cap above and an aquifer underneath. Drive mechanism of the reservoir is a combination of gas-cap-drive and water-drive. The reservoir is perforated 20 ft in the middle of oil zone. A well schematic of Case 8 is shown in Figure 5.48.

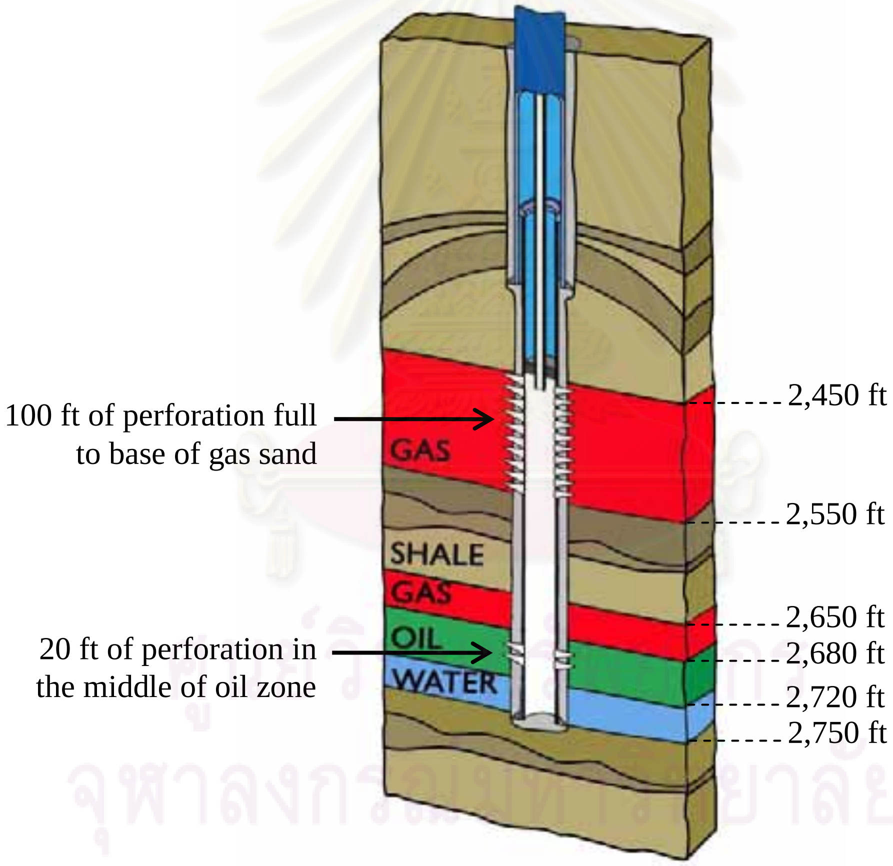

Figure 5.48: Well schematic for Case 8: G – G&O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.49 and comparative results are summarized in Table 5.8.

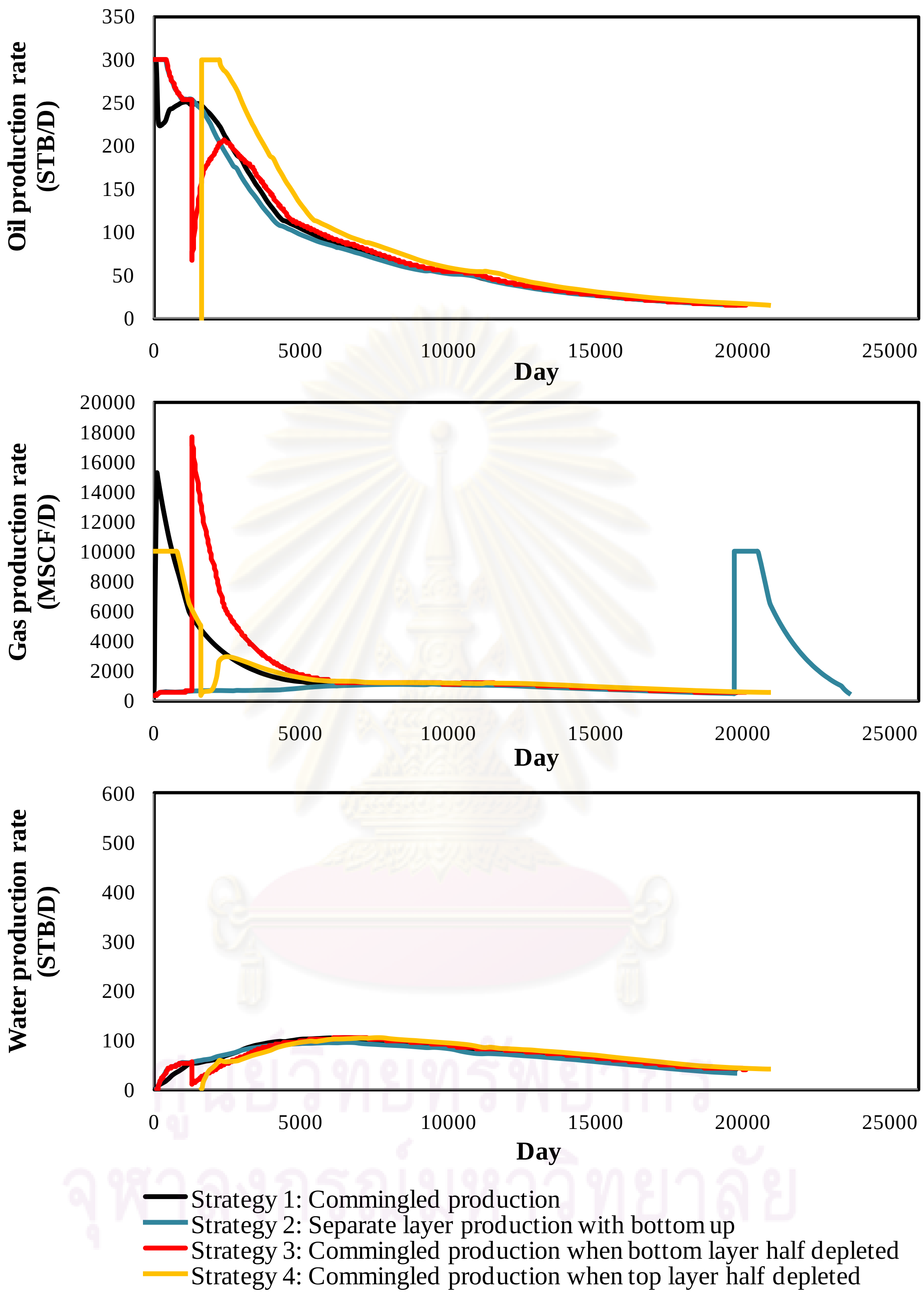

Figure 5.49: Production profiles of Case 8: G – G&O&W

Table 5.8: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 8: G – G&O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	1,626	1,596	1,649	1,553
Gas (MMSCF)	36,153	35,107	36,149	36,140
Free gas (MMSCF)	34,729	33,699	34,700	34,791
Solution gas (MMSCF)	1,423	1,408	1,449	1,348
MBOE	7,859	7,649	7,881	7,783
Water (STB)	1,431	1,315	1,426	1,434
Oil recovery factor (%) *	9.41	9.24	9.54	8.98
Gas recovery factor (%) **	67.18	65.23	67.17	67.15
Abandonment time (day)	19,813	23,649	20,119	20,909

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.8.1 Oil production

Figure 5.49 shows that all strategies give totally different oil production profiles. Figure 5.52A and 5.52B reveal that all of produced oil comes from the bottom layer which is a combination-drive reservoir. Table 5.8 indicates that cumulative oil production and recovery factor obtained from each strategy can be ranked from the top performance as strategies 3, 1, 2, and 4. However, there is not much different in cumulative oil production and recovery factor.

Strategy 3 yields the highest oil recovery since the smallest of crossflow takes place into the top layer reservoir as shown in Figure 5.52A. Strategy 1 yields a slightly lower oil recovery than strategy 3 because there is higher crossflow as shown in Figure 5.52A. The highest crossflow into the top layer reservoir obtained from strategy 4 as shown in Figure 5.52A, giving rise to the minimum oil recovery.

Although Figure 5.52A indicates that no crossflow takes place for strategy 2, but this strategy does not deliver the best performance because the reservoir is produced one layer at a time. Hence, less energy support due to separate production may be the possible reason.

In summary, strategies 1 and 3 are the best ways to maximize the ultimate production of oil as shown in Table 5.8 with the yellow highlight.

5.8.2 Gas production

For gas comparison, Figure 5.49 shows that all strategies give totally different gas production profiles. Figure 5.53A reveals that all strategies deliver similar gas production at the top layer while Figure 5.53B shows differences among 4 strategies at the bottom layer. Table 5.8 indicates that cumulative gas production and recovery factor obtained from strategies 1, 3 and 4 are very similar and these strategies yield better results than strategy 2.

Strategy 2 delivers minimum gas recovery because the reservoir is produced one layer at a time, resulting in relatively smaller pressure drop than other strategies which have commingled production with the gas reservoir at the top layer at least for a certain duration as depicted in Figure 5.51B. In general, as the reservoir pressure drops more, a higher amount of gas is produced, due to greater expansion of gas remaining in the reservoir.

Strategy 1 can produce the highest amount of gas since its pressure drop is the largest as shown in Figure 5.51B. This is because the bottom layer is produced in a commingled fashion with the gas reservoir all the production life. According to the explanation of strategy 2, as the reservoir pressure drops larger, the higher amount of gas is produced, due to a greater expansion of gas remaining in the reservoir.

In summary, strategies 1, 3 and 4 are the best approaches to maximize the ultimate production of gas as shown in Table 5.8 with the green highlight.

5.8.3 Summary

Strategies 1 and 3 which is commingled production and commingled production when the bottom layer is half depleted, respectively deliver the best outcomes in term of barrel of oil equivalent or BOE. Thus, strategies 1 and 3 are the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.8 with the brown highlight.

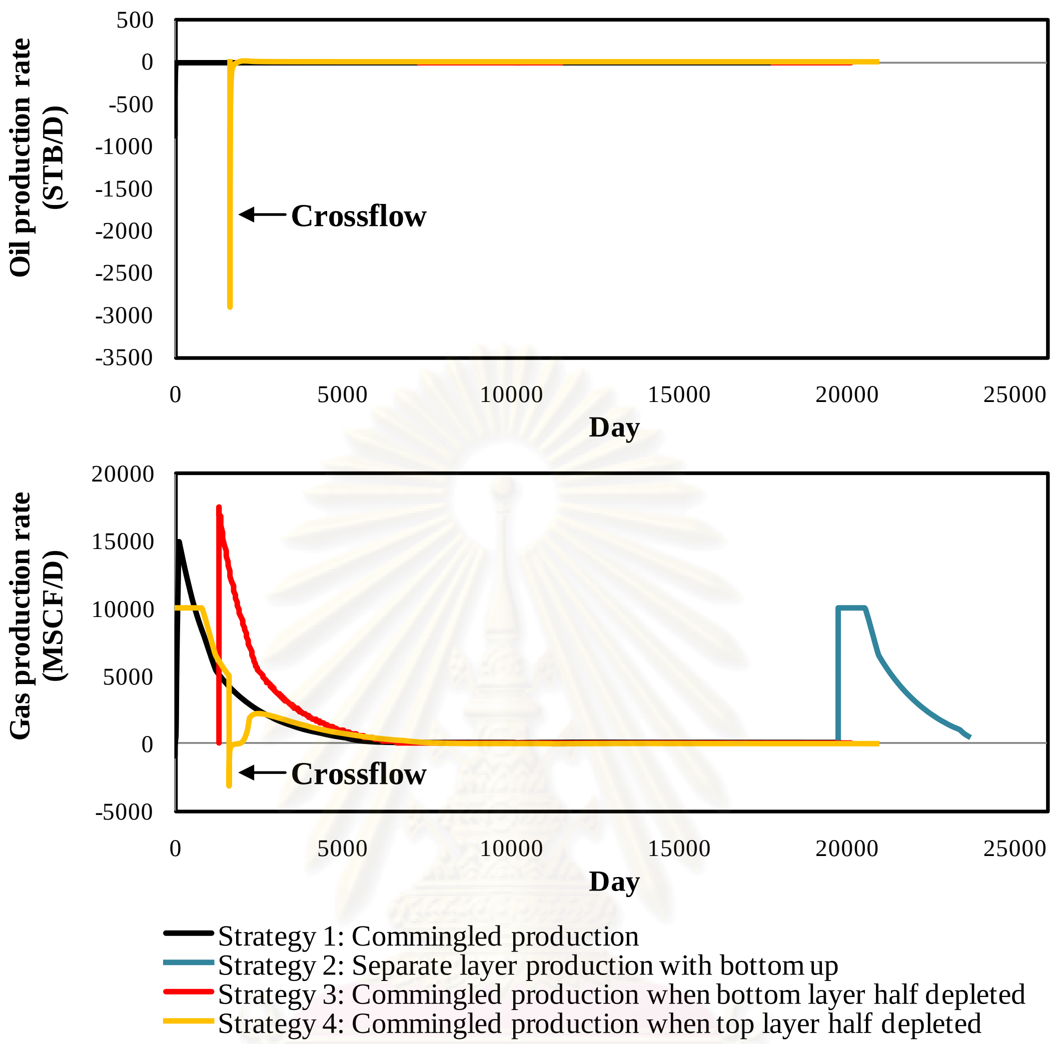

Figure 5.50: Production profiles of Case 8: G – G&O&W, at the top layer

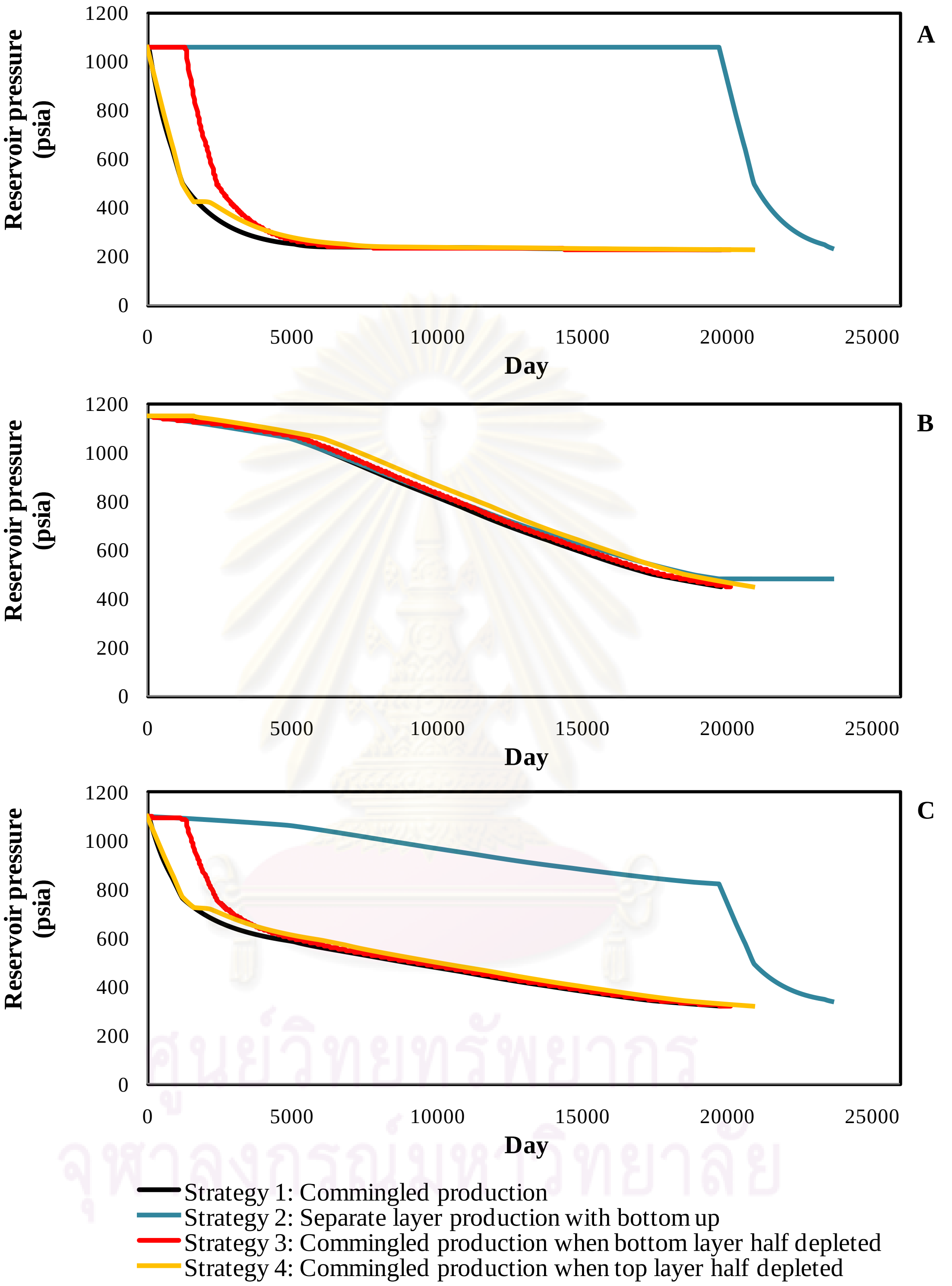

Figure 5.51: Reservoir pressure of Case 8: G – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

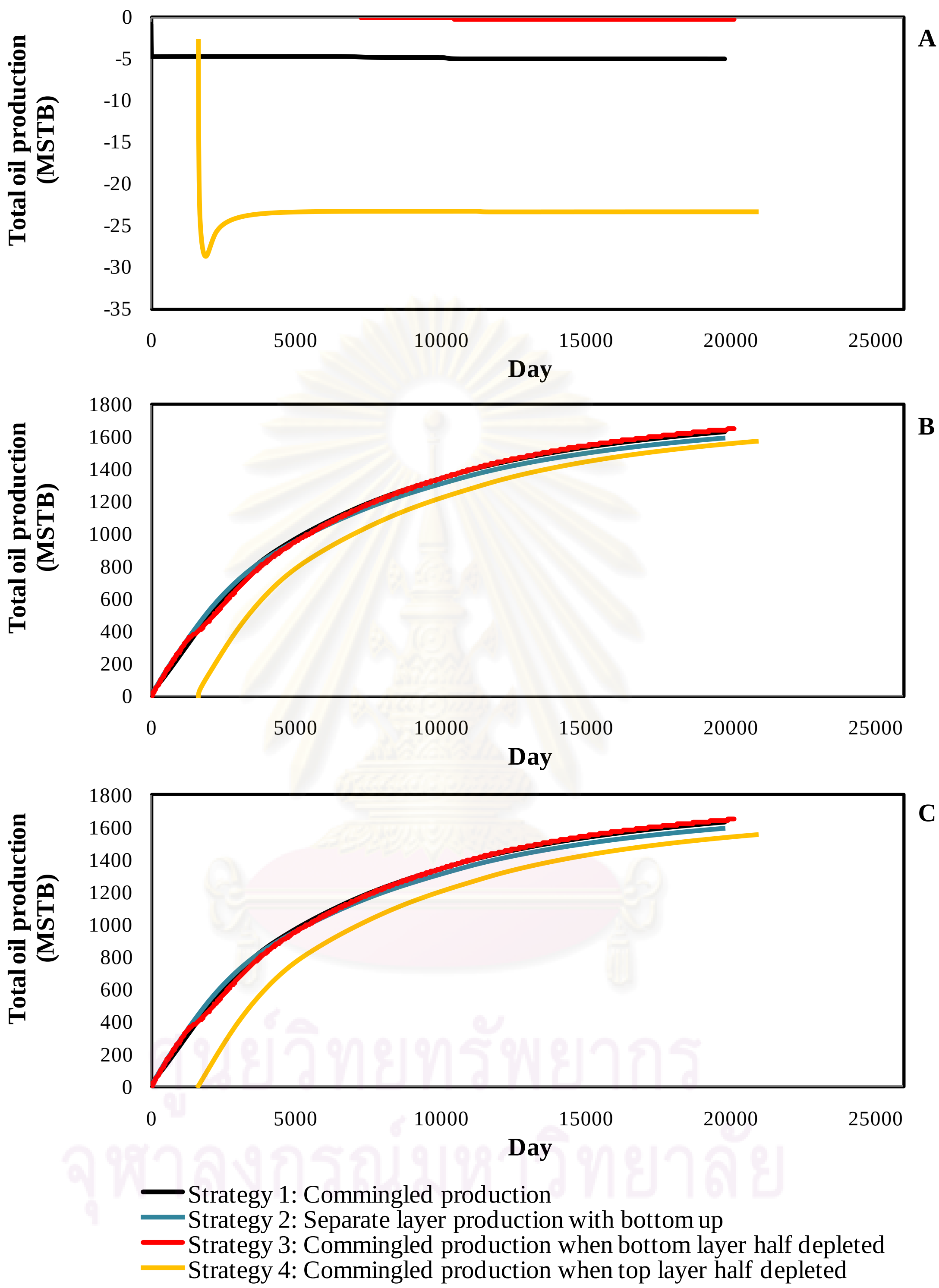

Figure 5.52: Total oil production of Case 8: G – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

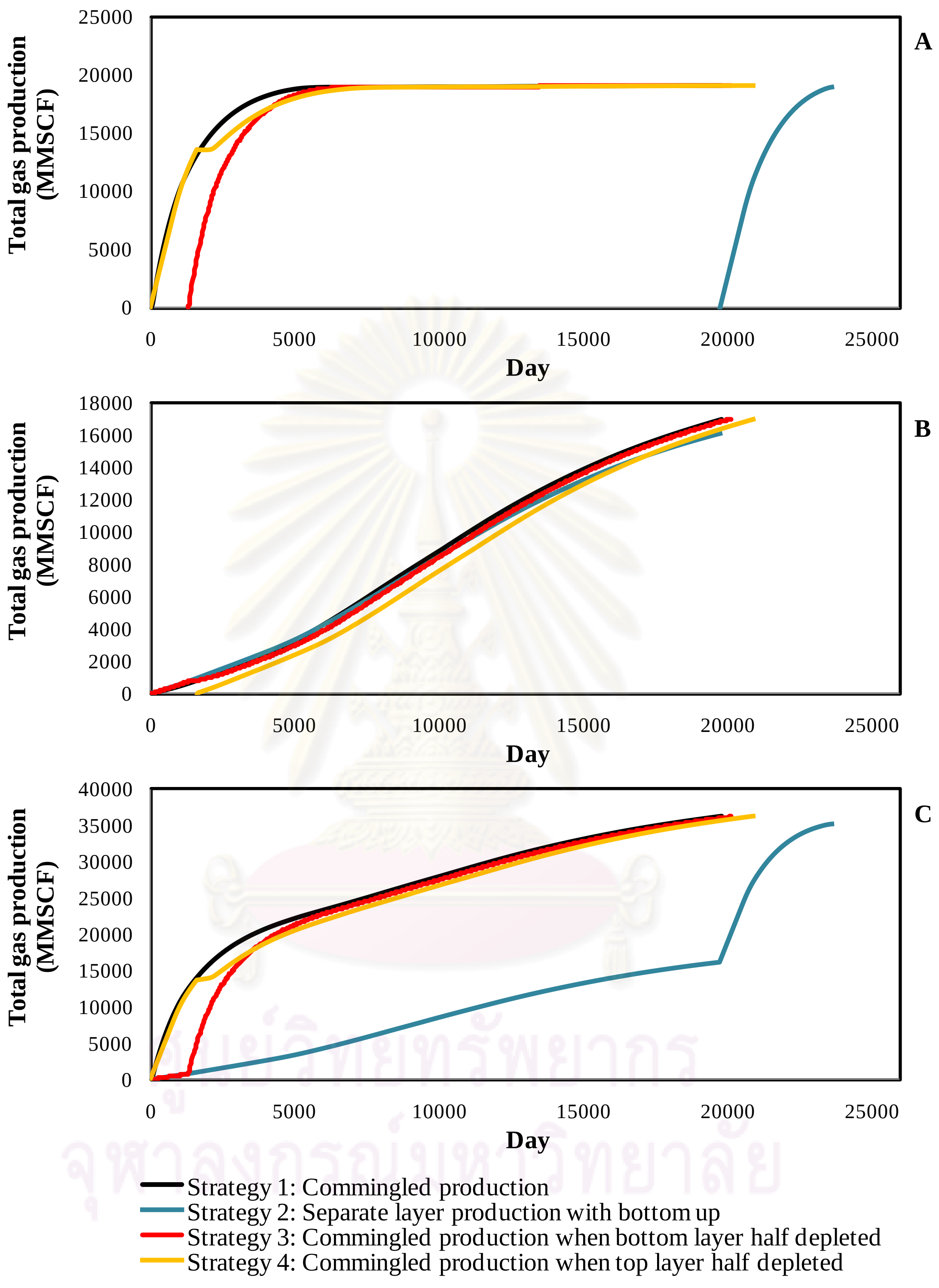

Figure 5.53: Total gas production of Case 8: G – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

5.9 Case 9: O – G&O&W

In this case, the reservoir consists of 100 ft of oil zone at the top layer and 30 ft, 40 ft and 30 ft of gas, oil and water zone, respectively at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is an undersaturated oil reservoir with depletion-drive. It is perforated 100 ft full to base of oil sand. The bottom layer is a saturated oil reservoir with a gas cap above and an aquifer underneath. Drive mechanism of the reservoir is a combination of gas-cap-drive and water-drive. The reservoir is perforated 20 ft at the middle of oil zone. A well schematic of Case 9 is shown in Figure 5.54.

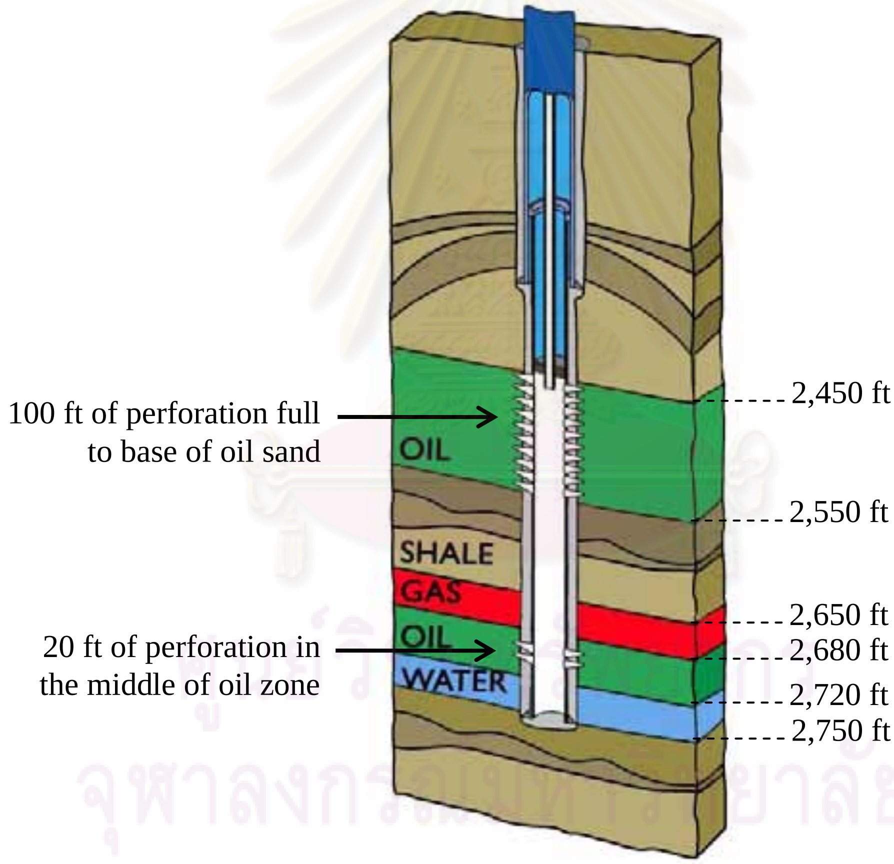

Figure 5.54: Well schematic for Case 9: O – G&O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.55 and comparative results are summarized in Table 5.9.

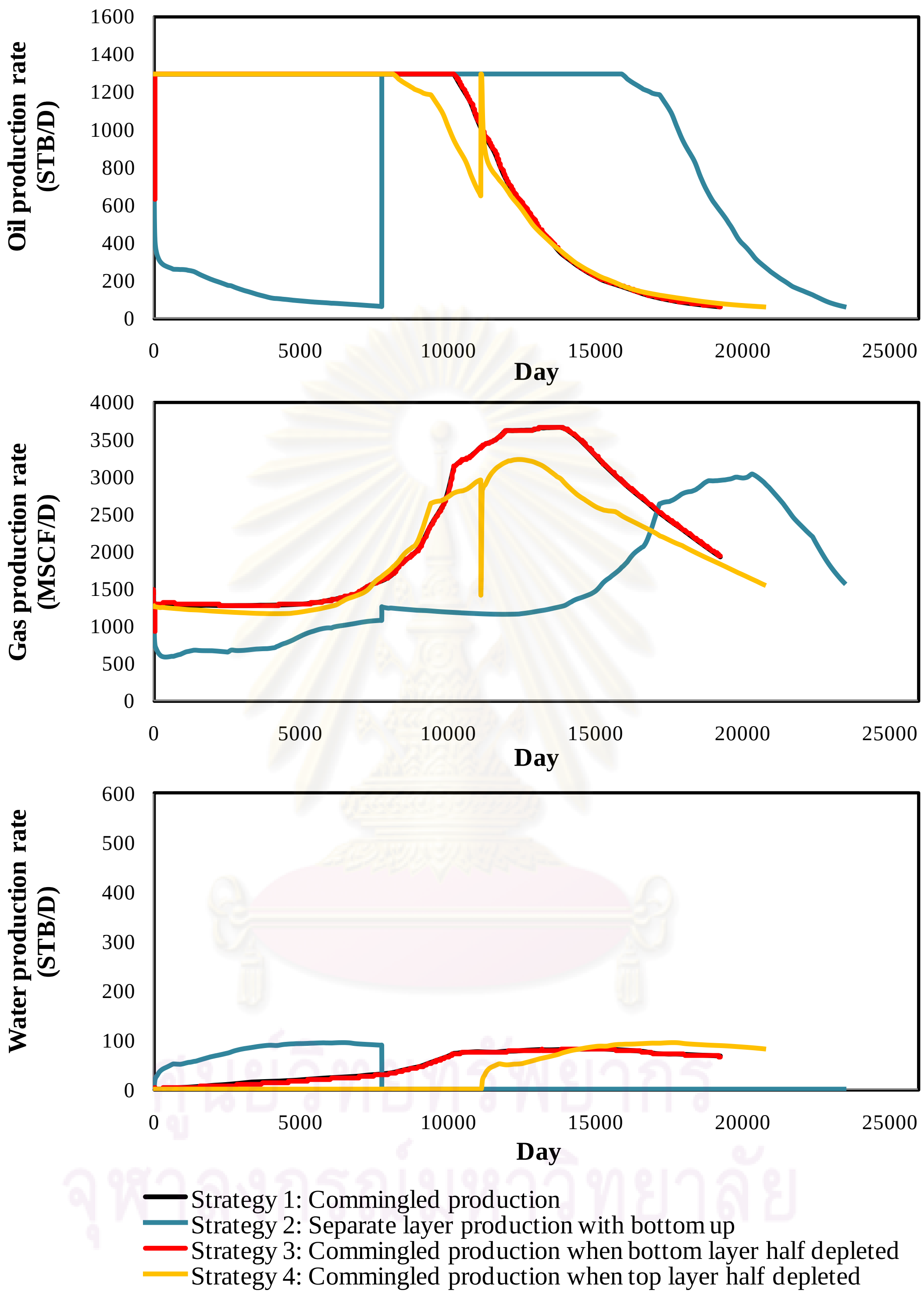

Figure 5.55: Production profiles of Case 9: O – G&O&W

Table 5.9: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 9: O – G&O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	16,963	16,176	16,949	16,444
Gas (MMSCF)	43,466	35,768	43,466	41,485
Free gas (MMSCF)	30,707	23,854	30,726	29,428
Solution gas (MMSCF)	12,758	11,914	12,740	12,057
MBOE	24,457	22,343	24,443	23,597
Water (STB)	920	602	905	760
Oil recovery factor (%) *	26.96	25.71	26.94	26.14
Gas recovery factor (%) **	60.01	49.39	60.01	57.28
Abandonment time (day)	19,297	23,466	19,297	20,758

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.9.1 Oil production

Figure 5.55 shows that strategies 1 and 3 give very similar oil production profiles. Figure 5.58A shows that total oil production obtained from each strategy is not different at the top layer reservoir. However, the differences of oil production come from the bottom layer as shown in Figure 5.58B. Hence, more focus is given to the bottom layer which has three-phase gas, oil and water.

Table 5.7 indicates that strategies 1 and 3 deliver the highest oil recovery. This is because the bottom layer is commingled with the top layer. Generally, the pressure drop of depletion-drive reservoir is more rapid than other kinds of reservoir. Therefore, producing oil from the top layer helps increase the pressure drawdown as shown in Figure 5.57B. As a result of higher pressure drop at the bottom layer, remaining gas in the reservoir expands more, and then drives a larger amount of oil out of the reservoir.

Strategy 4 creates a smaller pressure drawdown than strategies 1 and 3 as shown in Figure 5.57B because commingled production starts when some pressure of the depletion-drive reservoir partially drops. Thus, the influence of depletion-drive reservoir is less, and hence this strategy cannot recover the highest amount of oil. Moreover, there is crossflow between the two layers as shown in Figure 5.56. Hence, there is a large quantity of oil remaining in the reservoir.

Strategy 2 delivers the minimum oil recovery from the bottom layer since each layer is produced one at a time. This is the reason why the reservoir pressure at the bottom layer gradually drops as shown in Figure 5.57B and hence less amount of oil is produced comparing to the other strategies.

In summary, strategies 1 and 3 are the best ways to maximize the ultimate production of oil as shown in Table 5.9 with the yellow highlight.

5.9.2 Gas production

For gas comparison, Figure 5.55 shows that strategies 1 and 3 give very similar gas production profiles. Figure 5.59A and Figure 5.59B reveal that both layers have difference in total gas production for each strategy.

Table 5.9 indicates that strategies 1 and 3 recover the highest amount of gas. The main reason is that they can recover a lot of gas from the bottom layer. This is due to a larger pressure drawdown as explained in the oil case. As a result, gas can expands more, and then a lot of gas is produced.

Figure 5.59A shows that strategy 4 produces the highest amount gas from the top layer due to a larger pressure drawdown at the initial life of the reservoir. The reason is that the depletion-drive reservoir is separately produced. However, this strategy is not the best approach for gas production since the amount of gas recovery from the bottom layer is less. This is a result of the smaller pressure drawdown as shown in Figure 5.57B. Moreover, there is crossflow between the two layers as shown in Figure 5.56. Hence, there is a large quantity of gas remaining in the reservoir.

Strategy 2 delivers minimum gas recovery because the reservoir is produced one layer at a time, resulting in the smallest pressure drawdown as depicted in Figure 5.57B.

In summary, strategies 1 and 3 are the best ways to maximize the ultimate production of gas as shown in Table 5.9 with the green highlight.

5.9.3 Summary

Strategies 1 and 3 which is commingled production and commingled production when the bottom layer is half depleted, respectively deliver the best outcomes in term of barrel of oil equivalent or BOE. For economics life of the reservoir, there is no significant difference of abandonment time and water production. Thus, strategies 1 and 3 are the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.9 with the brown highlight.

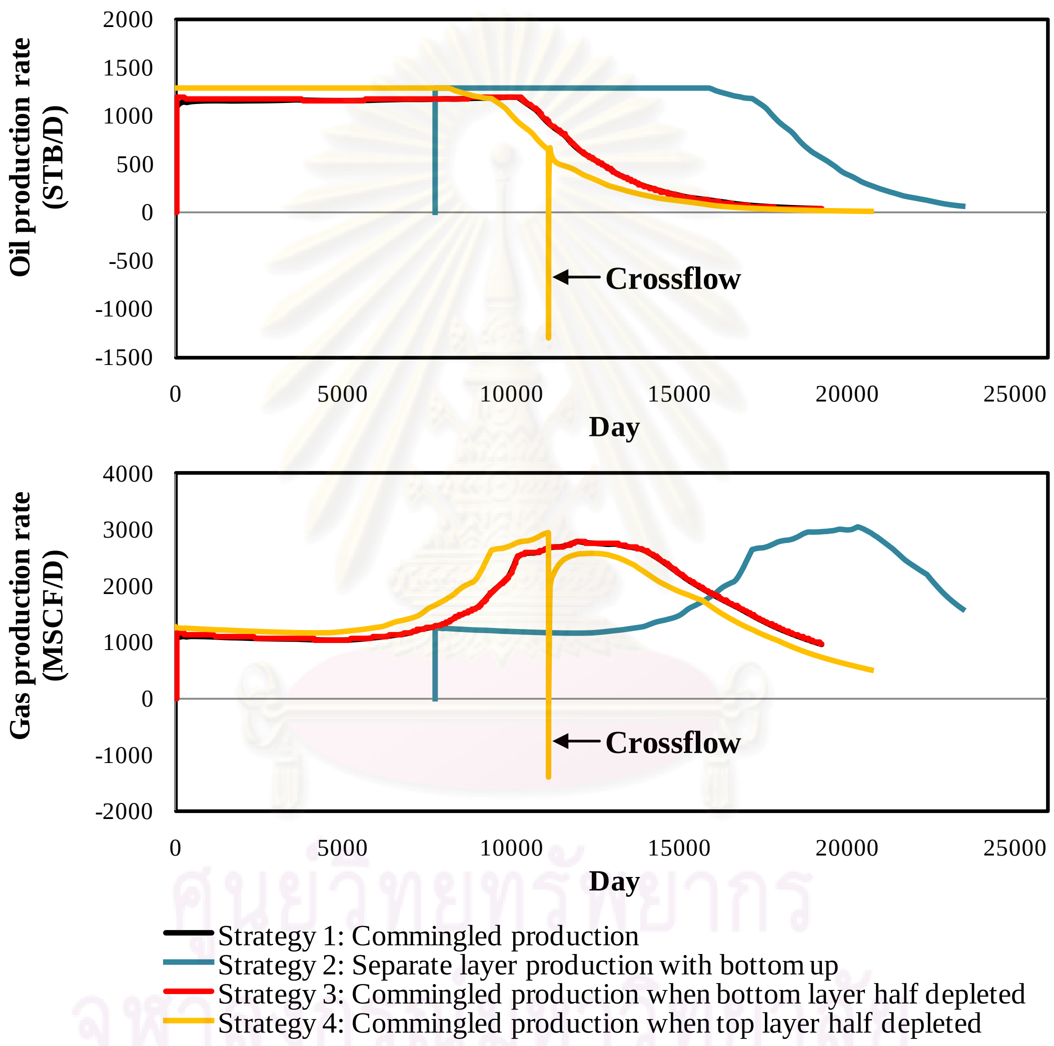

Figure 5.56: Production profiles of Case 9: O – G&O&W, at the top layer

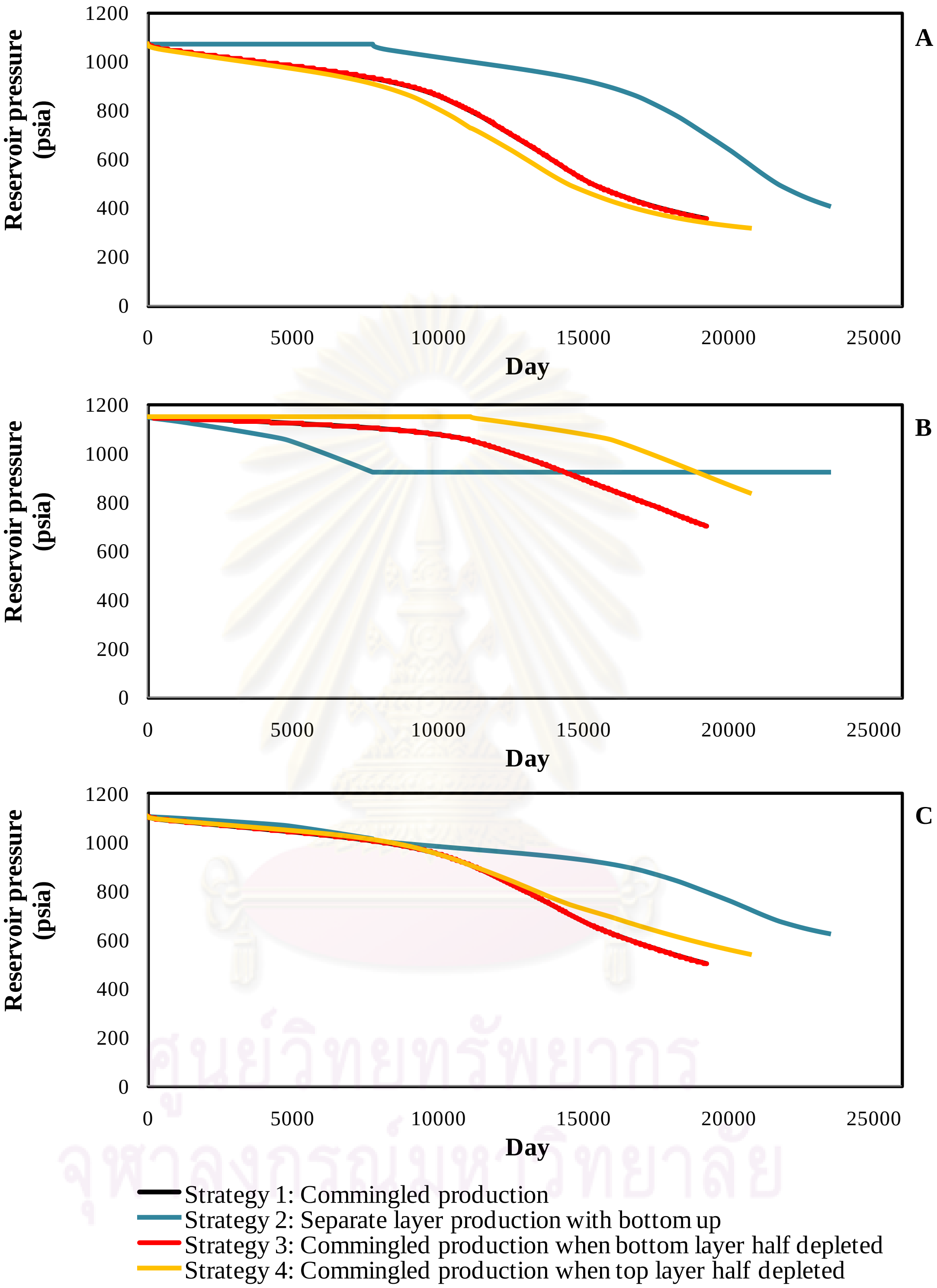

Figure 5.57: Reservoir pressure of Case 9: O – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

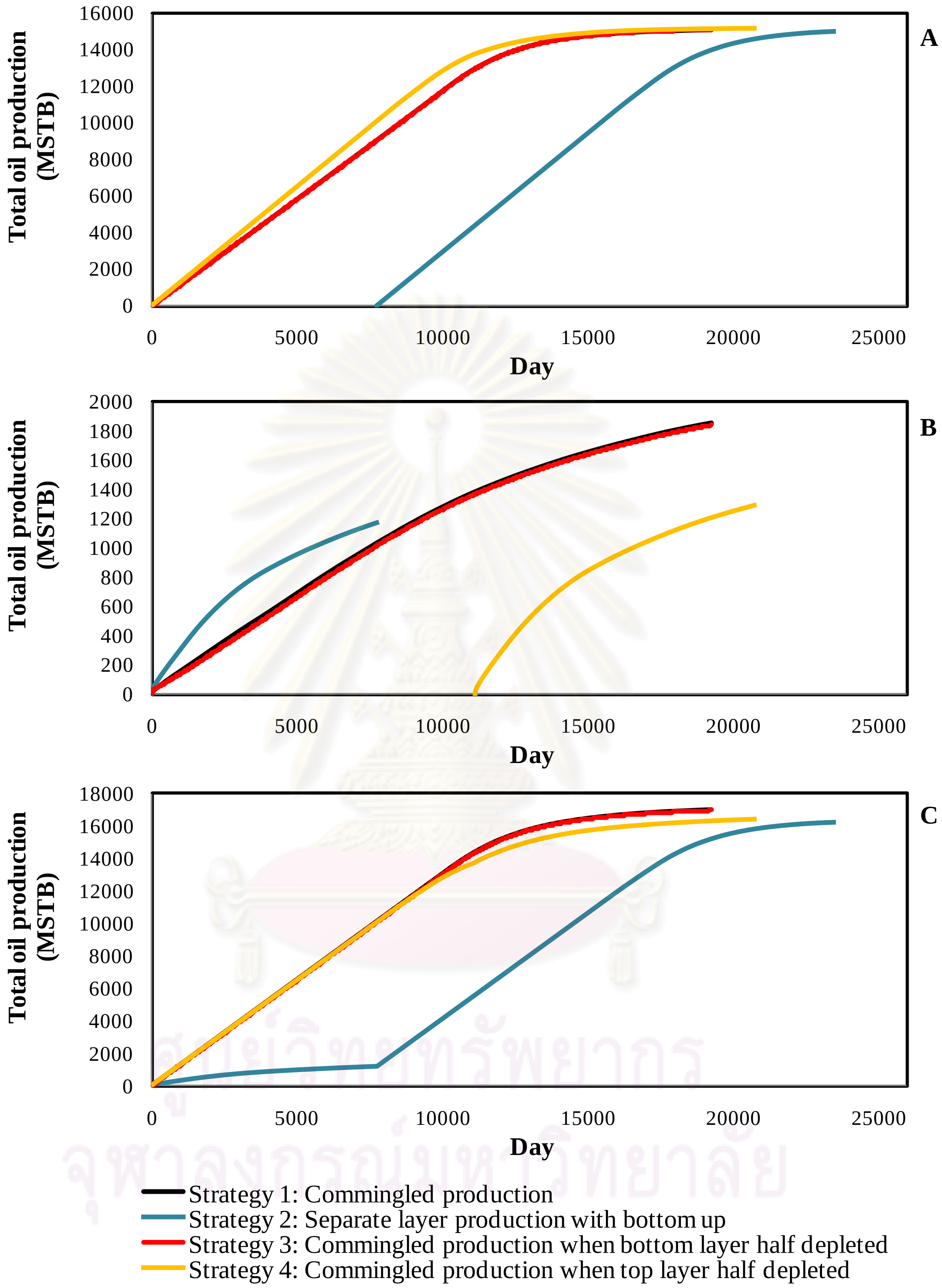

Figure 5.58: Total oil production of Case 9: O – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

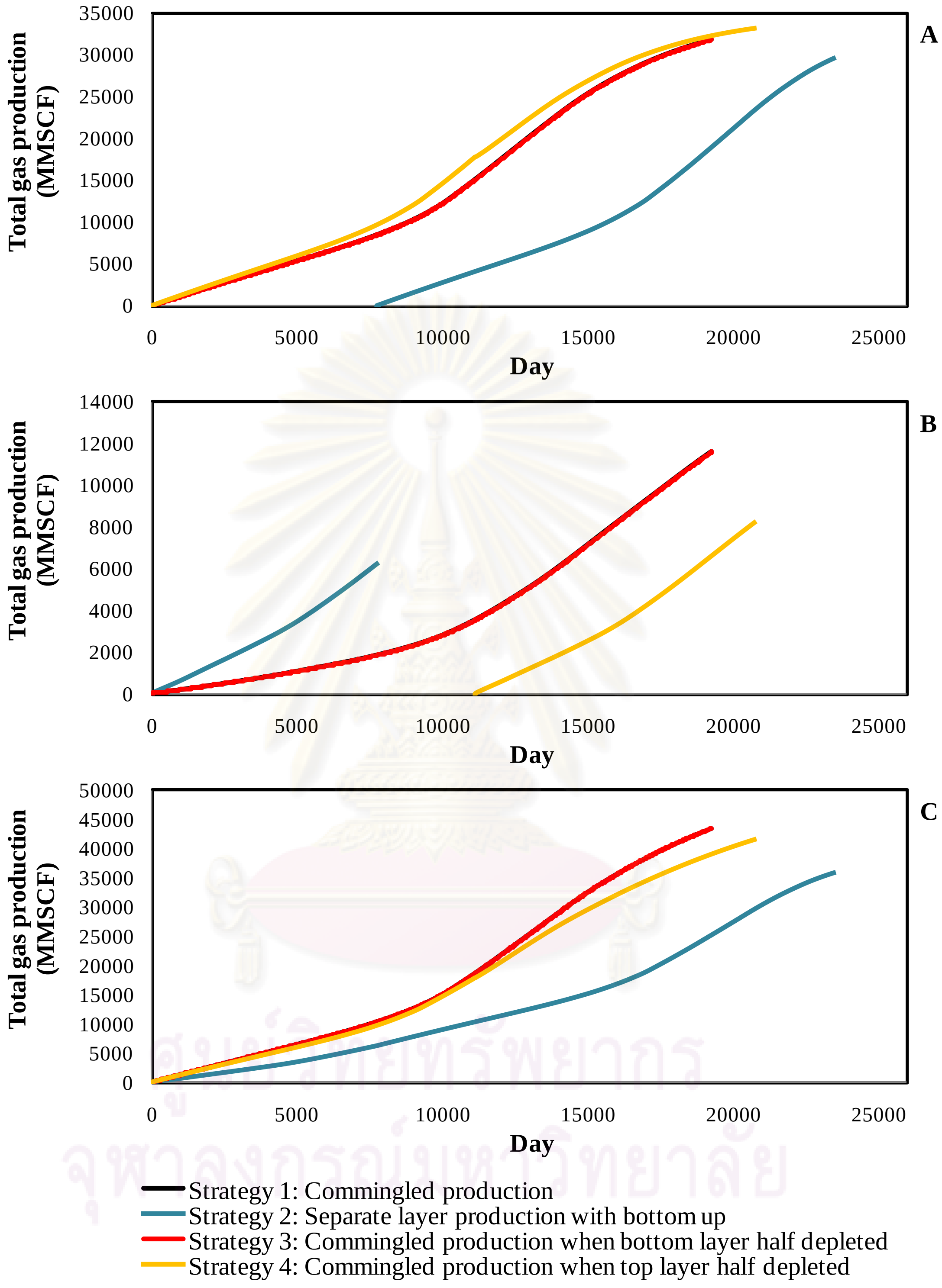

Figure 5.59: Total gas production of Case 9: O – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

5.10 Case 10: G&O – G&W

In this case, the reservoir consists of 50 ft of gas and oil zone each at the top layer and 50 ft of gas and water zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a saturated oil reservoir with a gas cap above. The reservoir is a gas-cap-drive and is perforated 30 ft from the bottom of oil zone. The bottom layer is a gas reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of gas zone. A well schematic of Case 10 is shown in Figure 5.60.

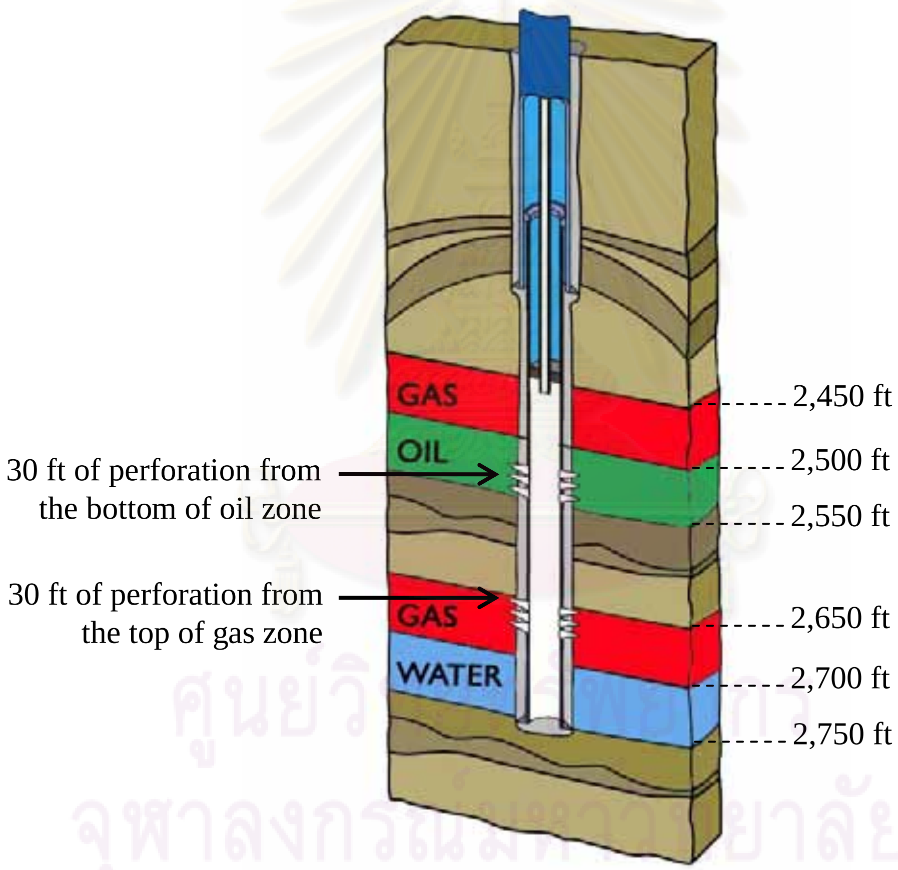

Figure 5.60: Well schematic for Case 10: G&O – G&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.61 and comparative results are summarized in Table 5.10.

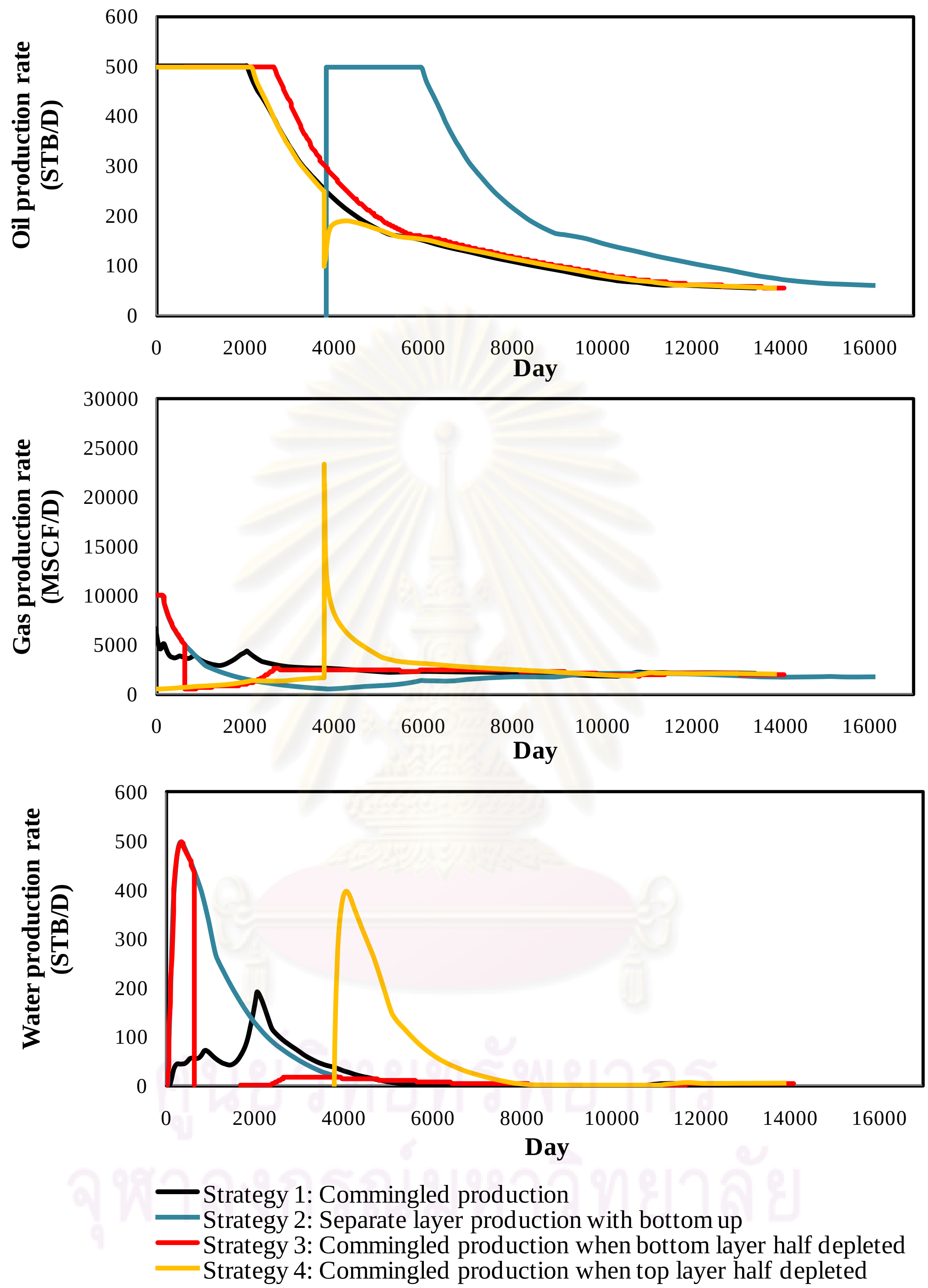

Figure 5.61: Production profiles of Case 10: G&O – G&W

Table 5.10: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 10: G&O – G&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	2,720	2,644	2,652	2,738
Gas (MMSCF)	32,921	29,854	32,615	32,890
Free gas (MMSCF)	30,996	27,956	30,755	30,942
Solution gas (MMSCF)	1,926	1,898	1,859	1,947
MBOE	8,396	7,791	8,275	8,408
Water (STB)	300	691	316	518
Oil recovery factor (%) *	11.93	11.60	11.63	12.01
Gas recovery factor (%) **	67.27	61.00	66.64	67.21
Abandonment time (day)	13,483	16,130	14,123	13,910

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.10.1 Oil production

Figure 5.61 shows that all strategies give totally different oil production profiles. Table 5.10 shows that oil production from all strategies are very much similar. Figure 5.64A reveals that oil is produced from the bottom layer only. This figure shows that strategies 1, 3 and 4 can deliver the same amount of oil recovery. Among these three strategies, strategy 3 delivers the least favorable results as shown in Table 5.10 because crossflow takes place between the two layers as shown in Figure 5.62 and 5.64B.

Strategy 4 delivers slightly better results than strategy 1 as shown in Table 5.10. The possible reason is that strategy 4 produces gas-cap-drive oil reservoir before commingled production with the water-drive gas reservoir starts. Thus, the water production is delayed.

Strategy 2 delivers the minimum recovery of oil because each layer is produced one at a time. This is a result of the smaller pressure drawdown at the top layer as shown in Figure 5.63A. The reservoir pressure in the strategy that oil reservoir is produced alone drops slower than the one when producing with the gas reservoir as in other strategies.

In summary, strategies 1 and 4 are the best ways to maximize the ultimate production of oil as shown in Table 5.10 with the yellow highlight.

5.10.2 Gas production

For gas production comparison, Figure 5.61 shows totally different gas production profiles for the four strategies. Figure 5.65A and 5.65B show that total gas productions obtained from strategies 1, 2 and 4 are quite similar at both layers. Table 5.10 indicates that strategy 1 gives slightly more gas production than strategy 4, and strategy 3 respectively. This is a result of a pressure drop at both layers as shown in Figure 5.63A and 5.63B.

Table 5.10 indicates that strategy 2 delivers the minimum gas recovery. Figure 5.65A and 5.65B indicate that strategy 2 delivers minimum gas recovery at both layers. This is a result of smaller pressure drawdown as described in the oil case.

In summary, strategies 1 and 4 give very high values for ultimate production of gas as shown in Table 5.9 with the green highlight.

5.10.3 Summary

Strategies 1 and 4 which is commingled production and commingled production when the top layer is half depleted, respectively deliver the best outcomes in term of barrel of oil equivalent or BOE. Thus, they are the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.10 with the brown highlight.

Looking to the economics life of the well, strategy 1 is more worthwhile compared with strategy 4 because its abandonment time is shorter as shown in Table 5.10. Moreover, strategy 1 delivers smaller amount of water production than strategy 4 as shown in Table 5.10, resulting the lower cost for water handling facilities. Thus, strategy 1 which is a commingled production is the most excellent strategy for this kind of multilayer reservoirs in the economics value.

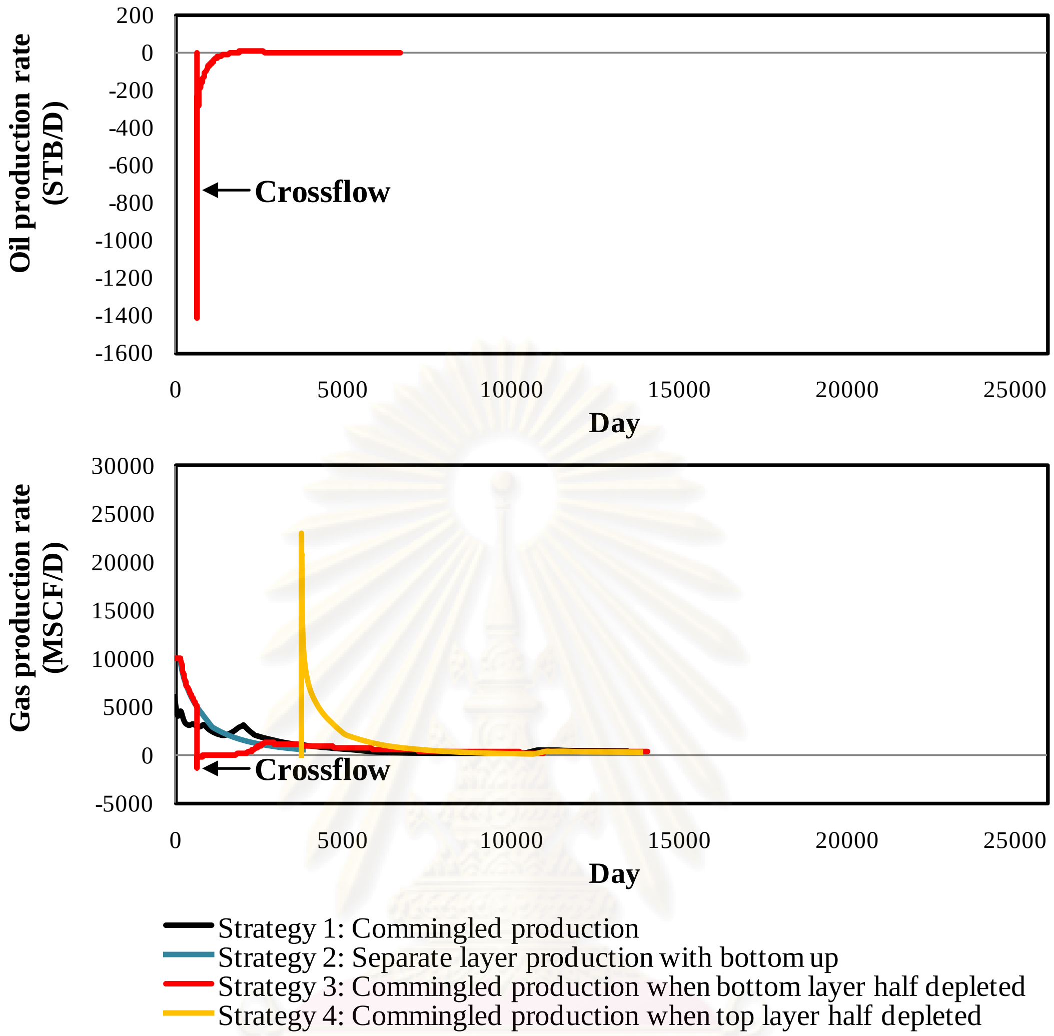

Figure 5.62: Production profiles of Case 10: G&O – G&W, at the bottom layer

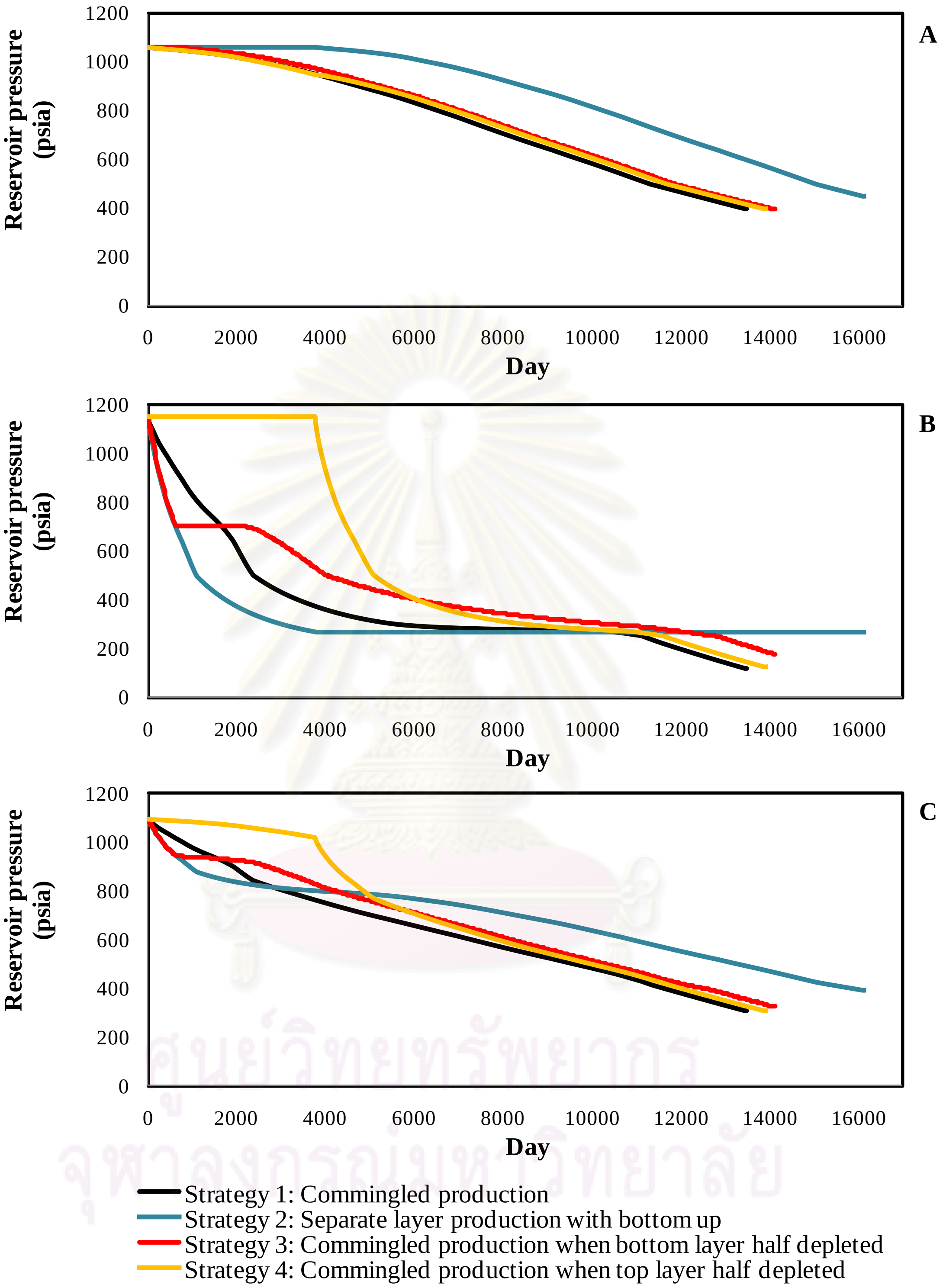

Figure 5.63: Reservoir pressure of Case 10: G&O – G&W at (A) the top layer, (B) the bottom layer and (C) both layers

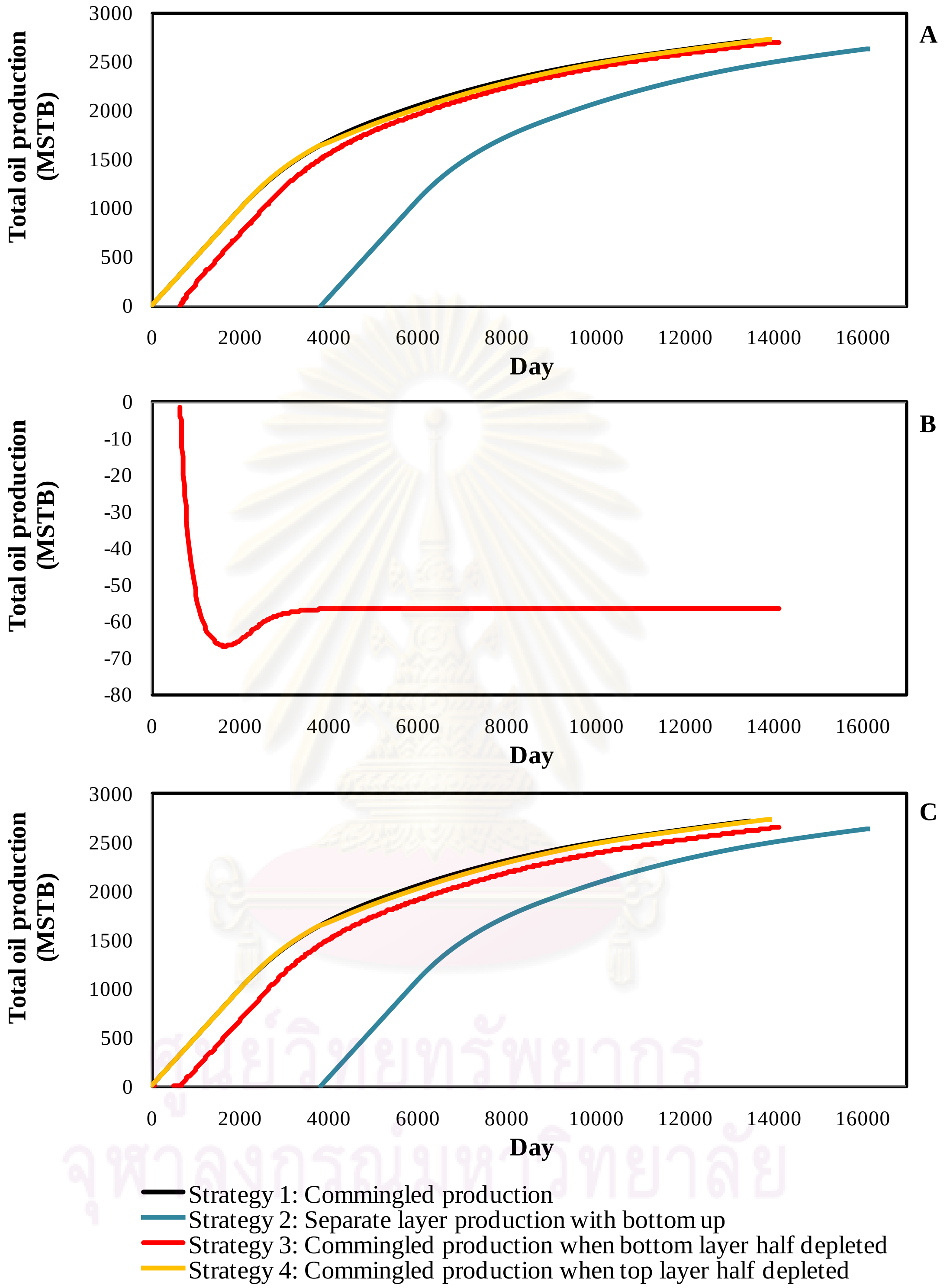

Figure 5.64: Total oil production of Case 10: G&O – G&W at (A) the top layer, (B) the bottom layer and (C) both layers

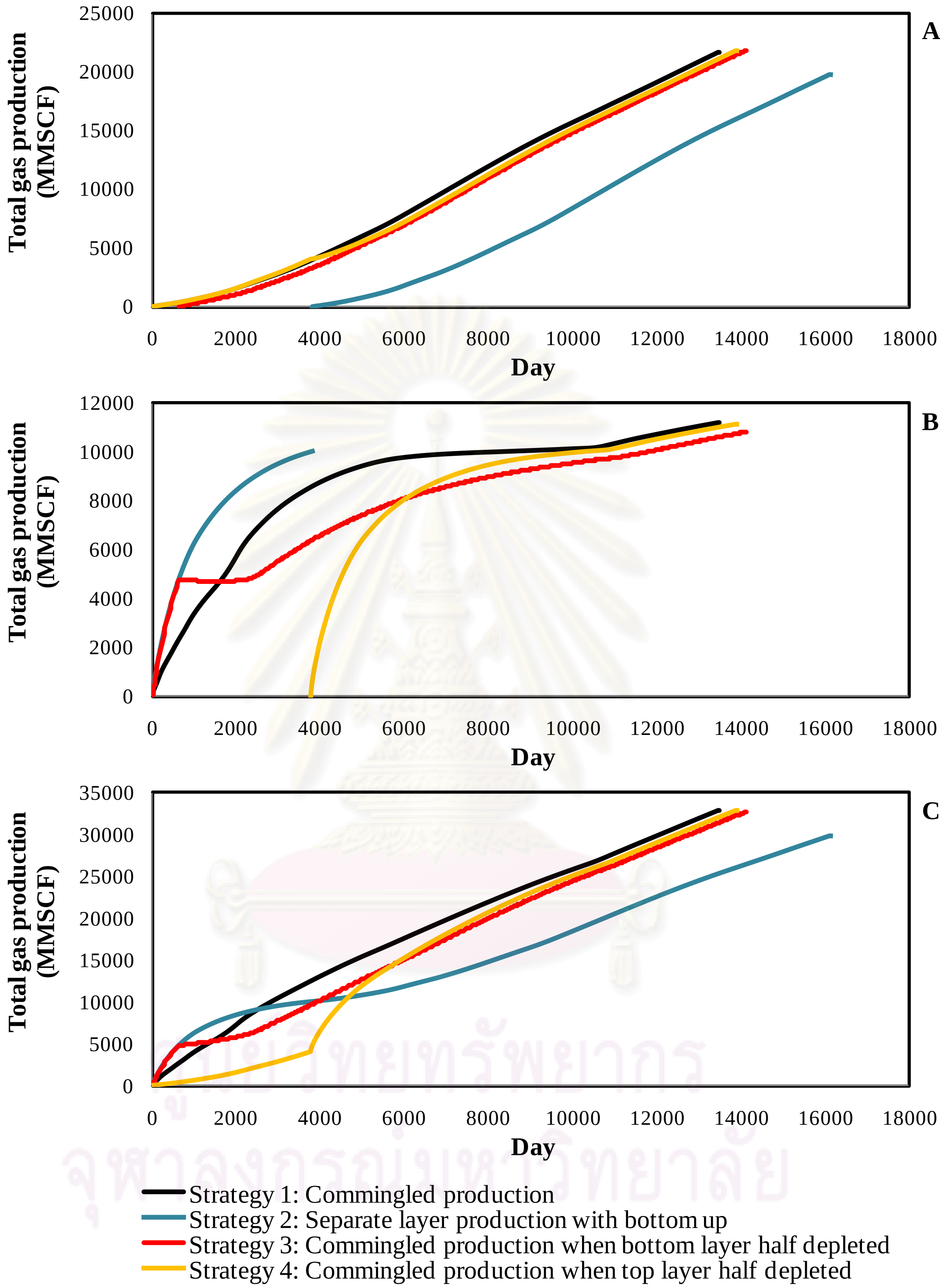

Figure 5.65: Total gas production of Case 10: G&O – G&W at (A) the top layer, (B) the bottom layer and (C) both layers

5.11 Case 11: G&O – O&W

In this case, the reservoir consists of 50 ft of gas and oil zone each at the top layer and 50 ft of oil and water zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a saturated oil reservoir with a gas cap above. The reservoir is a gas-cap-drive and is perforated 30 ft from the bottom of oil zone. The bottom layer is an undersaturated oil reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of oil zone. A well schematic of Case 11 is shown in Figure 5.66.

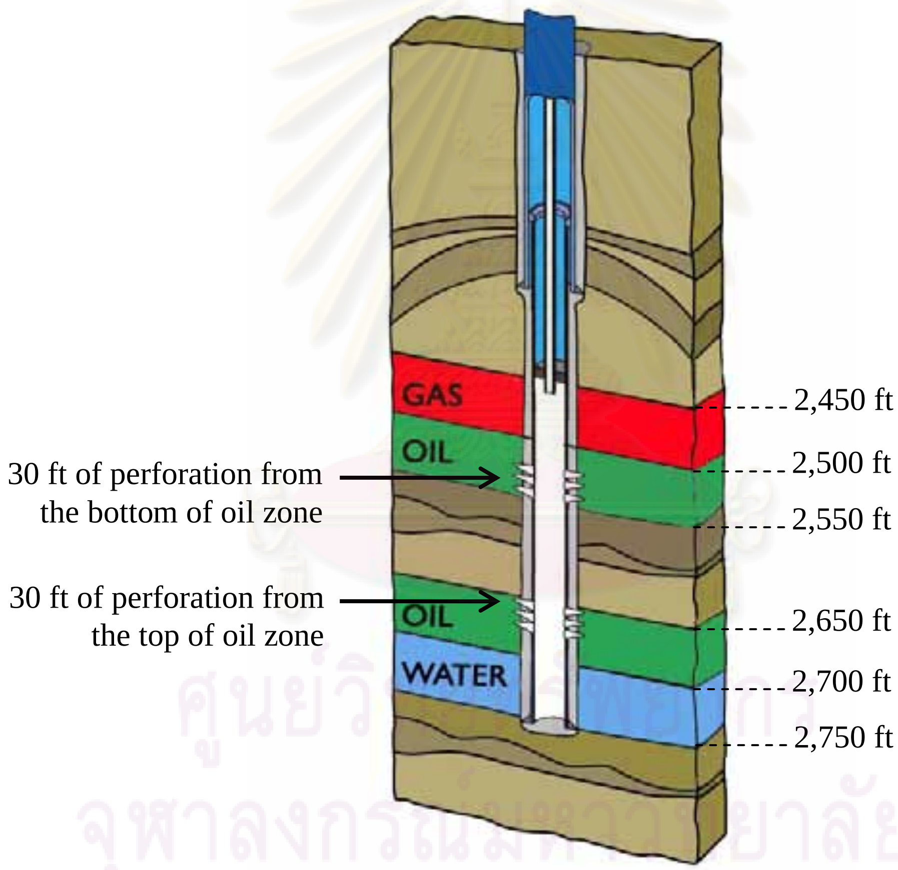

Figure 5.66: Well schematic for Case 11: G&O – O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.67 and comparative results are summarized in Table 5.11.

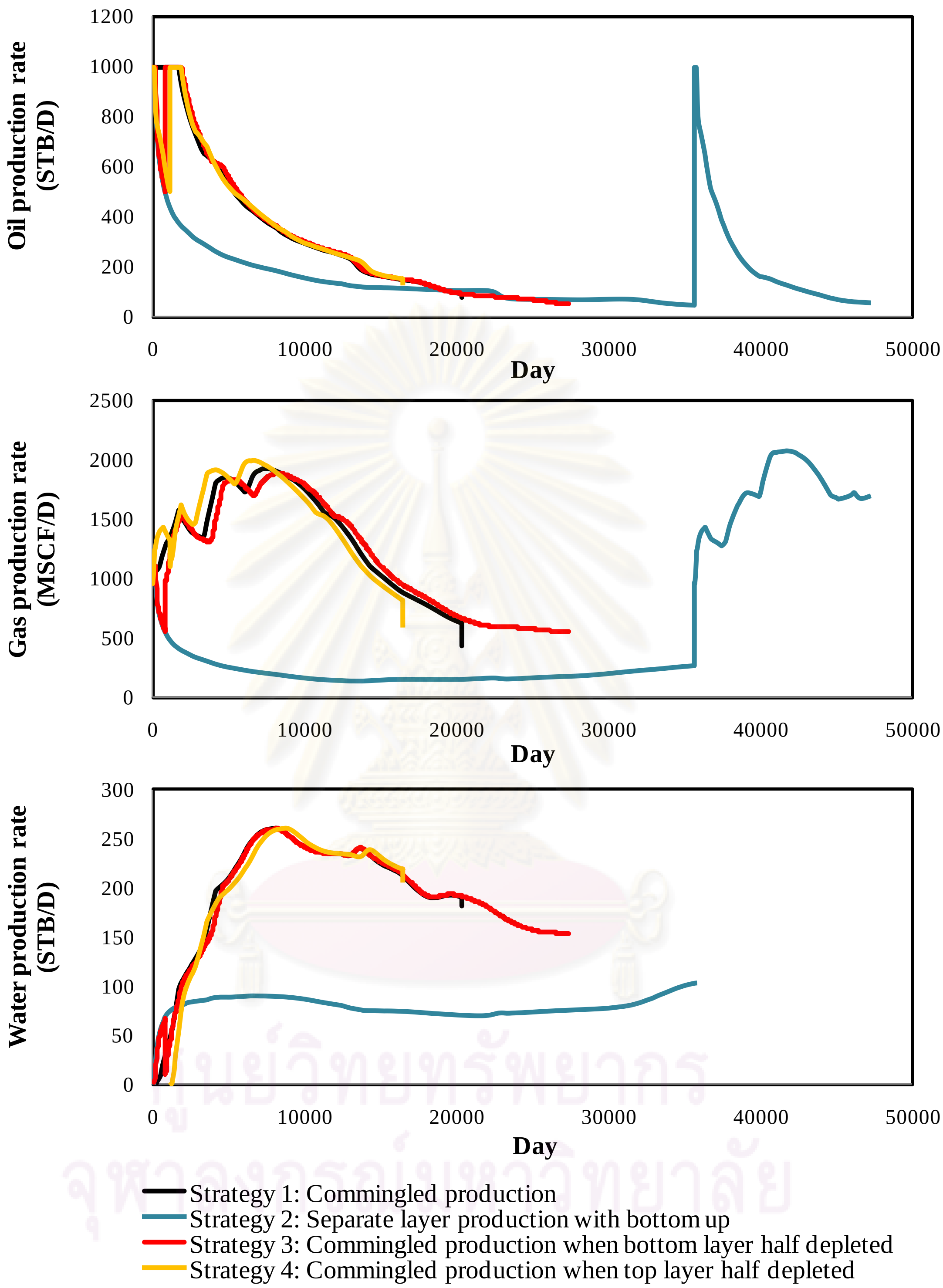

Figure 5.67: Production profiles of Case 11: G&O – O&W

Table 5.11: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 11: G&O – O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	7,812	7,822	8,268	7,106
Gas (MMSCF)	27,970	27,471	31,887	25,121
Free gas (MMSCF)	21,634	20,849	25,359	19,375
Solution gas (MMSCF)	6,336	6,623	6,528	5,746
MBOE	12,634	12,559	13,765	11,438
Water (STB)	4,050	2,796	5,225	3,196
Oil recovery factor (%) *	17.59	17.61	18.62	16.00
Gas recovery factor (%) **	46.83	45.99	53.38	42.06
Abandonment time (day)	20,393	47,206	27,393	16,467

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.11.1 Oil production

Figure 5.67 shows that all strategies give different oil production profile. Figure 5.70A reveals that total oil production at the top layer obtained from each strategy can be ordered from the top performance as strategies 3, 1, 4, and 2. The top layer is a gas-cap-drive reservoir of which performance is rate sensitive, as higher producing rate usually results in decreased oil recovery. In theory, the producing gas-oil ratio from a well completed in such reservoir increases to high values, as shown in Figure 5.72 that strategy 2 has a very high GOR. This is the reason why strategy 2 delivers the minimum oil from the top layer as shown in Figure 5.70A. Strategy 3 delivers the highest oil recovery since it is the only case that the well produces until the economic limit.

Figure 5.70B reveals that total oil production at the bottom layer obtained from each strategy can be ordered from the top performance as strategies 2, 3, 1, and 4. Since the top layer is a water-drive oil reservoir, in order to maximize the benefit from water-drive reservoir, the water rate and gas rate should be minimized to maintain the reservoir pressure. Therefore, strategy 2 is the best way for the bottom layer since the reservoir is produced one layer at a time without gas producing, and hence the pressure can better maintained as shown in Figure 5.69B. Strategy 4 delivers the minimum oil from the bottom layer because crossflow takes place as shown in Figure 5.68.

After combining the two layers together, Figure 5.70C reveals that total oil production from each strategy can be ordered from the top performance as strategies 3, 2, 1, and 4. In summary, strategy 3 is the best way to maximize the ultimate production of oil as shown in Table 5.11 with the yellow highlight.

5.11.2 Gas production

Figure 5.67 shows that all strategies give different gas production profile. Since most of the produced gas is free gas coming from the top layer, more focus is given to the top layer. Figure 5.71A reveals that the total gas production at the top layer obtained from each strategy can be ordered from the top performance as strategies 3, 1, 2, and 4, which is an effect of the pressure drop as shown in Figure 5.69A. The higher the pressure drop, the larger the amount produced gas.

In summary, strategy 3 is the best way to maximize the ultimate production of gas as shown in Table 5.11 with the green highlight.

5.11.3 Summary

Strategy 3 is the best way for oil and gas production and also in term of BOE as shown in Table 5.11 with the brown highlight. Thus, strategy 3 which is a commingled production when the bottom layer is half depleted is the most excellent strategy for this kind of multilayer reservoirs.

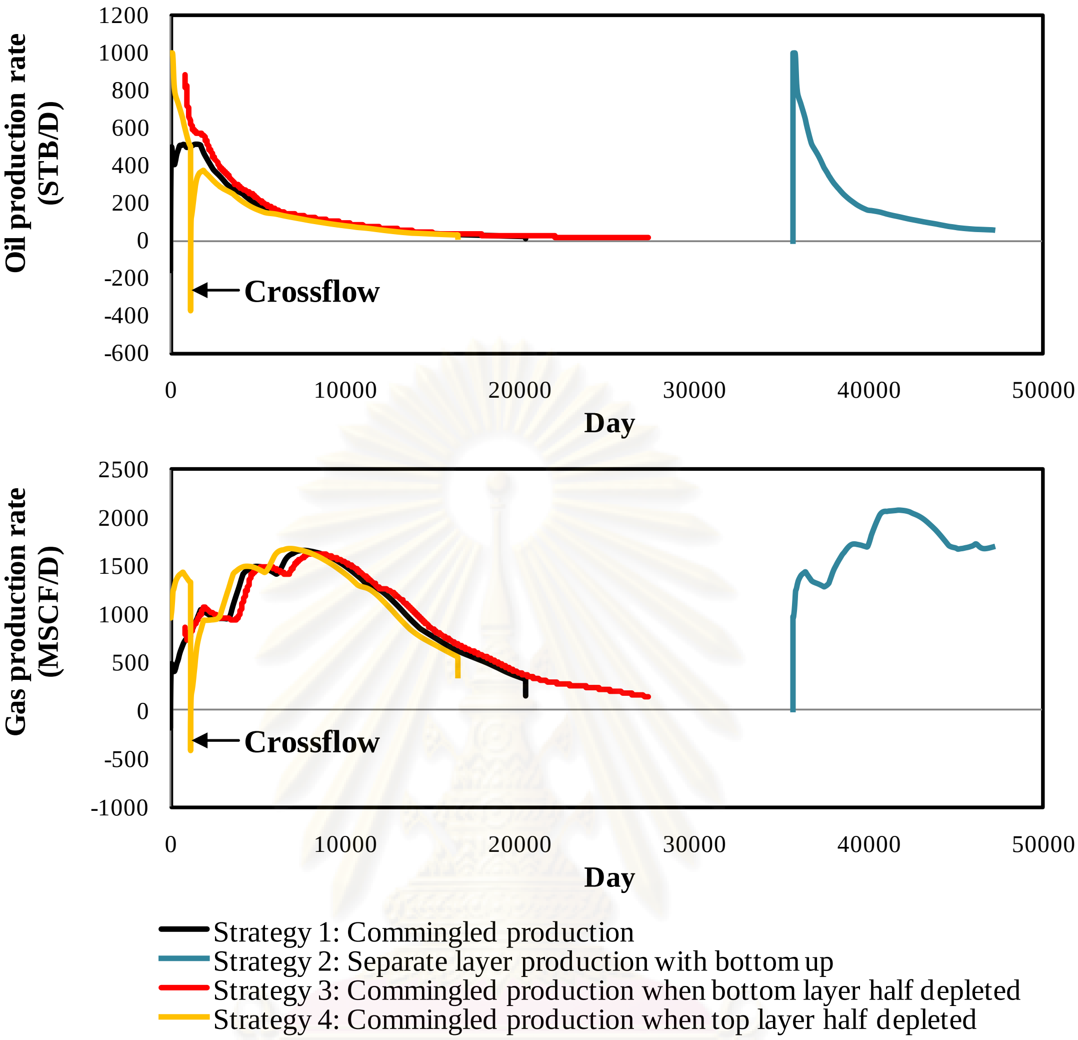

Figure 5.68: Production profiles of Case 11: G&O – O&W, at the top layer

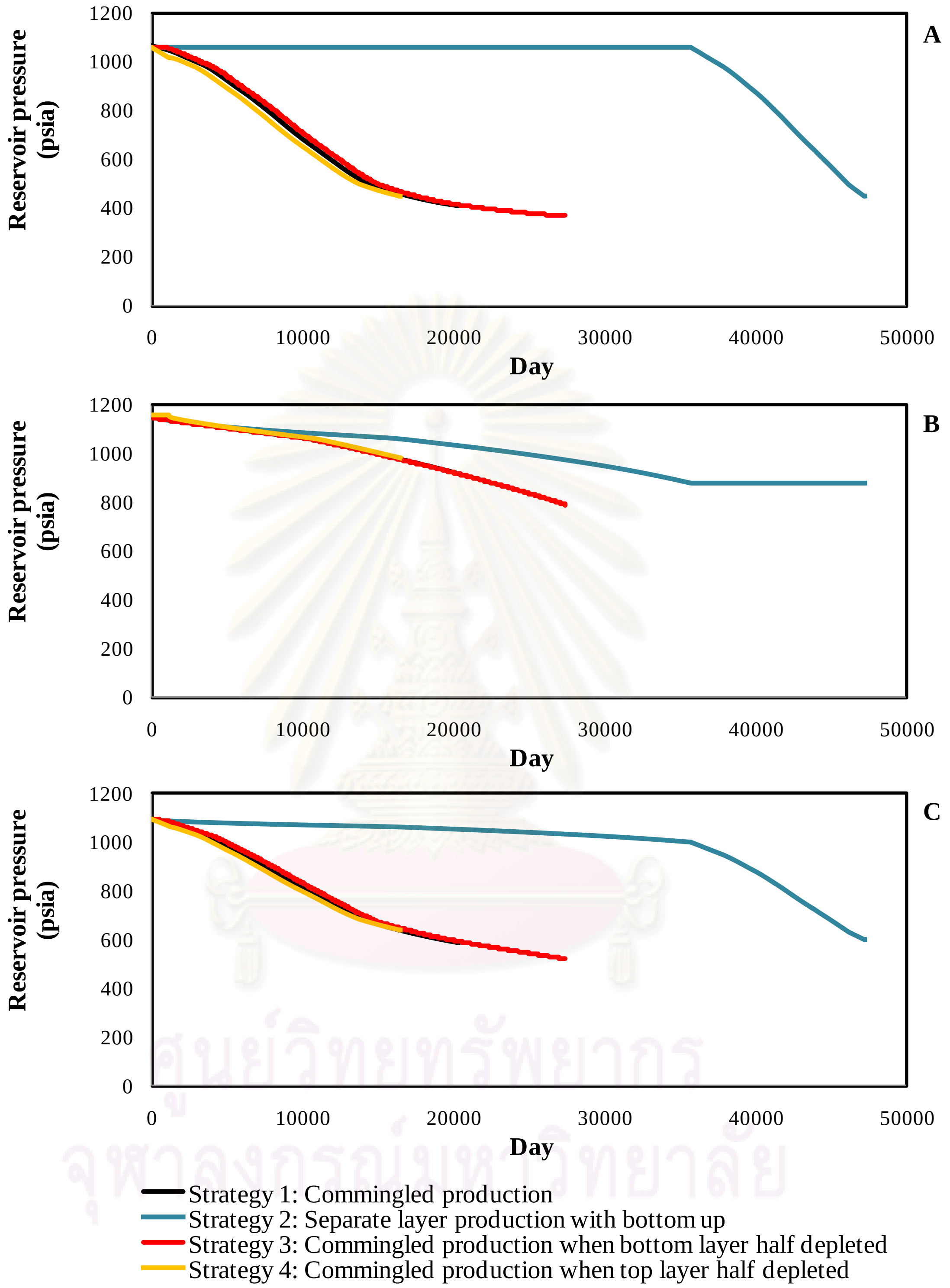

Figure 5.69: Reservoir pressure of Case 11: G&O – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

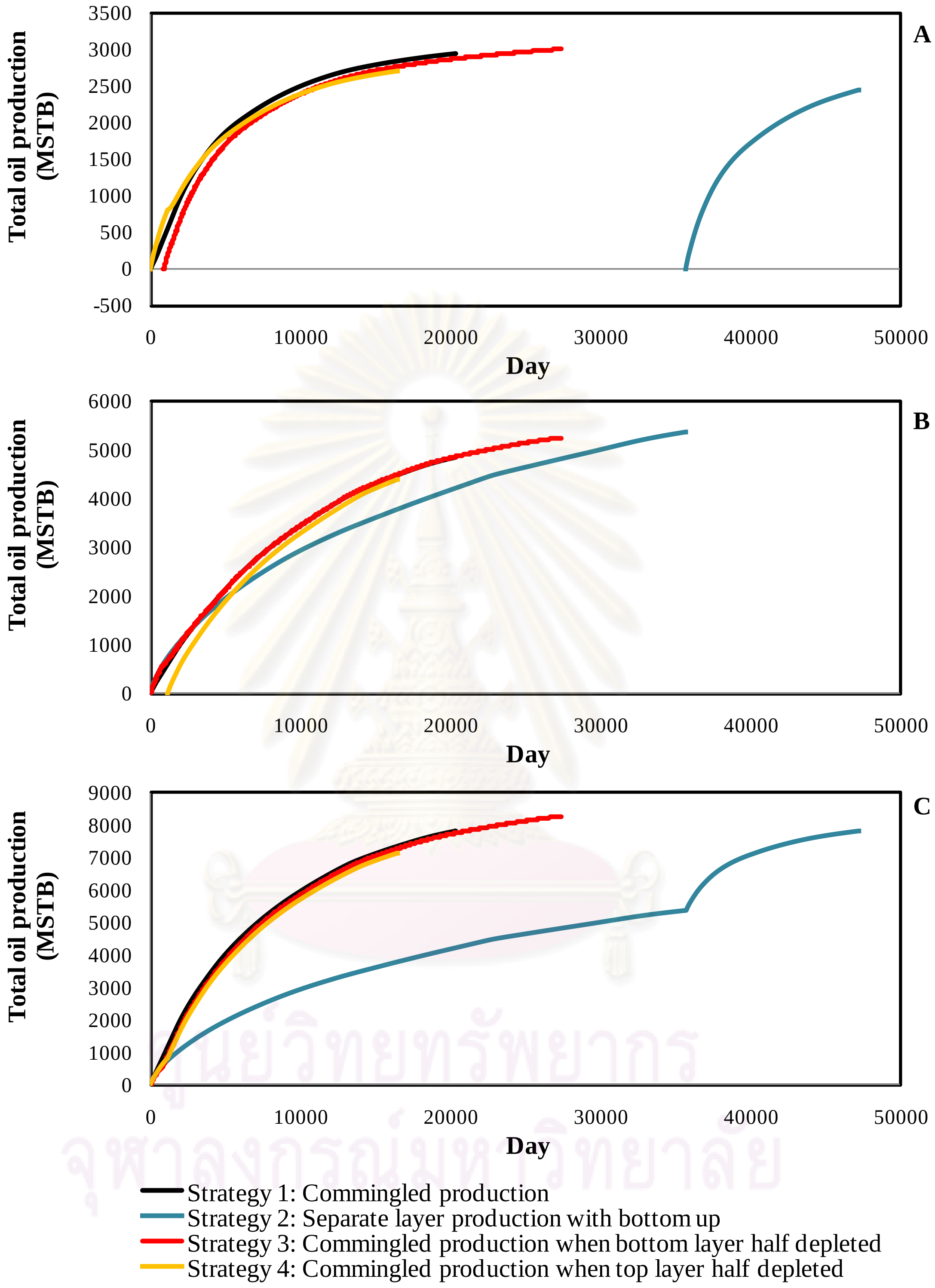

Figure 5.70: Total oil production of Case 11: G&O – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

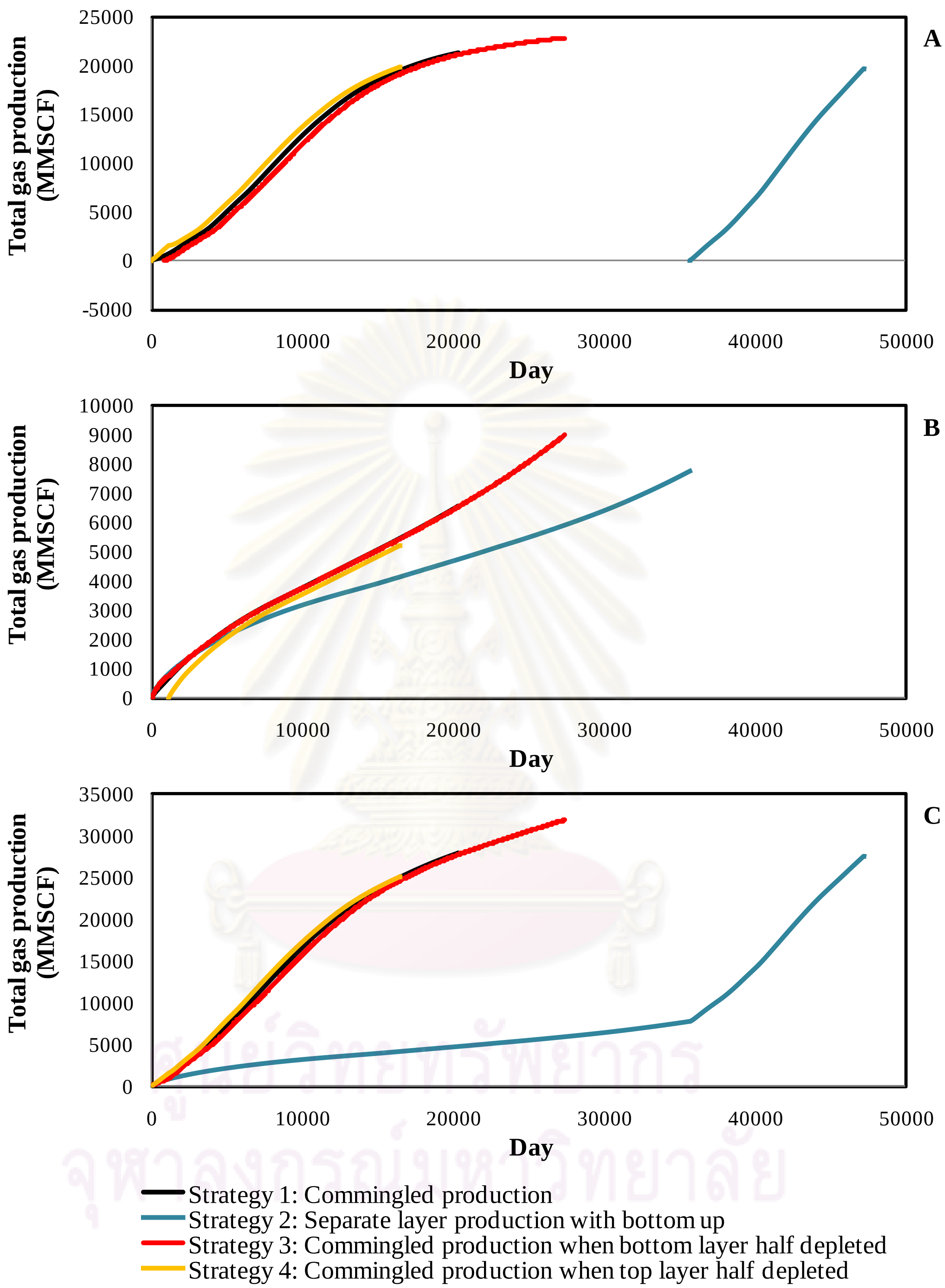

Figure 5.71: Total gas production of Case 11: G&O – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

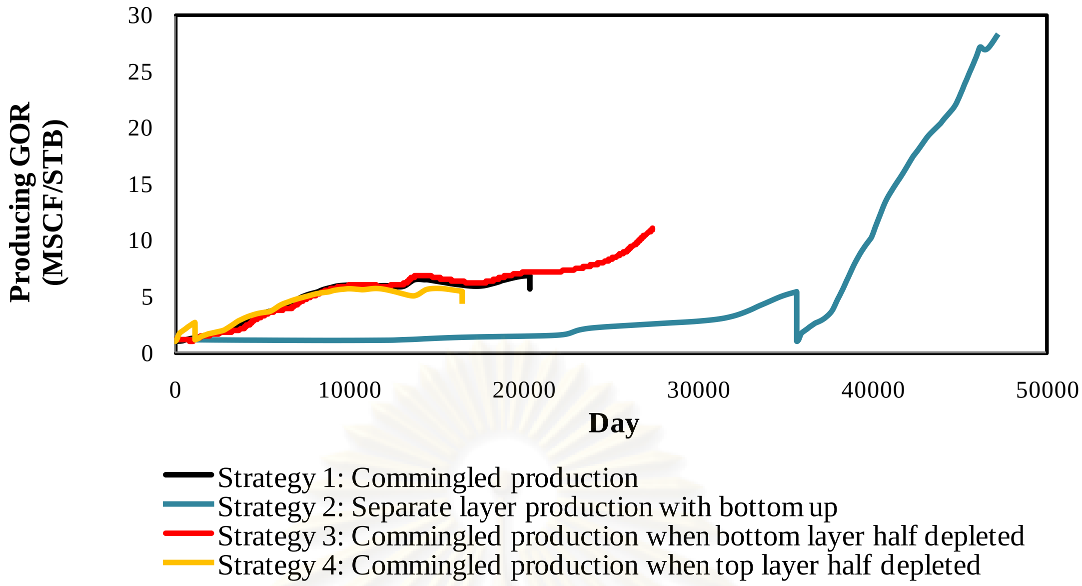

Figure 5.72: Producing GOR of Case 11: G&O – O&W

5.12 Case 12: G&W –O&W

In this case, the reservoir consists of 50 ft of gas and water zone each at the top layer and 50 ft of oil and water zone each at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a gas reservoir with an aquifer underneath. The reservoir is a water-drive and is perforated 30 ft from the top of gas zone. The bottom layer is an undersaturated oil reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of oil zone. A well schematic of Case 12 is shown in Figure 5.73.

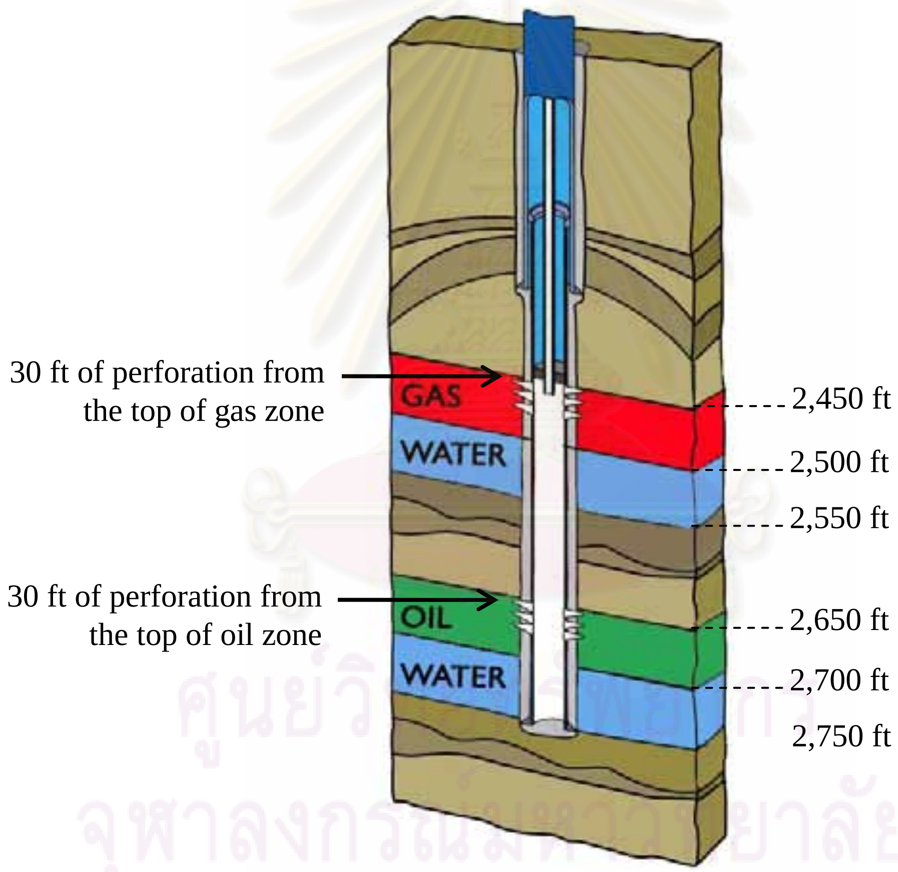

Figure 5.73: Well schematic for Case 12: G&W – O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.74 and comparative results are summarized in Table 5.12.

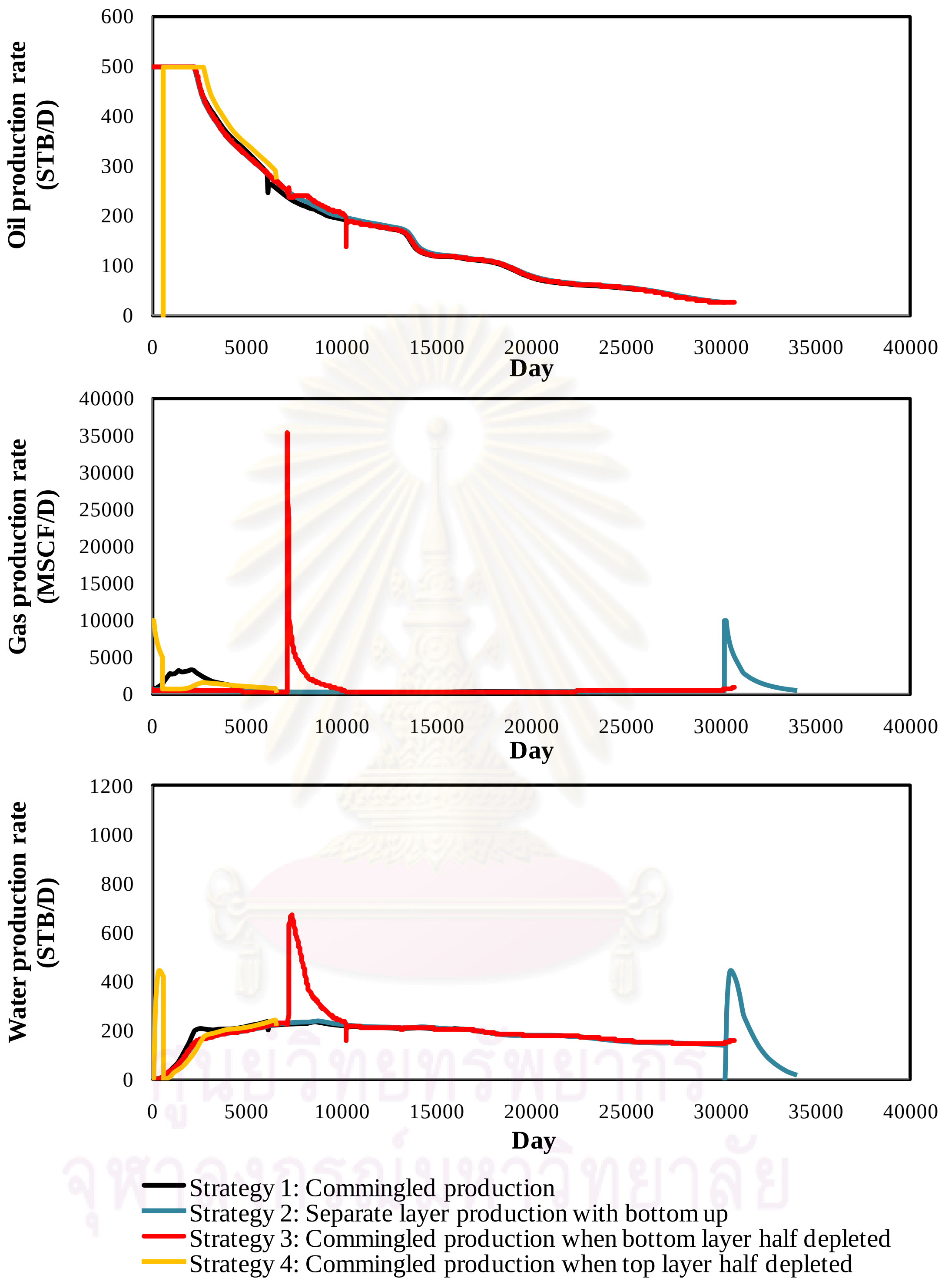

Figure 5.74: Production profiles of Case 12: G&W – O&W

Table 5.12: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 12: G&W – O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	5,120	5,336	5,331	2,483
Gas (MMSCF)	15,877	18,988	18,230	9,503
Free gas (MMSCF)	11,457	14,441	13,688	7,170
Solution gas (MMSCF)	4,420	4,547	4,542	2,333
MBOE	7,858	8,610	8,474	4,122
Water (STB)	4,778	5,990	5,862	1,141
Oil recovery factor (%) *	23.69	24.69	24.66	11.49
Gas recovery factor (%) **	42.28	50.57	48.55	25.31
Abandonment time (day)	25,567	33,906	30,740	6,574

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.12.1 Oil production

Figure 5.74 shows that all strategies give different oil production profiles. Figure 5.77A and 5.77B reveal that all of producing oil comes from the bottom layer which is a water-drive oil reservoir. Table 5.12 indicates that cumulative oil production and recovery factor obtained from each strategy can be ordered from the top performance as strategies 2, 3, 1, and 4.

Strategy 2 yields the highest oil recovery since there is no crossflow between the two layers. Strategy 3 yields a slightly lower oil recovery than strategy 2 because there is a small amount of crossflow into the top layer as shown in Figure 5.77A. A large amount of crossflow into the top layer reservoir is seen in strategy 4 as shown in Figure 5.77A, resulting in a decrease in oil recovery.

In summary, strategies 2 and 3 are the best ways to maximize the ultimate production of oil as shown in Table 5.12 with the yellow highlight.

5.12.2 Gas production

For gas production comparison, Figure 5.74 shows that all strategies give totally different gas production profile. Since all produced gas from the bottom layer is liberated from oil, thus the reason is the same as the oil case. Therefore, more focus is given to the top layer which is a water-drive gas reservoir. Figure 5.78B reveals that cumulative production at the top layer obtained from each strategy can be ordered from the top performance as strategies 2, 3, 1, and 4. The rank in the top performance is an effect of pressure drawdown as shown in the Figure 5.76A.

In summary, strategies 2 and 3 are the best ways to maximize the ultimate production of gas as shown in Table 5.12 with the green highlight.

5.12.3 Summary

Strategy 2 which is separate layer production delivers the best outcome in term of barrel of oil equivalent or BOE. Thus, it is the most excellent strategy for this kind of multilayer reservoirs as shown in Table 5.12 with the brown highlight.

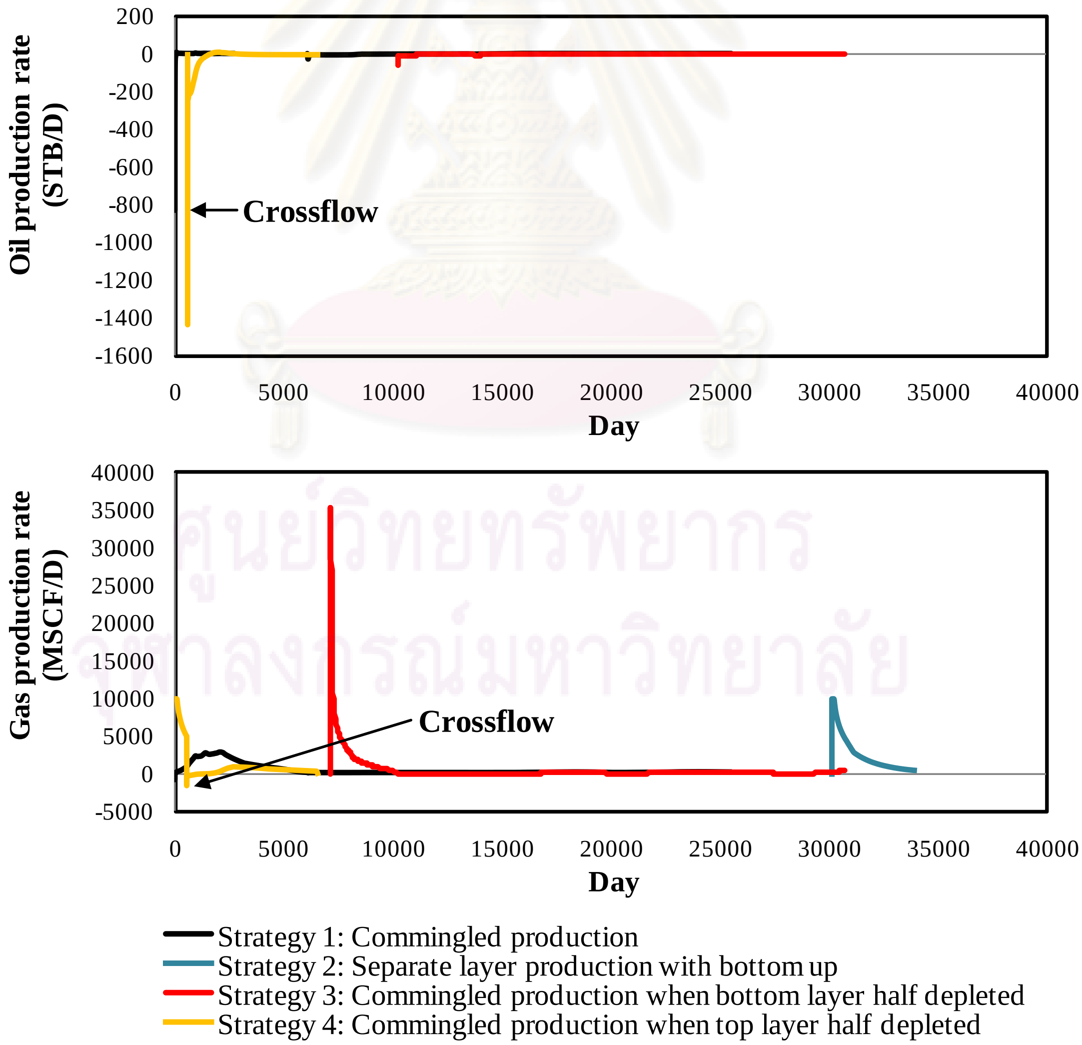

Figure 5.75: Production profiles of Case 12: G&W – O&W, at the top layer

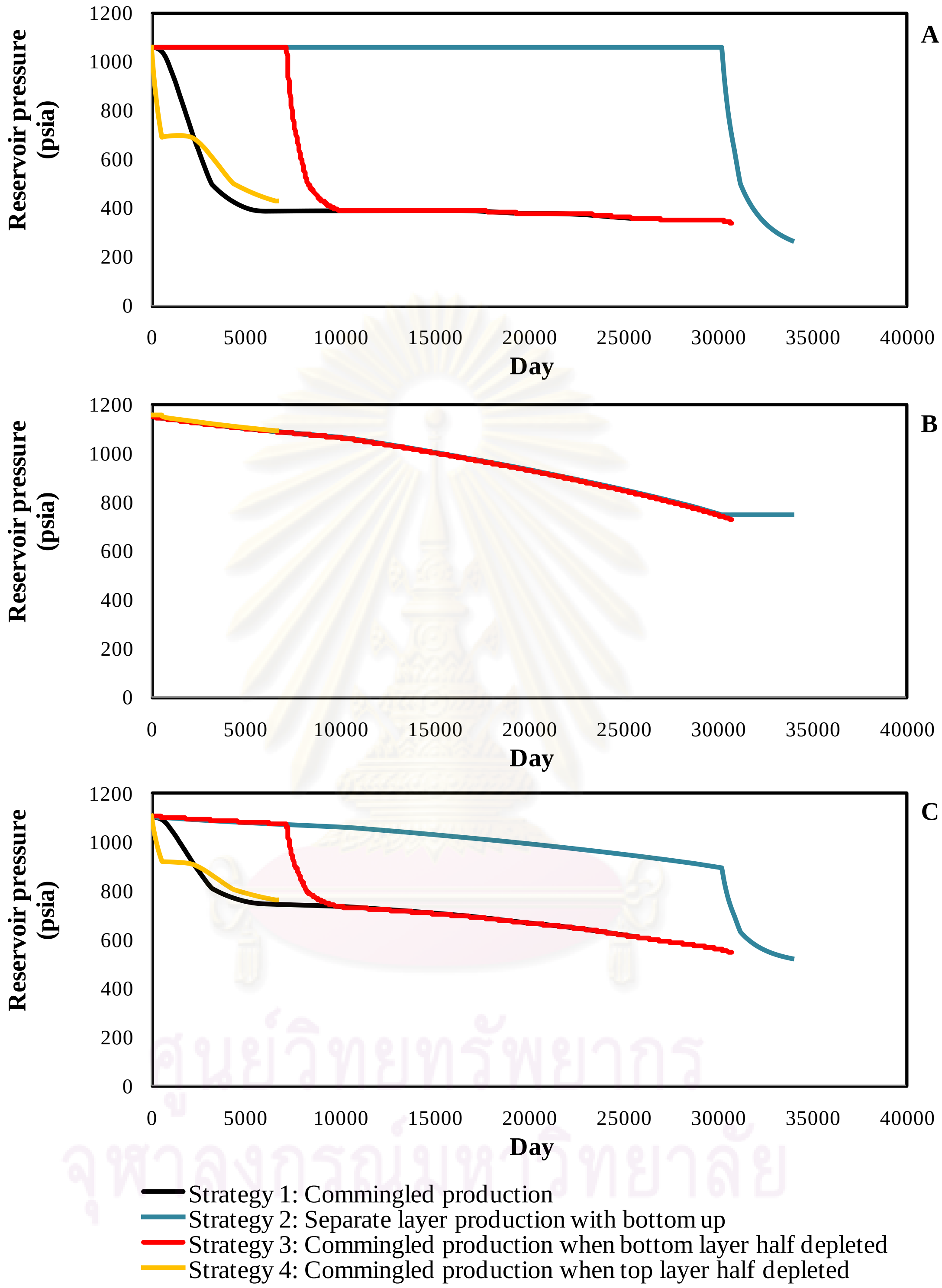

Figure 5.76: Reservoir pressure of Case 12: G&W – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

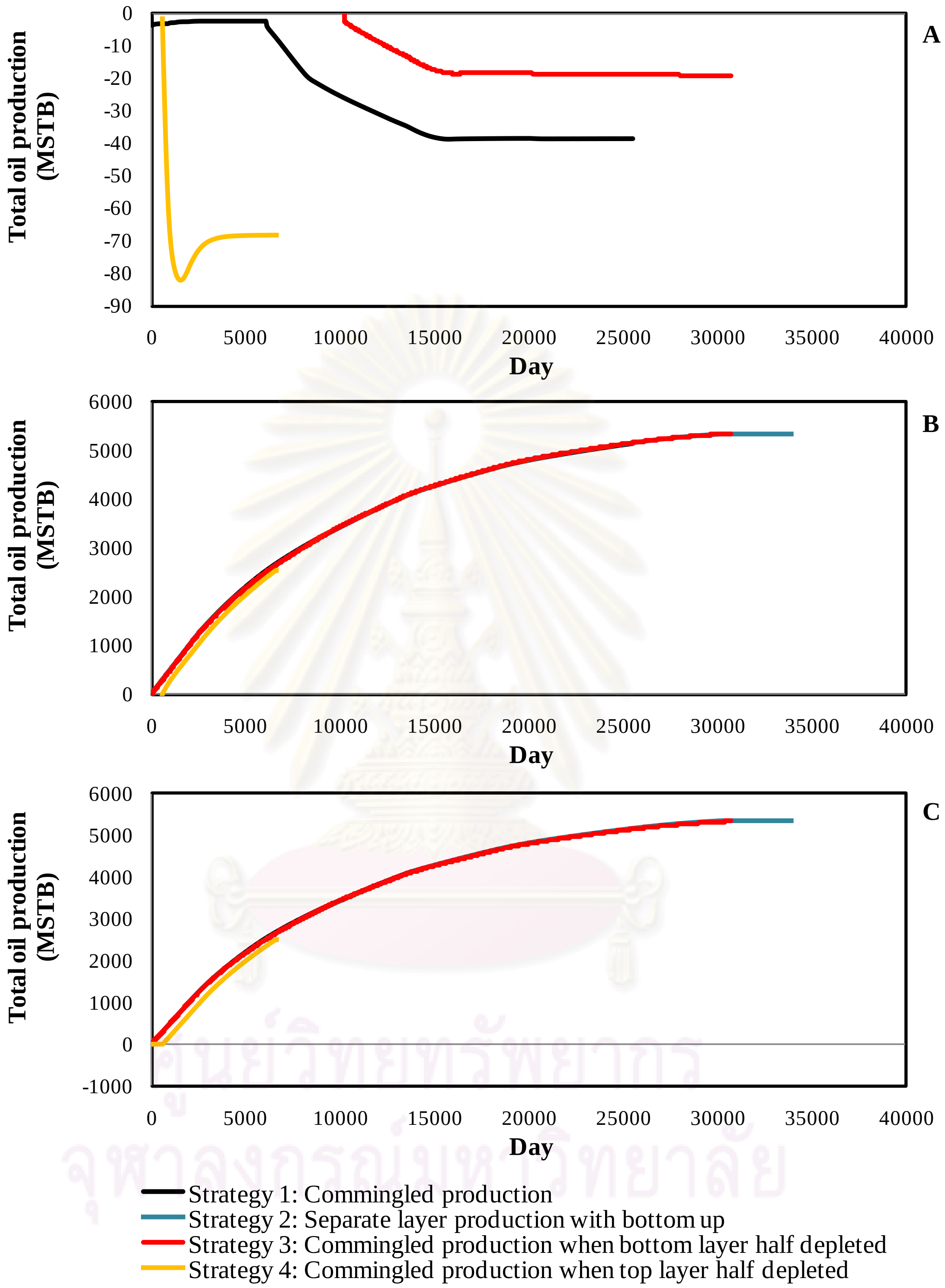

Figure 5.77: Total oil production of Case 12: G&W – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

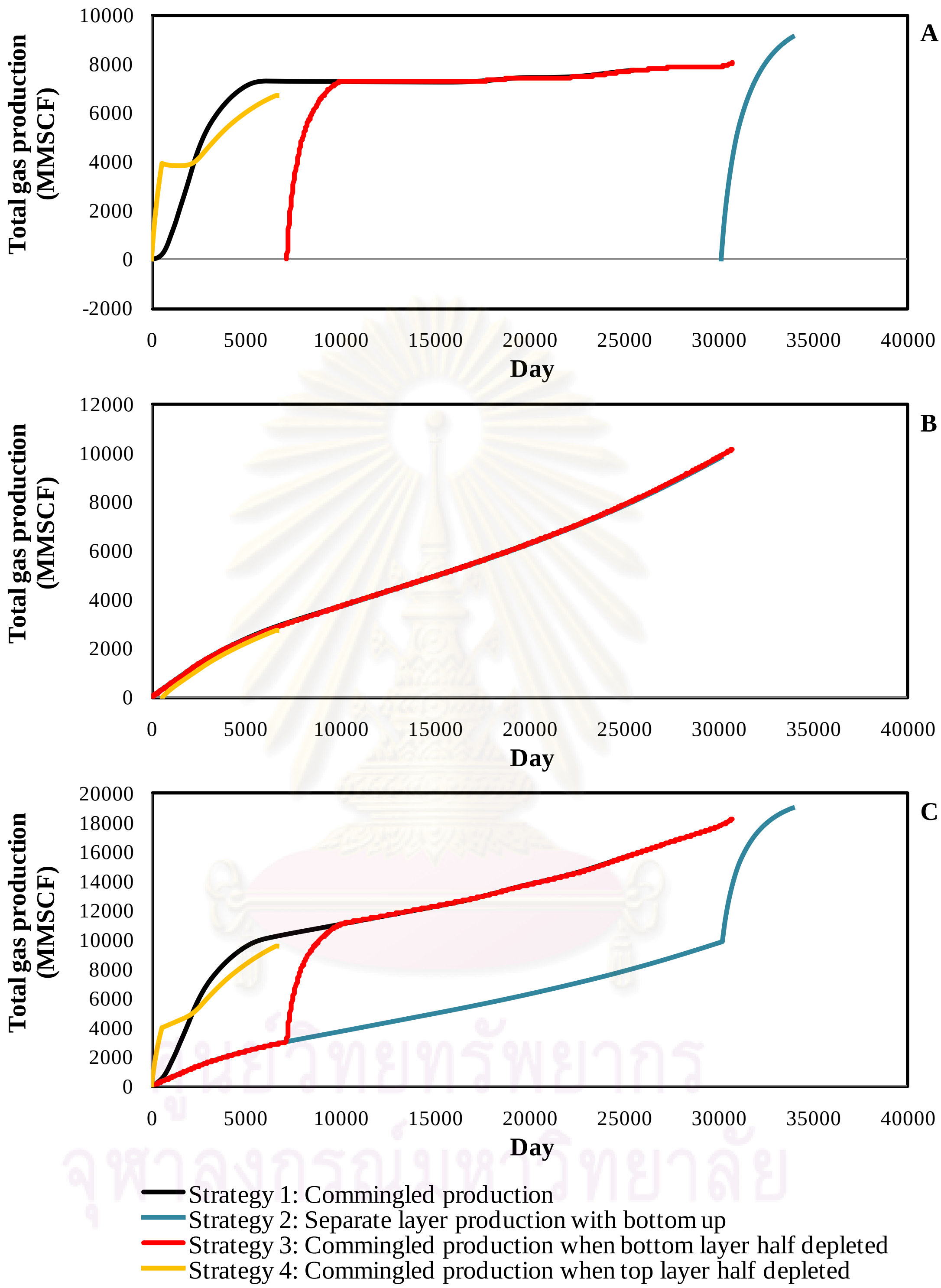

Figure 5.78: Total gas production of Case 12: G&W – O&W at (A) the top layer, (B) the bottom layer and (C) both layers

5.13 Case 13: G&O – G&O&W

In this case, the reservoir consists of 50 ft of gas and oil zone each at the top layer and 30 ft, 40 ft and 30 ft of gas, oil and water zone, respectively at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a saturated oil reservoir with a gas cap above. The reservoir is a gas-cap-drive and is perforated 30 ft from the bottom of oil zone. The bottom layer is a saturated oil reservoir with a gas cap above and an aquifer underneath. Drive mechanism of the reservoir is a combination of gas-cap-drive and water-drive. The reservoir is perforated 20 ft in the middle of oil zone. A well schematic of Case 13 is shown in Figure 5.79.

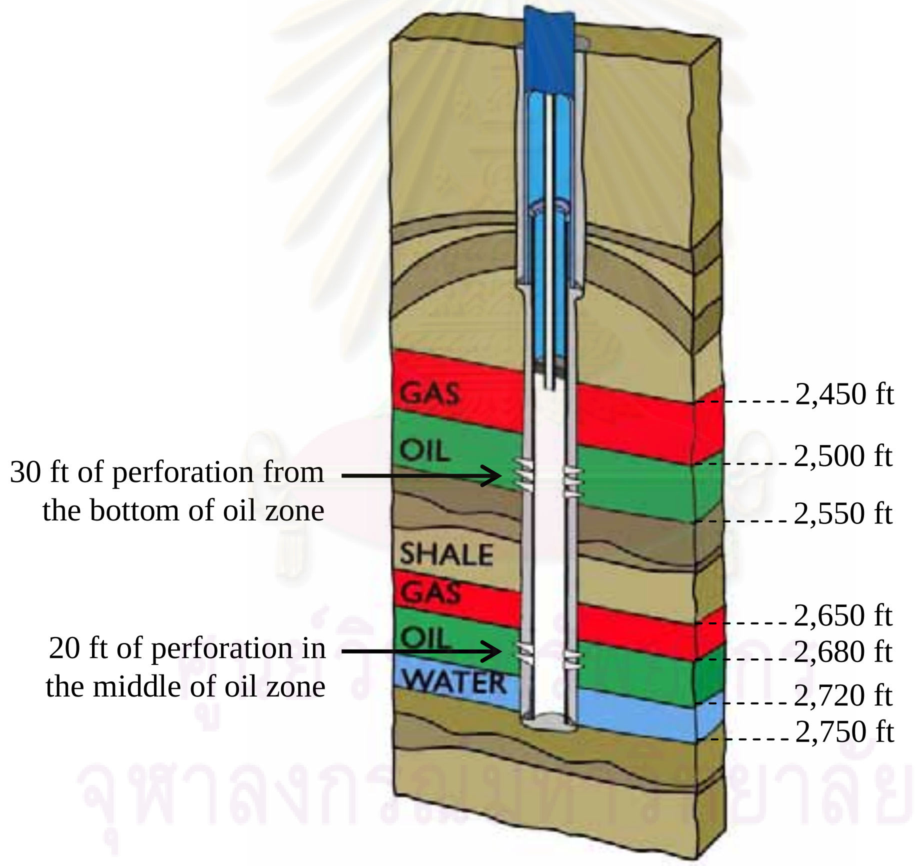

Figure 5.79: Well schematic for Case 13: G&O – G&O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.80 and comparative results are summarized in Table 5.13.

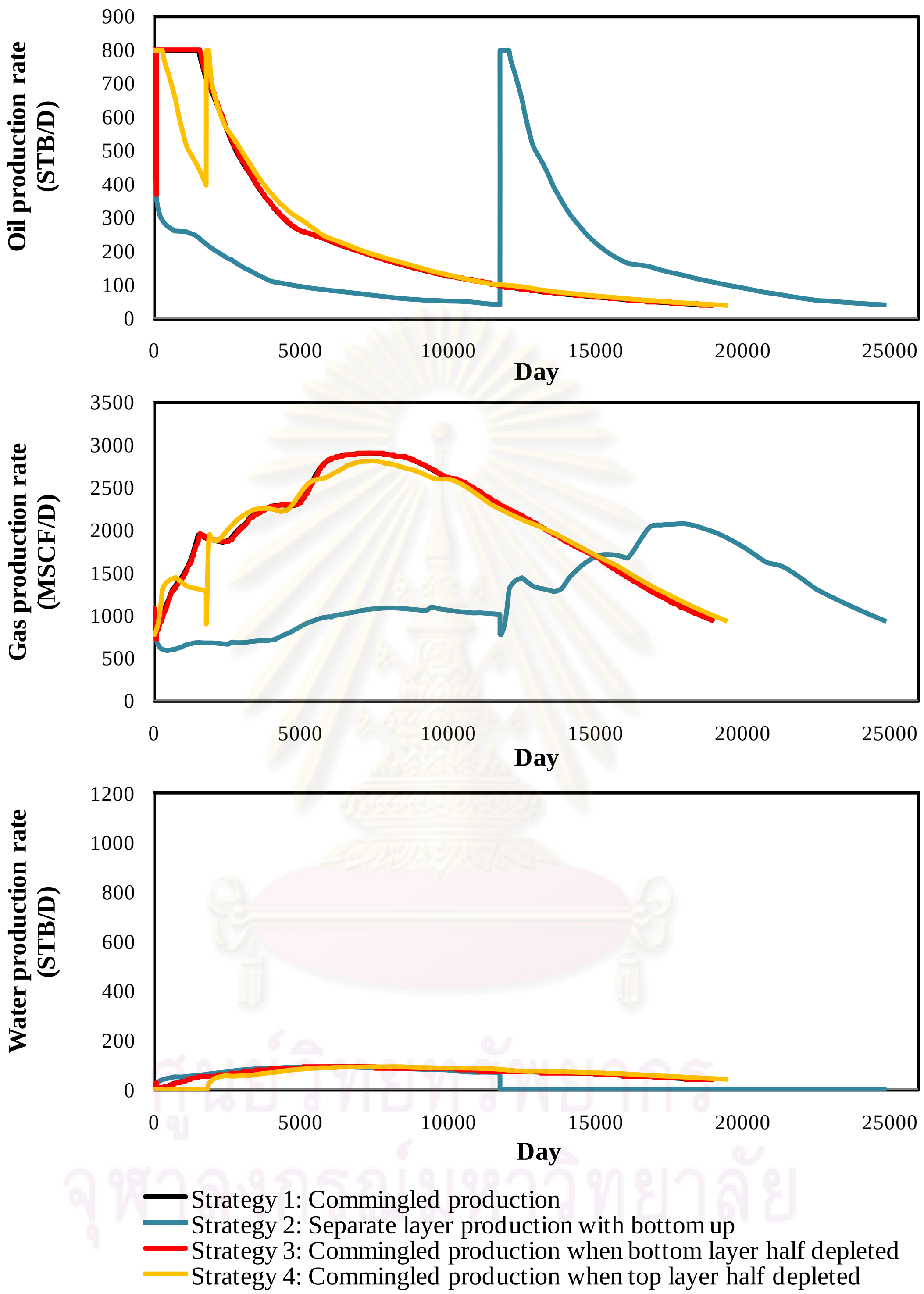

Figure 5.80: Production profiles of Case 13: G&O – G&O&W

Table 5.13: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 13: G&O – G&O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	4,424	3,894	4,414	4,269
Gas (MMSCF)	39,244	30,984	39,249	39,143
Free gas (MMSCF)	35,889	27,984	35,910	35,984
Solution gas (MMSCF)	3,354	2,999	3,339	3,159
MBOE	11,190	9,235	11,181	11,018
Water (STB)	1,278	919	1,275	1,260
Oil recovery factor (%) *	11.04	9.72	11.01	10.65
Gas recovery factor (%) **	62.18	49.09	62.19	62.02
Abandonment time (day)	18,993	24,837	18,993	19,448

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.13.1 Oil production

Figure 5.80 shows that oil production profiles obtained from strategies 1 and 3 are very similar and totally different from strategies 2 and 4. Table 5.13 indicates that ultimate oil production obtained from strategies 1 and 3 are very close while strategy 2 gives the lowest results. The cumulative productions are investigated closely at each layer in Figure 5.84.

Figure 5.84B shows cumulative oil production from the bottom layer which is a combination-drive reservoir. It shows that strategies 1, 3 and 4 recover similar amount of oil because they can produce oil from the bottom layer until the reservoir reaches the economic limit. However, strategy 4 yields ultimate oil recovery less than strategies 1 and 3 because the reservoir commences withdrawing the oil when some pressure drop has occurred due to a production of the overlying reservoir at the very beginning as shown in Figure 5.83. Moreover, crossflow takes place into the top layer when the bottom layer starts producing according to strategy 4 as shown in Figure 5.81.

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Strategy 2 withdraws the minimum amount of oil from the bottom layer as demonstrated in Figure 5.84B. The reason is that producing one layer at a time causes a relatively rapid pressure decline as shown in Figure 5.83B due to a high production rate as pointed out in Figure 5.81 at the very beginning of the production period. As the pressure is reduced, gas evolves throughout the reservoir and flows toward the wellbore, and eventually resulting in a large quantity of oil remaining in the reservoir. Figure 5.82 illustrates the higher gas rate at the bottom layer of strategy 2 in comparison with the other strategies.

Figure 5.84A shows cumulative oil production from the top layer which is a gas-cap-drive reservoir. It shows that strategies 1, 3 and 4 recover similar ultimate oil production while strategy 2 recovers the lowest amount of oil from the top layer. A possible reason is the rapid decline of reservoir pressure as shown in Figure 5.83B. This is a result of high oil production rate from the layer since the reservoir is produced from one layer at a time.

Conclusion, strategies 1 and 3 are excellent ways to maximize the ultimate production of oil as shown in Table 5.13 with the yellow highlight.

5.13.2 Gas production

Figure 5.80 shows that gas production profiles obtained from strategies 1 and 3 are very similar and totally different from the other two. Table 5.13 indicates that ultimate gas production obtained from strategies 1, 3 and 4 are very similar and strategy 2 gives the minimum result. The cumulative productions are investigated closely at each layer in Figure 5.85.

Figure 5.85 reveals that gas performances for all strategies are the same as oil in Figure 5.84. Strategy 2 is gives the minimum outcomes at both layers and the other strategies give similar results at the top and bottom layers. Therefore, the reason is the same as explained in the oil production.

In summary, strategies 1 and 3 are excellent ways to maximize the ultimate production of gas as shown in Table 5.13 with the green highlight.

5.13.3 Summary

Since there is no difference of water production and abandonment time between strategies 1 and 3 as shown in Table 5.13 and they can deliver the best outcomes for oil, gas, as well as BOE. Therefore, they are the most excellent strategies for this kind of multilayer reservoirs. However, startegy 1 is easier to implement since it requires only one run of perforation while strategy 3 needs two.

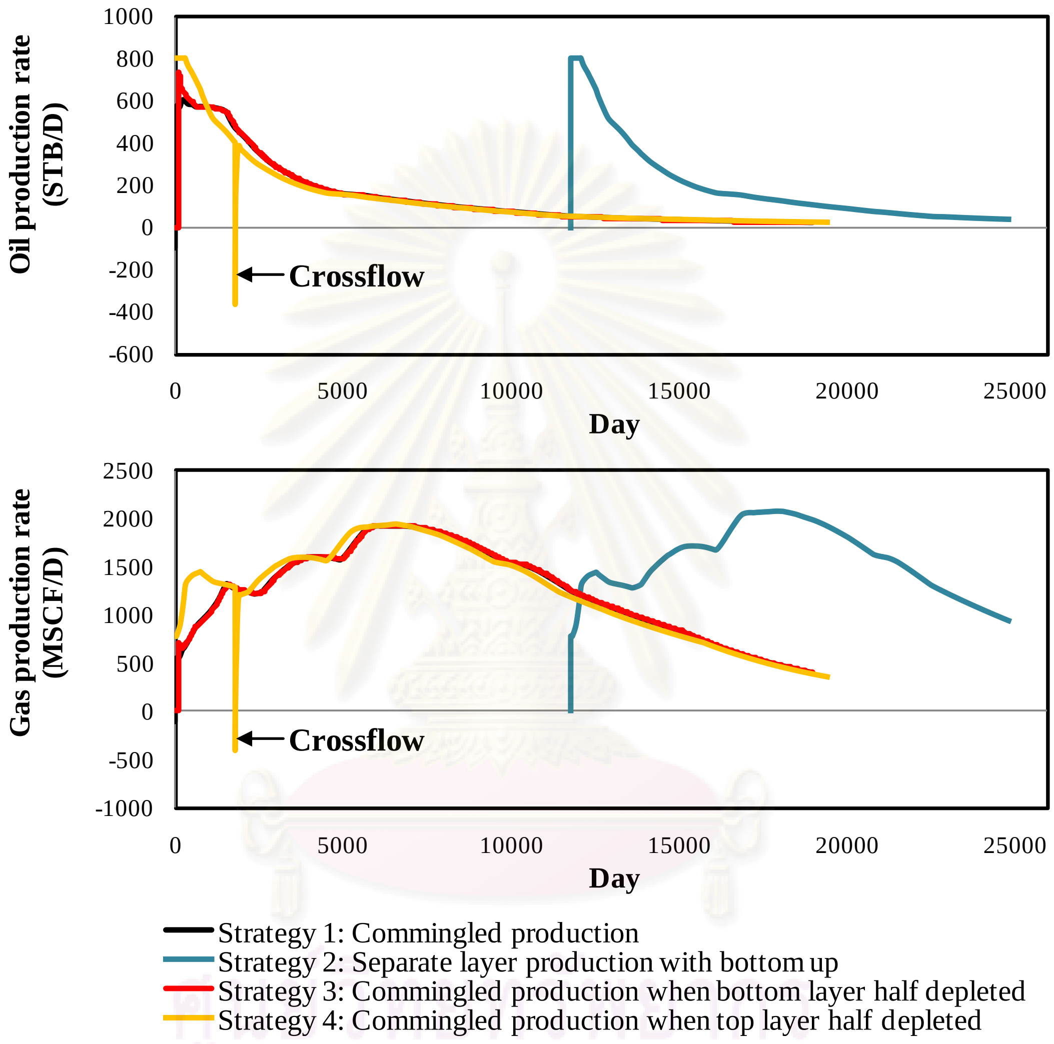

Figure 5.81: Production profiles of Case 13: G&O – G&O&W, at the top layer

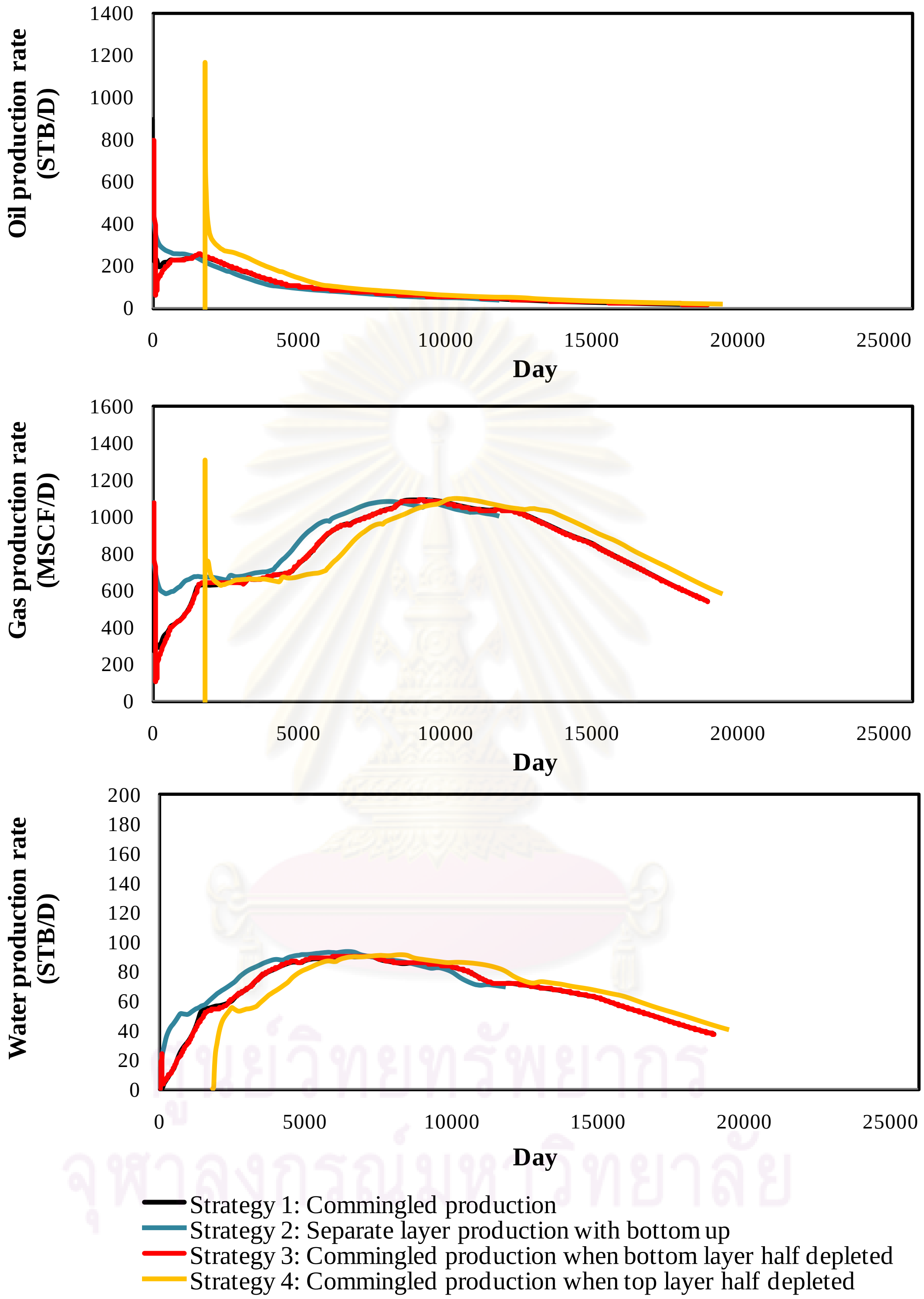

Figure 5.82: Production profiles of Case 13: G&O – G&O&W, at the bottom layer

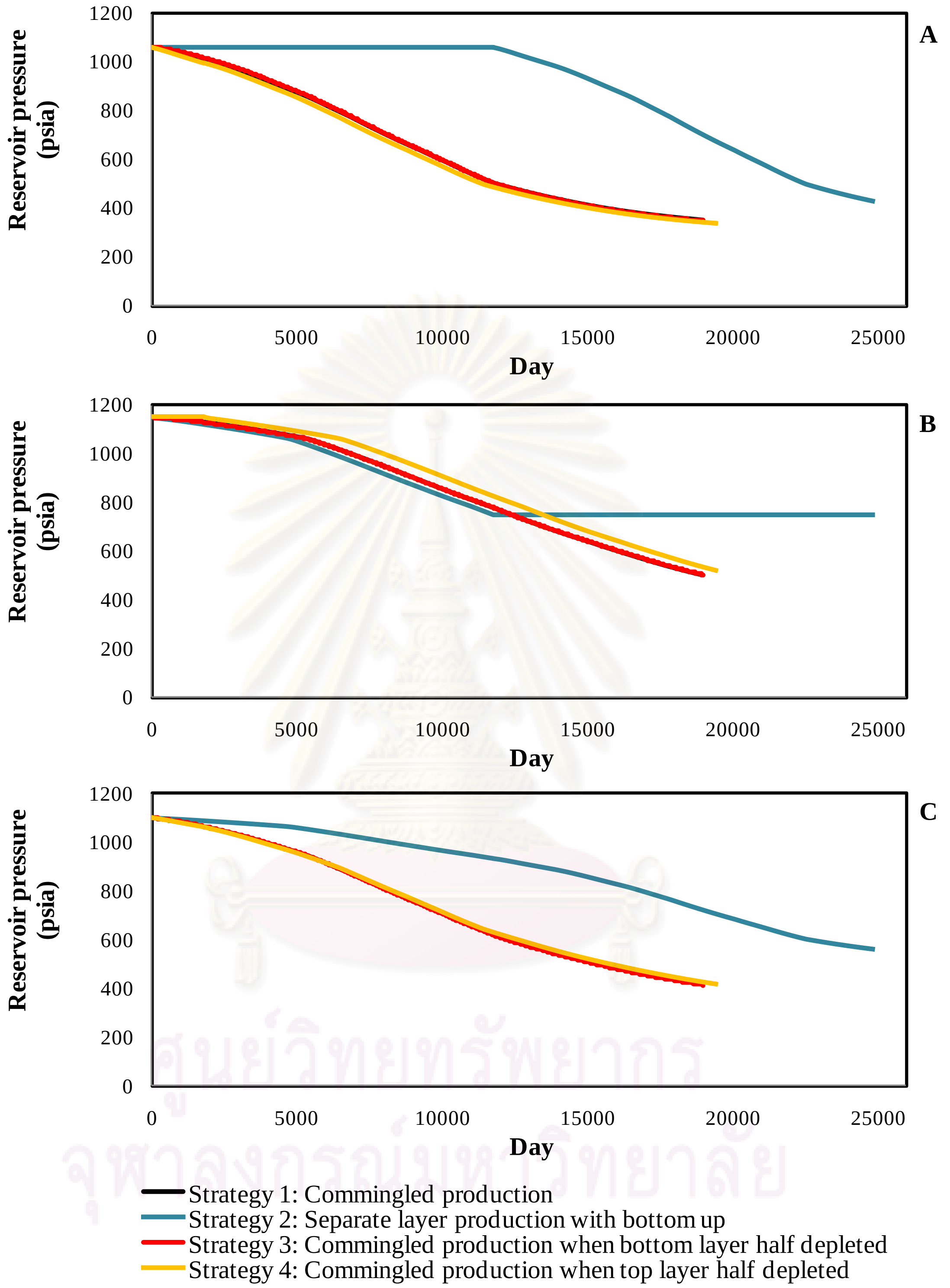

Figure 5.83: Reservoir pressure of Case 13: G&O – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

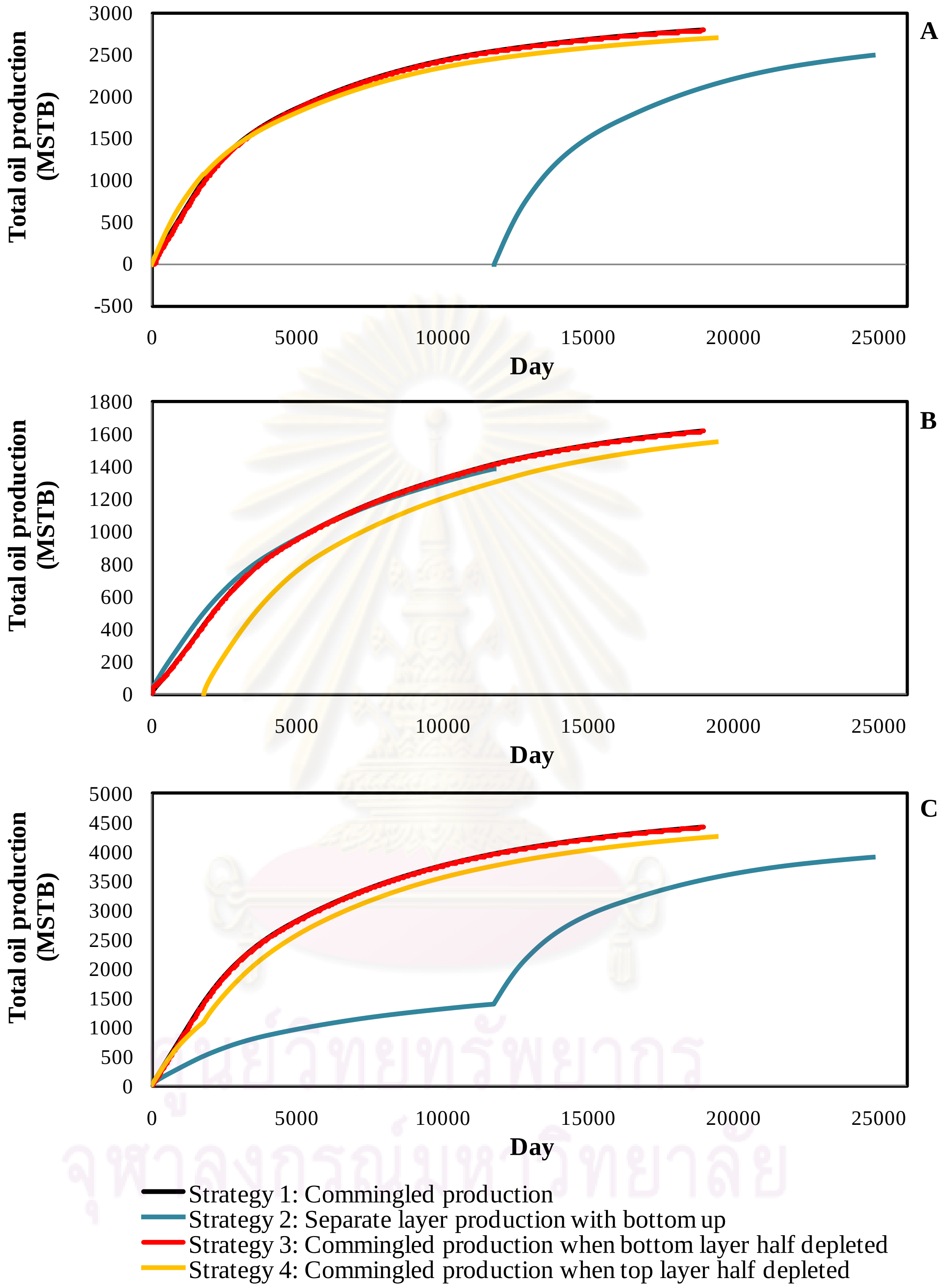

Figure 5.84: Total oil production of Case 13: G&O – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

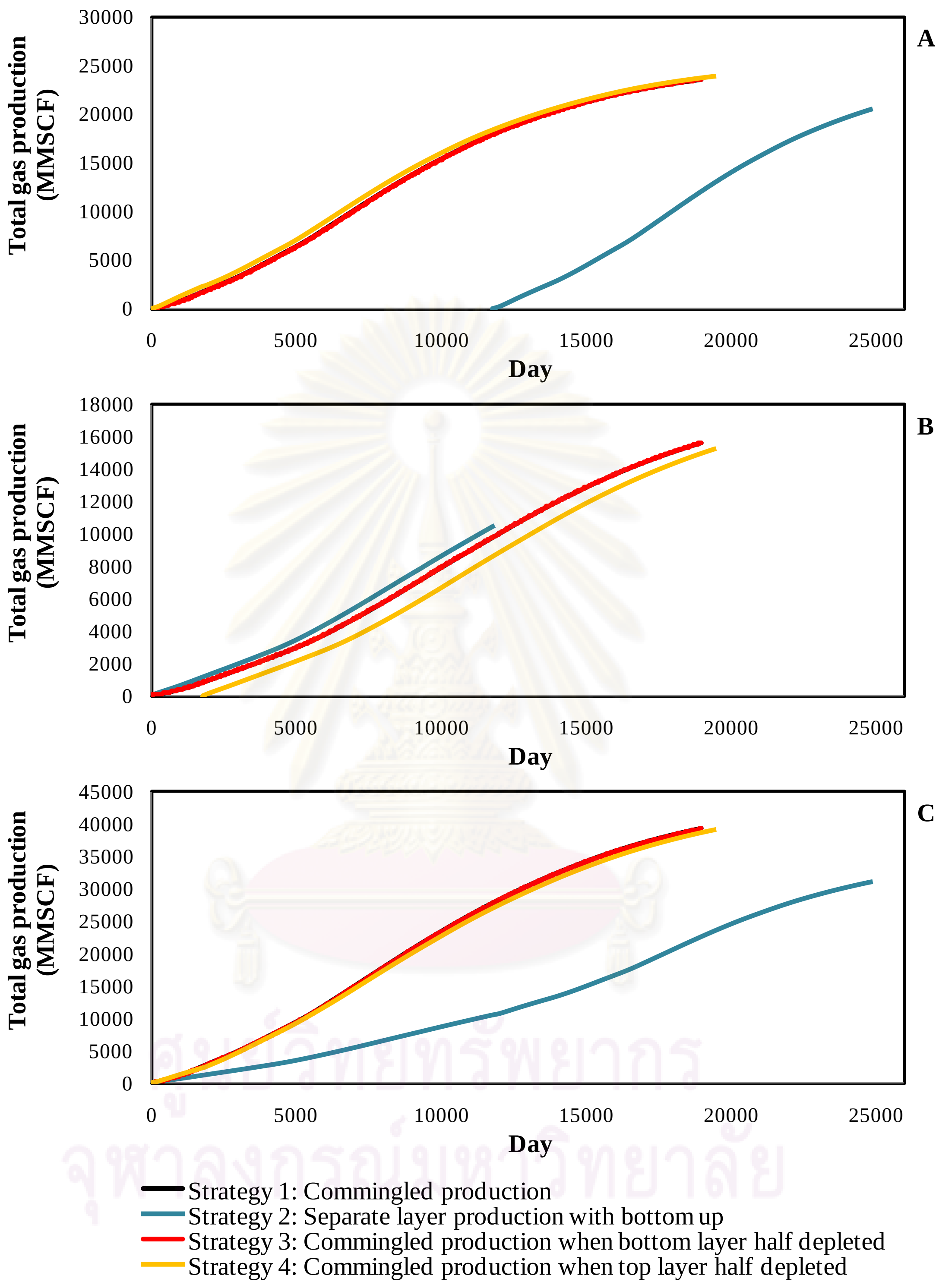

Figure 5.85: Total gas production of Case 13: G&O – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

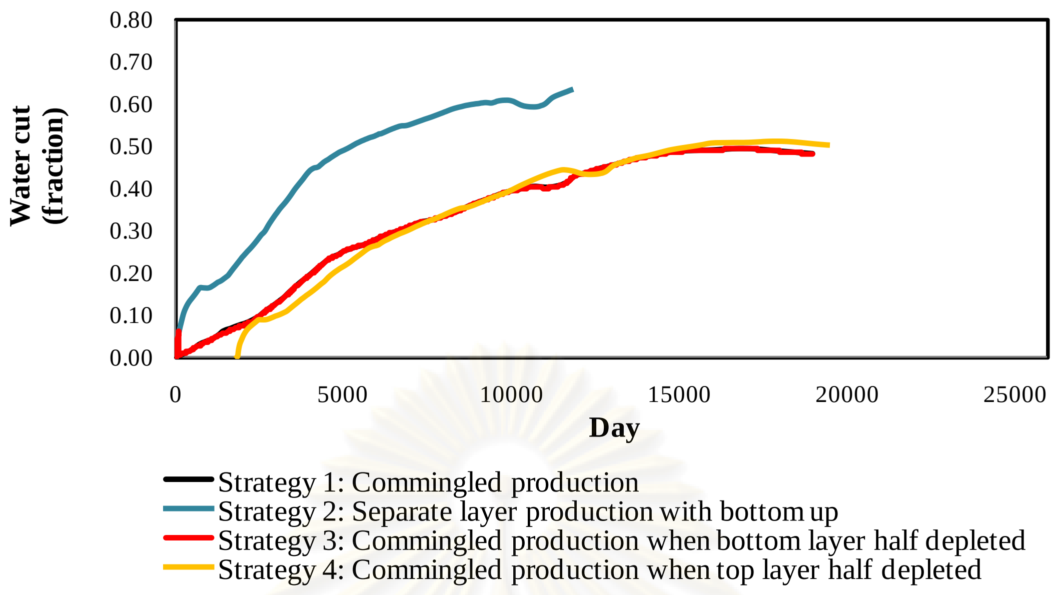

Figure 5.86: Water Cut of Case 13: G&O – G&O&W

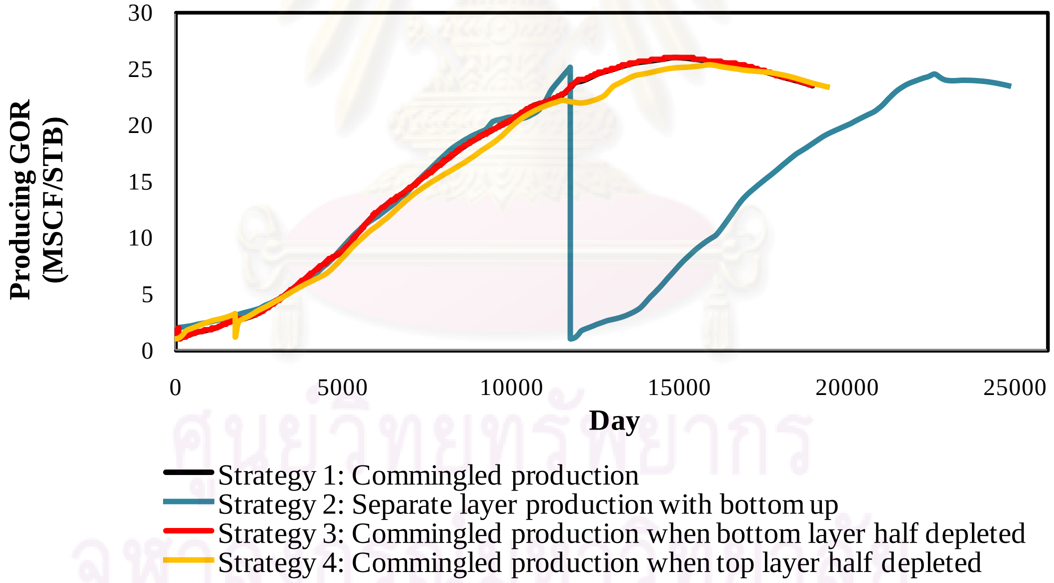

Figure 5.87: Producing GOR of Case 13: G&O – G&O&W

5.14 Case 14: G&W – G&O&W

In this case, the reservoir consists of 50 ft of gas and water zone each at the top layer and 30 ft, 40 ft and 30 ft of gas, oil and water zone, respectively at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is a gas reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of gas zone. The bottom layer is a saturated oil reservoir with a gas cap above and an aquifer underneath. Drive mechanism of the reservoir is a combination of gas-cap-drive and water-drive. It is perforated 20 ft in the middle of oil zone. A well schematic of Case 14 is shown in Figure 5.88.

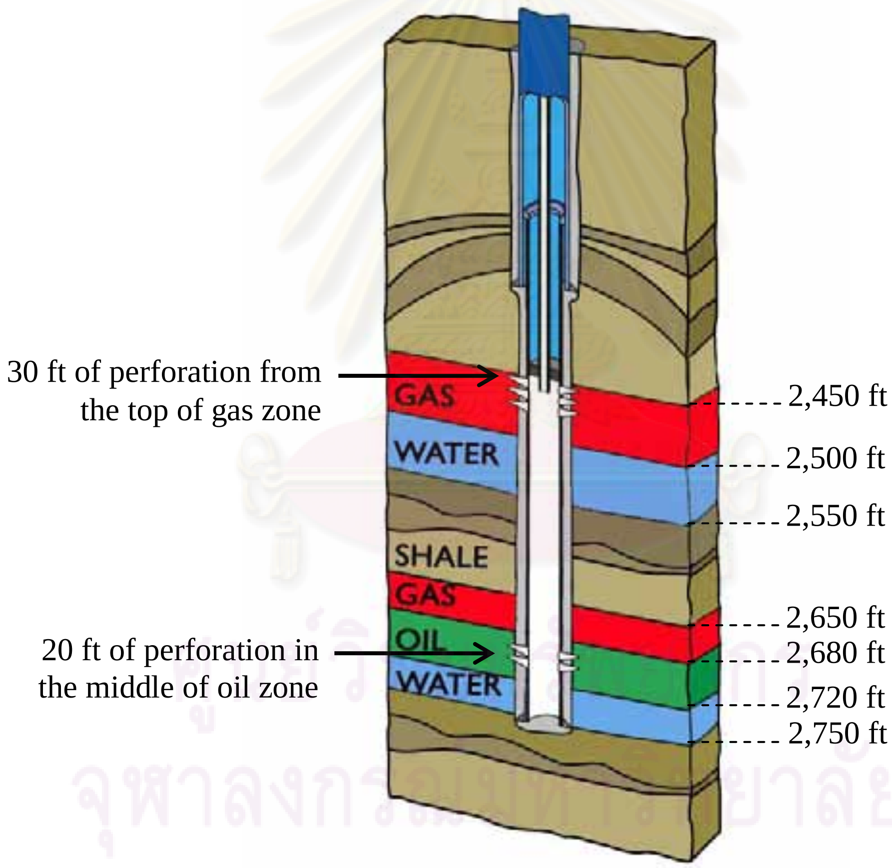

Figure 5.88: Well schematic for Case 14: G&W – G&O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.89 and comparative results are summarized in Table 5.14.

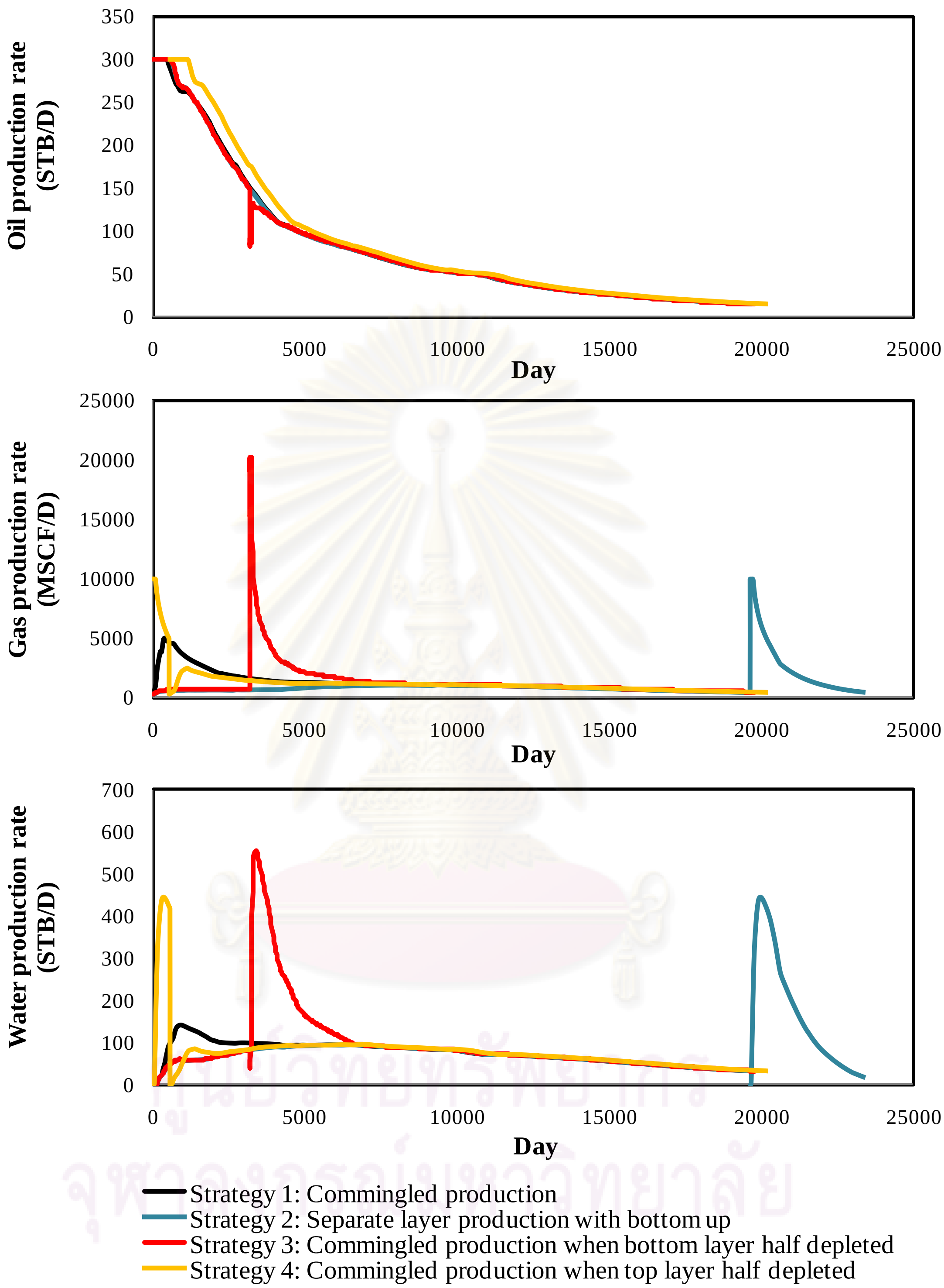

Figure 5.89: Production profiles of Case 14: G&W – G&O&W

Table 5.14: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 14: G&W – G&O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	1,587	1,586	1,593	1,573
Gas (MMSCF)	24,933	25,203	24,899	24,933
Free gas (MMSCF)	23,536	23,807	23,497	23,551
Solution gas (MMSCF)	1,397	1,396	1,403	1,381
MBOE	5,886	5,932	5,886	5,872
Water (STB)	1,465	1,936	1,808	2,758
Oil recovery factor (%) *	9.18	9.18	9.22	9.10
Gas recovery factor (%) **	60.91	61.57	60.83	60.97
Abandonment time (day)	19,691	23,344	19,812	20,178

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.14.1 Oil production

Figure 5.89 shows that oil production profiles obtained from strategies 1 and 2 are very similar. Strategy 3 gives similar profile with strategies 1 and 2, except for the point of time that the top layer starts producing. However, a totally different oil production profile is obtained from strategy 4. Table 5.14 indicates that ultimate oil production obtained from strategies 1, 2 and 3 are very similar while strategy 4 gives the lowest results. The reason is that the majority of oil production comes from the bottom layer which is a saturated reservoir with a gas cap above and an aquifer underneath. Figure 5.92B shows that all strategies give the same amount of total oil production from the bottom layer. However, strategy 4 delivers outcomes not as good as the others because crossflow takes place into the top layer when we start producing fluid from the bottom layer as shown in Figure 5.90.

To sum up, strategies 1, 2 and 3 yield excellent outcomes in term of ultimate production of oil as shown in Table 5.14 with the yellow highlight.

5.14.2 Gas production

Figure 5.89 shows that all gas production profiles are totally different. Table 5.14 indicates that the ultimate gas production obtained from strategy 2 is the highest. Figure 5.93B shows that all strategies give the same amount of ultimate gas production from the bottom layer. For the top layer which is a water-drive gas reservoir, only strategy 2 shows a different result.

Strategy 2 delivers the highest gas production because the top layer is produced separately from the bottom one, causing a large pressure drawdown as shown in Figure 5.91A. Because of the large pressure drawdown at the top layer, gas remaining in the reservoir can expand better in order to drive a large amount of gas into the wellbore and up to the surface.

In summary, strategy 2 is the most excellent approach to maximize the ultimate production of gas as shown in Table 5.14 with the green highlight.

5.14.3 Summary

Strategies 1, 2 and 3 are favorable for oil production while strategy 2 is the best for gas production. When looking at the BOE, strategy 2 gives the highest amount as shown in Table 5.14 with the brown highlight. Thus, strategy 2 which is separate layer production is the most excellent strategy for this kind of multilayer reservoirs.

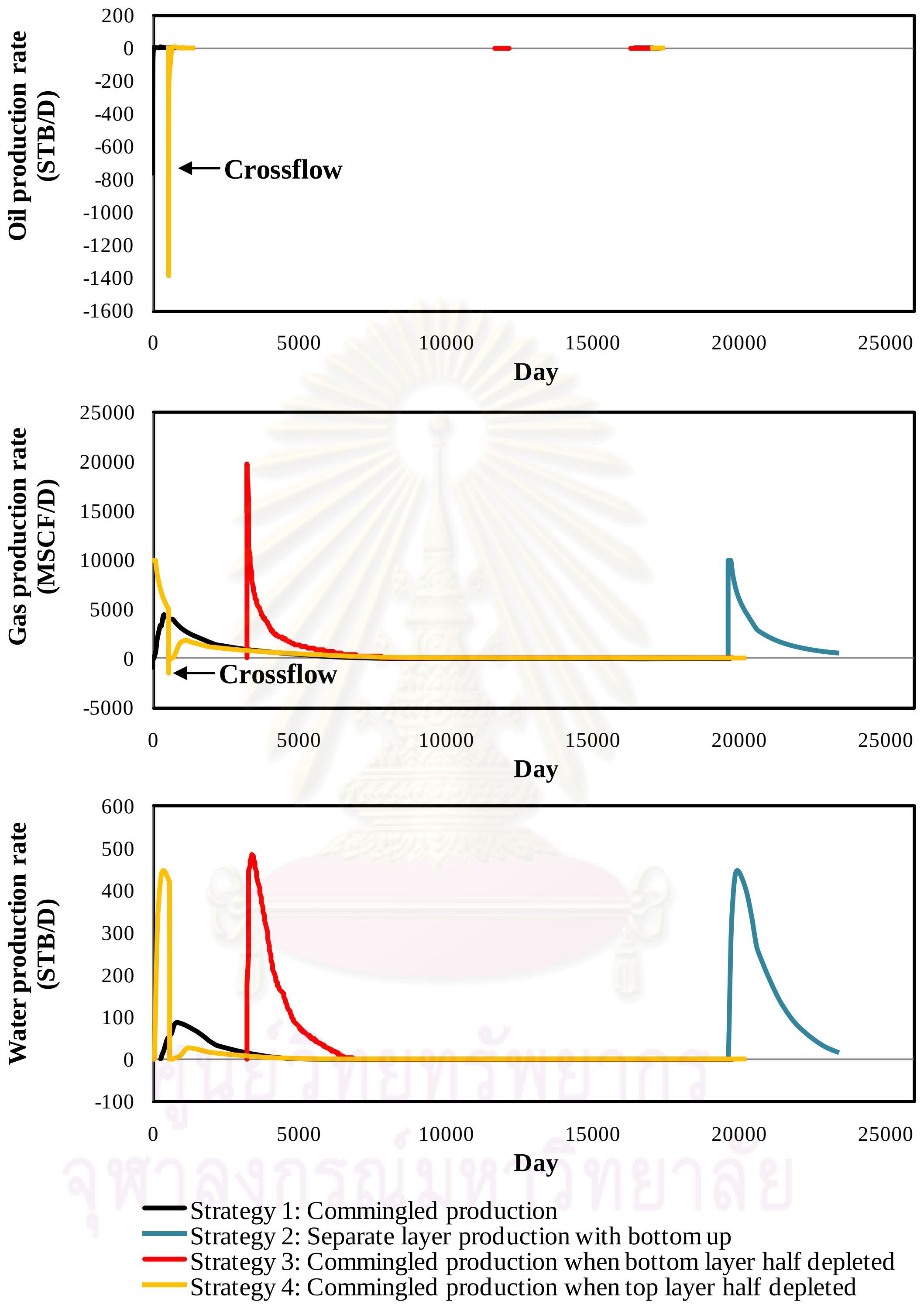

Figure 5.90: Production profiles of Case 14: G&W – G&O&W, at the top layer

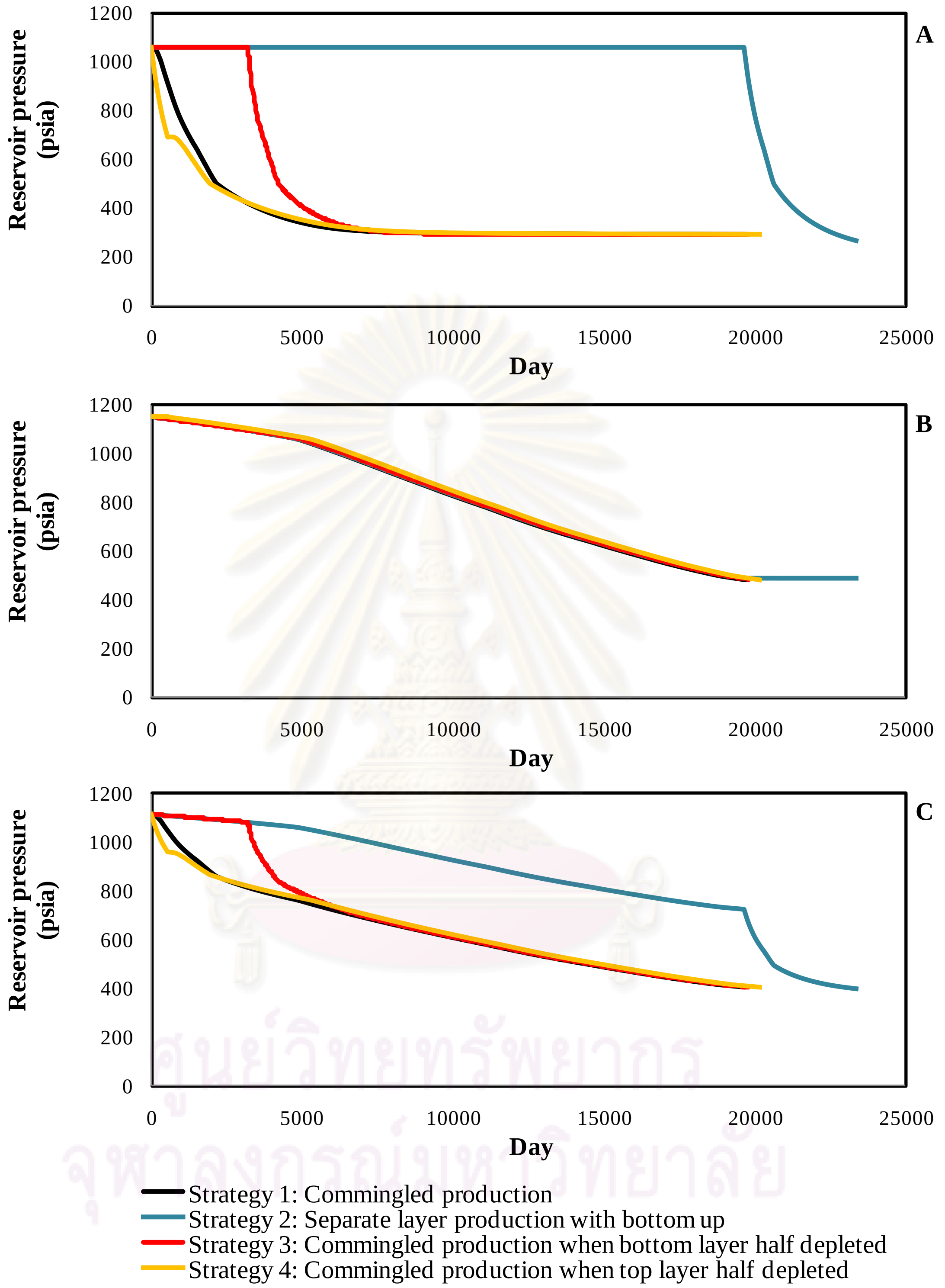

Figure 5.91: Reservoir pressure of Case 14: G&W – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

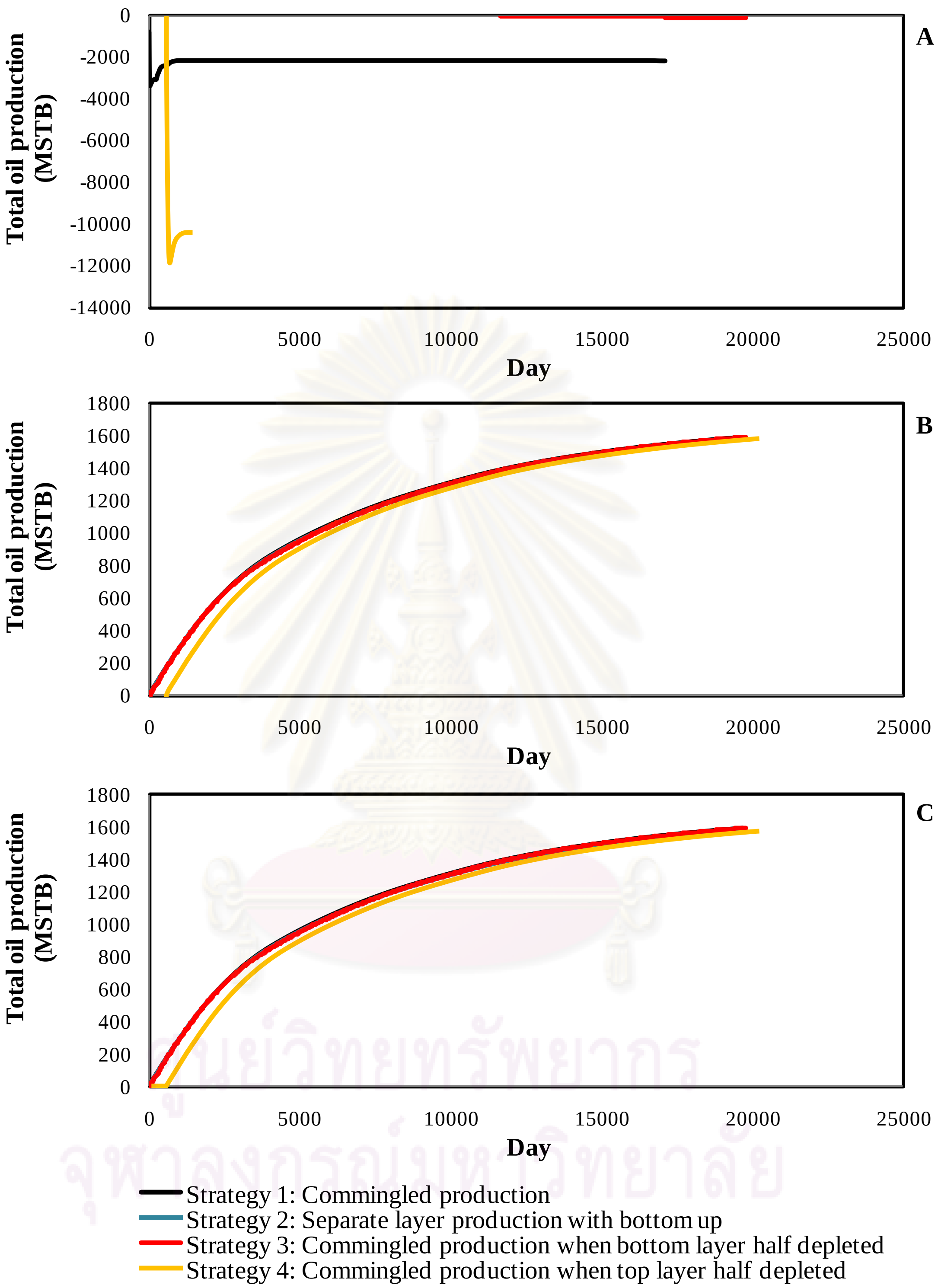

Figure 5.92: Total oil production of Case 14: G&W – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

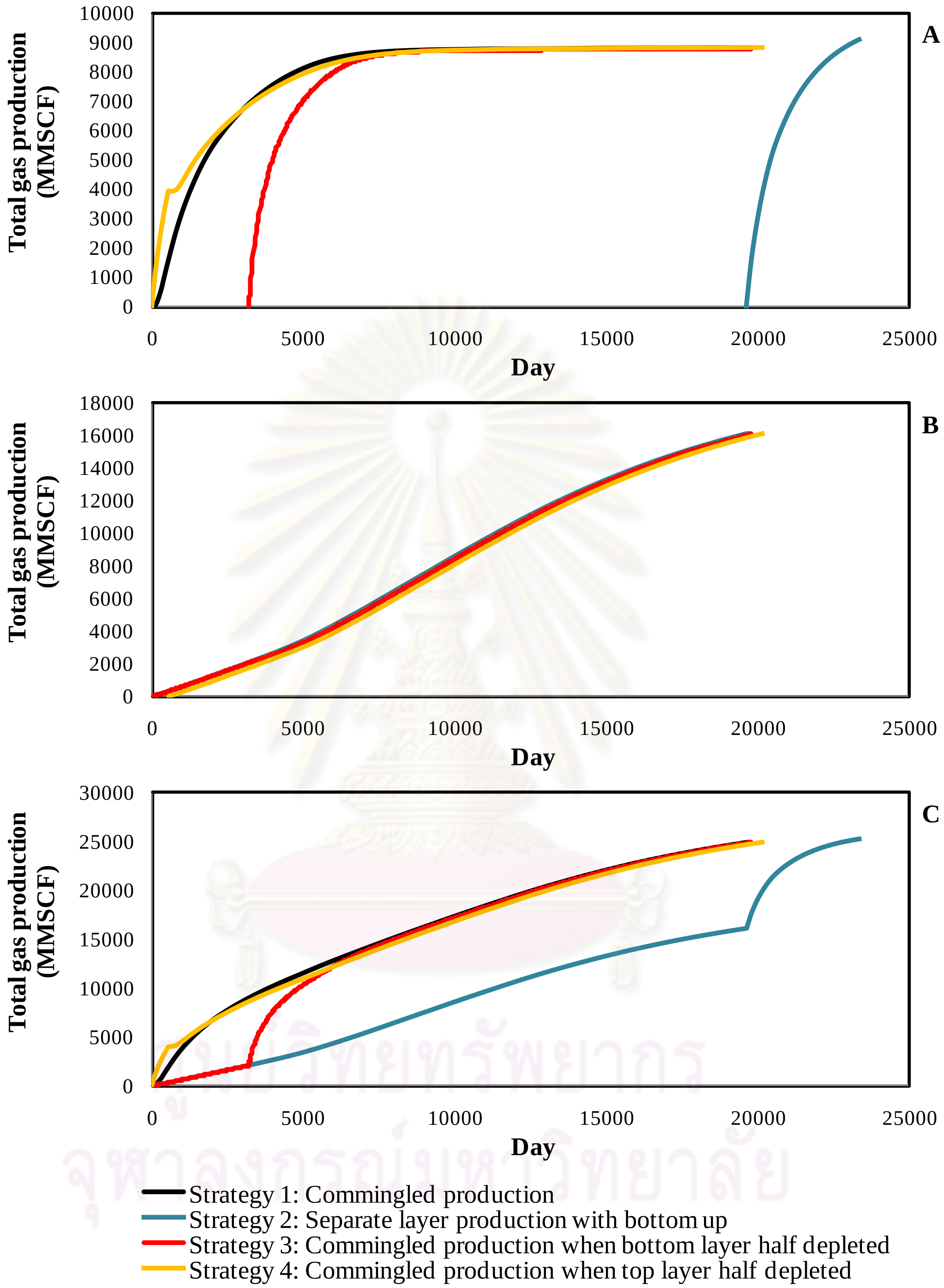

Figure 5.93: Total gas production of Case 14: G&W – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

5.15 Case 15: O&W – G&O&W

In this case, the top layer reservoir consists of 50 ft of oil and water zone each at the and 30 ft, 40 ft and 30 ft of gas, oil and water zone, respectively at the bottom layer. These two layers are separated by 100 ft of impermeable layer. The top layer is an undersaturated oil reservoir with an aquifer underneath. The reservoir is water-drive and is perforated 30 ft from the top of oil zone. The bottom layer is a saturated oil reservoir with a gas cap above and an aquifer underneath. Drive mechanism of the reservoir is a combination of gas-cap-drive and water-drive. It is perforated 20 ft in the middle of oil zone. A well schematic of Case 15 is shown in Figure 5.94.

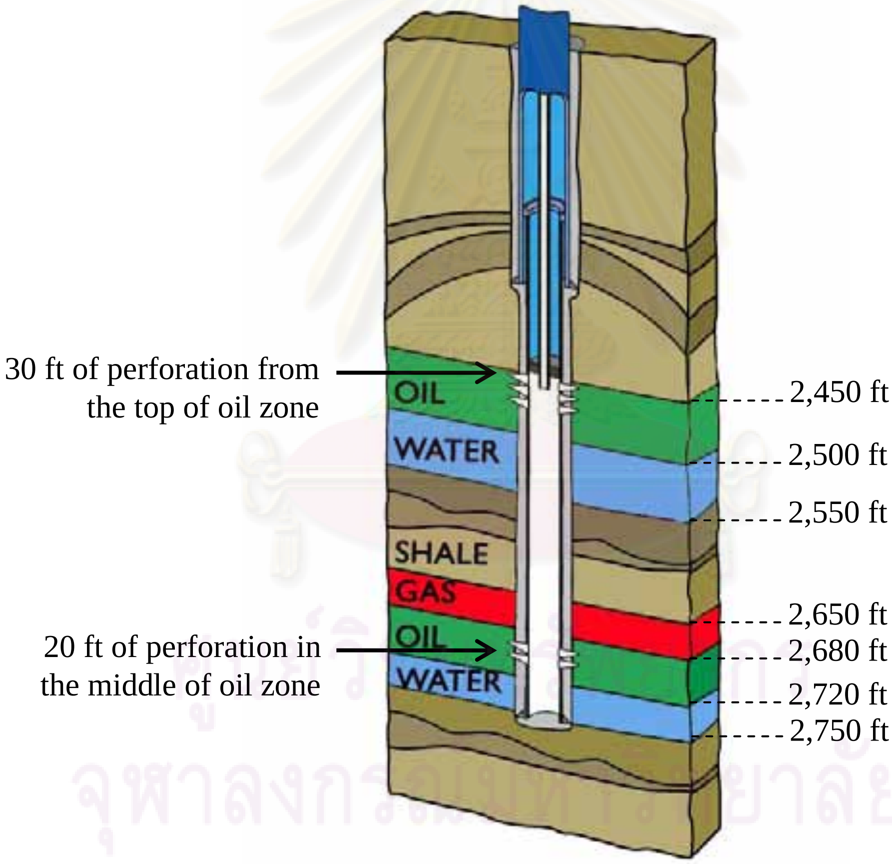

Figure 5.94: Well schematic for Case 15: O&W – G&O&W

After applying different production strategies to this multilayer reservoirs, results generated from simulation are analyzed. The production profiles of oil, gas and water obtained from different production strategies are plotted in Figure 5.95 and comparative results are summarized in Table 5.15.

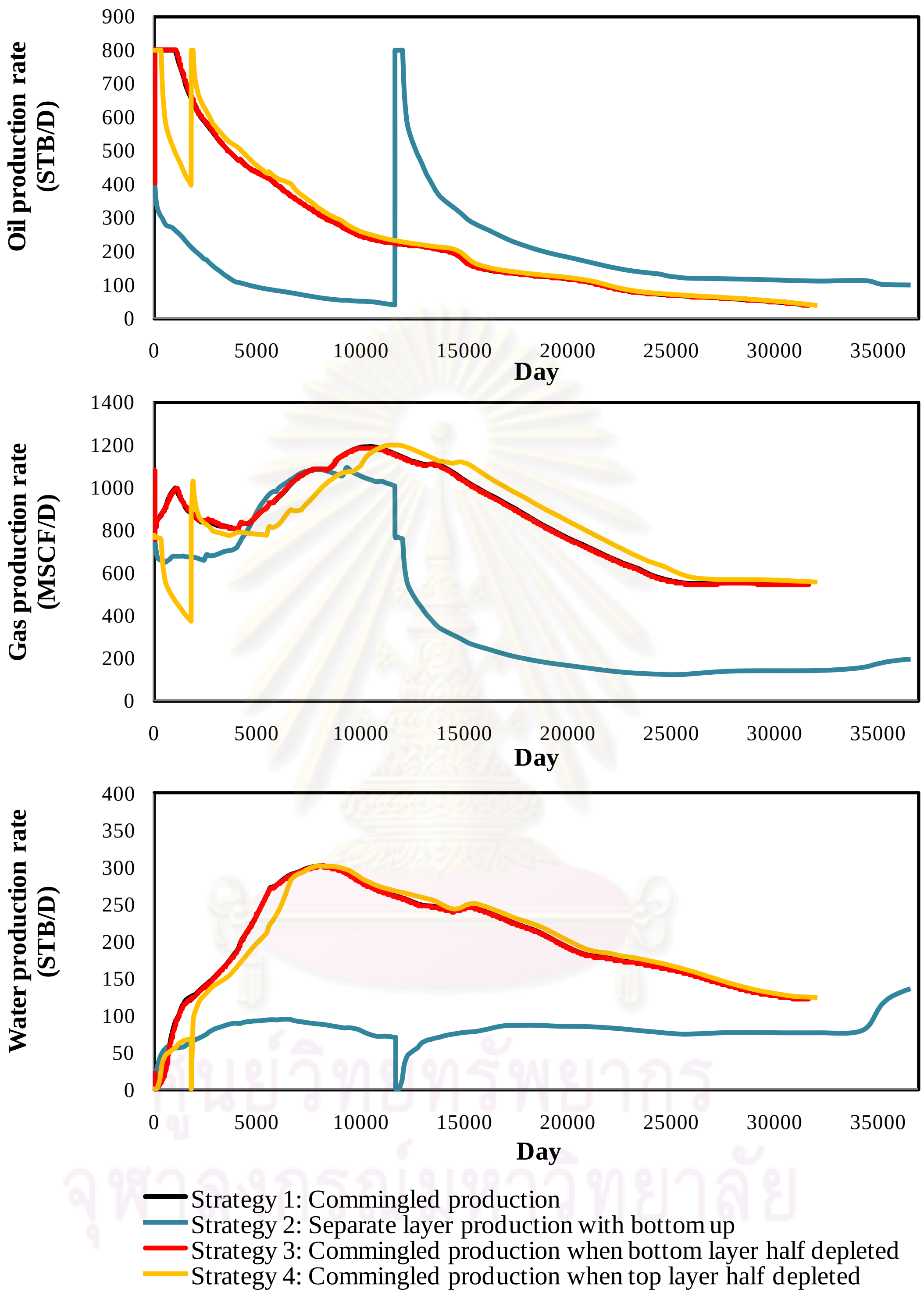

Figure 5.95: Production profiles of Case 15: O&W – G&O&W

Table 5.15: Comparison of cumulative production, recovery factor and abandonment time for different production strategies of Case 15: O&W – G&O&W

Production strategy	**Strategy 1:** Commingled production	**Strategy 2:** Separate layer production with bottom up	**Strategy 3:** Commingled production when bottom layer half depleted	**Strategy 4:** Commingled production when top layer half depleted
Cumulative production				
Oil (MSTB)	7,336	6,135	7,325	7,308
Gas (MMSCF)	26,588	15,264	26,593	26,443
Free gas (MMSCF)	20,891	10,075	20,913	20,774
Solution gas (MMSCF)	5,697	5,189	5,680	5,670
MBOE	11,920	8,767	11,910	11,868
Water (STB)	6,273	2,885	6,270	6,265
Oil recovery factor (%) *	18.30	15.31	18.28	18.24
Gas recovery factor (%) **	52.95	30.40	52.96	52.66
Abandonment time (day)	31,684	36,524	31,683	31,989

** Oil recovery factor = total oil production / OOIP*

** Gas recovery factor = (total free gas production + total solution gas production) / OGIP*

5.15.1 Oil production

Figure 5.95 shows that oil production profiles obtained from strategies 1 and 3 are very similar and totally different from the other two. Table 5.15 indicates that the ultimate oil production obtained from strategies 1, 3 and 4 are very similar while strategy 2 gives the lowest ultimate oil production. The cumulative productions are investigated closely at each layer in Figure 5.99.

Figure 5.99B shows cumulative oil production from the bottom layer which is a combination-drive reservoir. It shows that strategies 1, 3 and 4 recover almost the same ultimate oil production because they can produce oil from the bottom layer until the reservoir reaches the economic limit. However, strategy 4 yields poorer results than strategies 1 and 3 because crossflow takes place into the top layer after we start producing fluid from the bottom layer as shown in Figure 5.96.

Strategy 2 withdraws the lowest amount of oil from the bottom layer as demonstrated in Figure 5.99B. The explanation is that the production from one layer at a time causes a relatively rapid pressure decline as shown in Figure 5.98B due to a high oil production rate as pointed out in Figure 5.97 at the very beginning of the production period. As pressure is reduced, gas evolves throughout the reservoir and flows toward the wellbore, and eventually resulting in a large quantity of oil remaining in the reservoir. Figure 5.102 shows high values of gas-oil ratio obtained from this strategy.

Figure 5.99A shows cumulative oil production from the top layer which is a water-drive oil reservoir. It shows that strategies 1, 3 and 4 recover the same ultimate oil production because they withdraw oil from the top layer until the reservoir reaches the economic limit. Conversely, strategy 2 produces the lowest amount of oil from the top layer. The reason is that the reservoir dies before the production reaches the economic limit is due to the fact that the reservoir pressure is not enough to lift the fluid up to the surface. This is due to high water production from the bottom layer during the early period as indicated in Figure 5.101 which leads to early loading of water in the wellbore.

In summary, strategies 1 and 3 are excellent methods to maximize the ultimate production of oil as shown in Table 5.15 with the yellow highlight.

5.15.2 Gas production

Figure 5.95 shows that gas production profiles obtained from strategies 1 and 3 are very similar and totally different from the others. Table 5.15 indicates that the ultimate gas production obtained from strategies 1, 3 and 4 are very similar and strategy 2 gives the lowest ultimate gas production. The cumulative productions are investigated closely at each layer in Figure 5.100.

Figure 5.100 reveals that gas performances for all strategies are the same as oil in Figure 5.99. Strategy 2 is the least favorable strategy at both layers and the other strategies give the similar results at the top and the bottom layers. The reason for gas production performance is the same as described in the oil case.

In summary, strategies 1 and 3 are the excellent methods to maximize the ultimate production of gas as shown in Table 5.15 with the green highlight.

5.15.3 Summary

Since there is no difference of water production and abandonment time between strategies 1 and 3 as shown in Table 5.15 and they can deliver the best outcomes for oil, gas, as well as BOE. Therefore, they are excellent strategies for this kind of multilayer reservoirs. However, startegy 1 is easier to implement since it requires only one run of perforation while strategy 3 needs two.

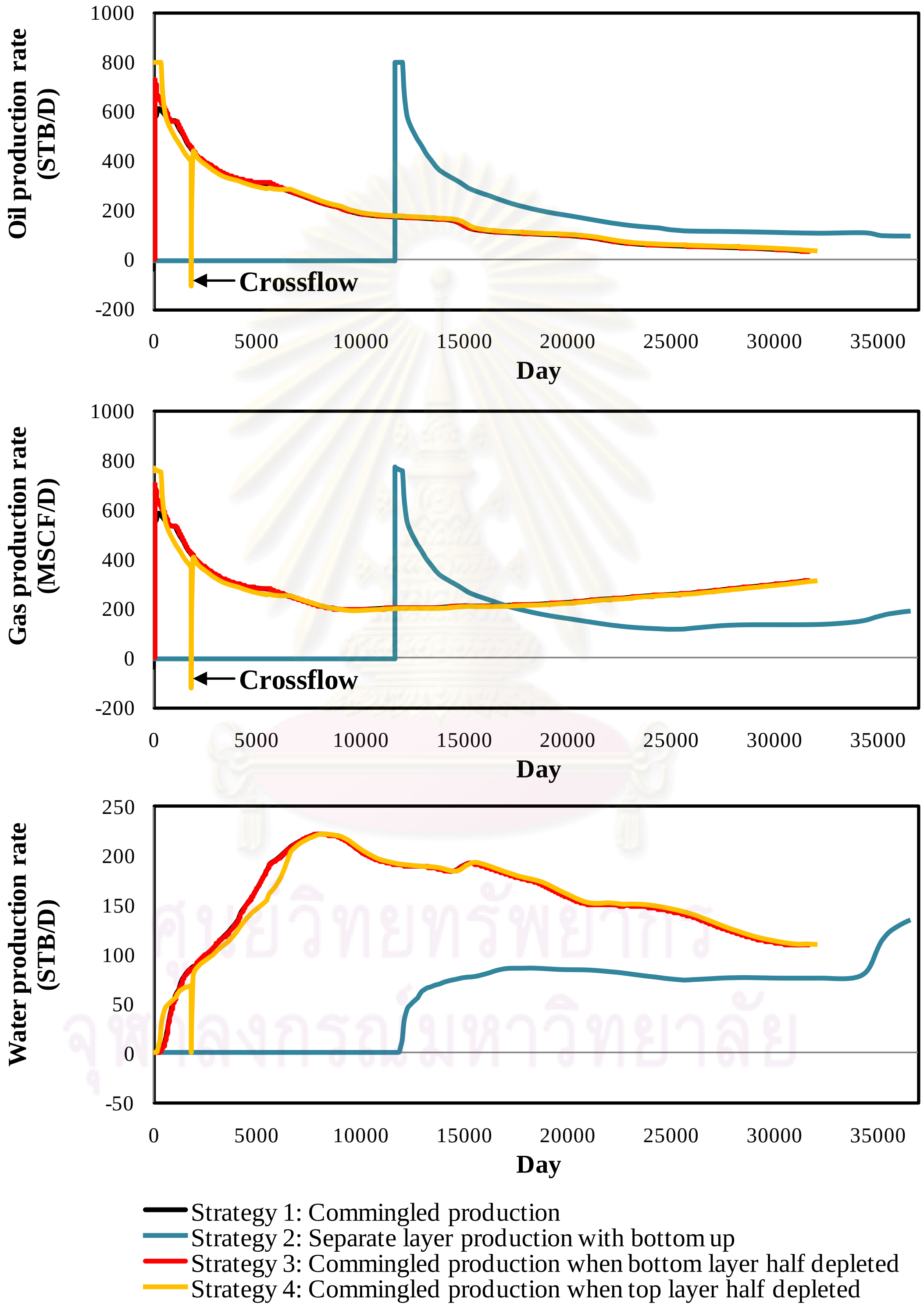

Figure 5.96: Production profiles of Case 15: O&W – G&O&W, at the top layer

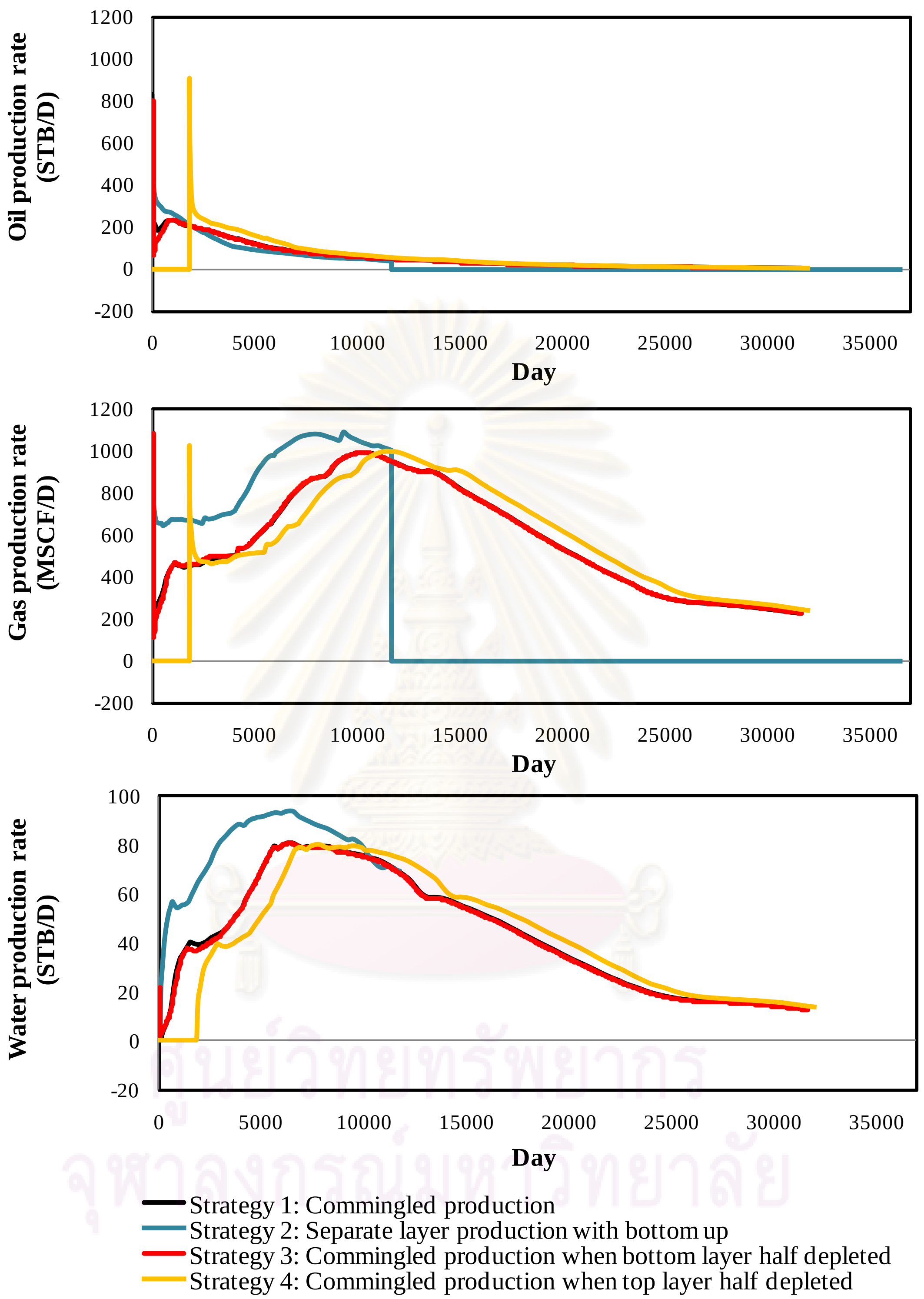

Figure 5.97: Production profiles of Case 15: O&W – G&O&W, at the bottom layer

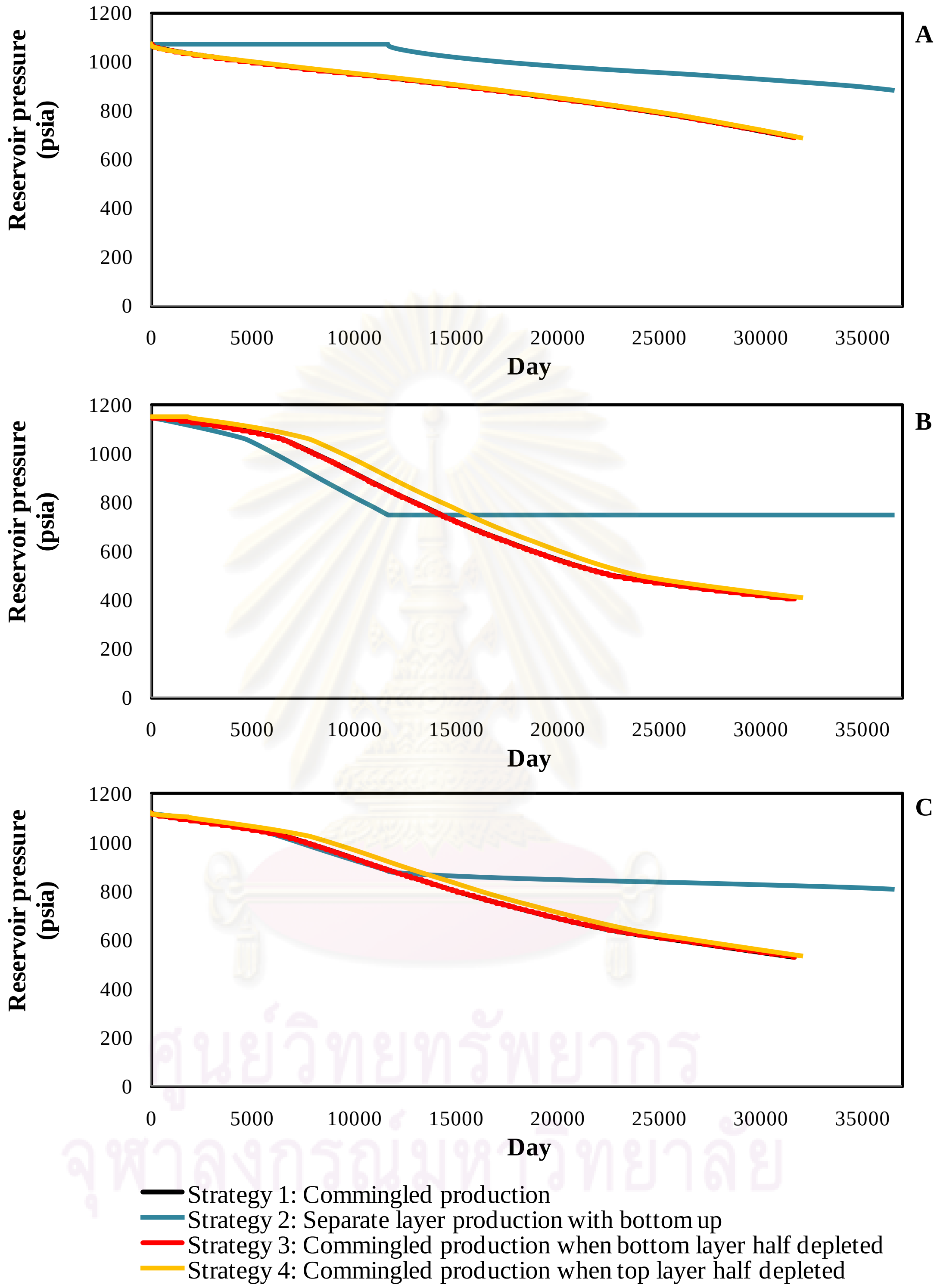

Figure 5.98: Reservoir pressure of Case 15: O&W – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

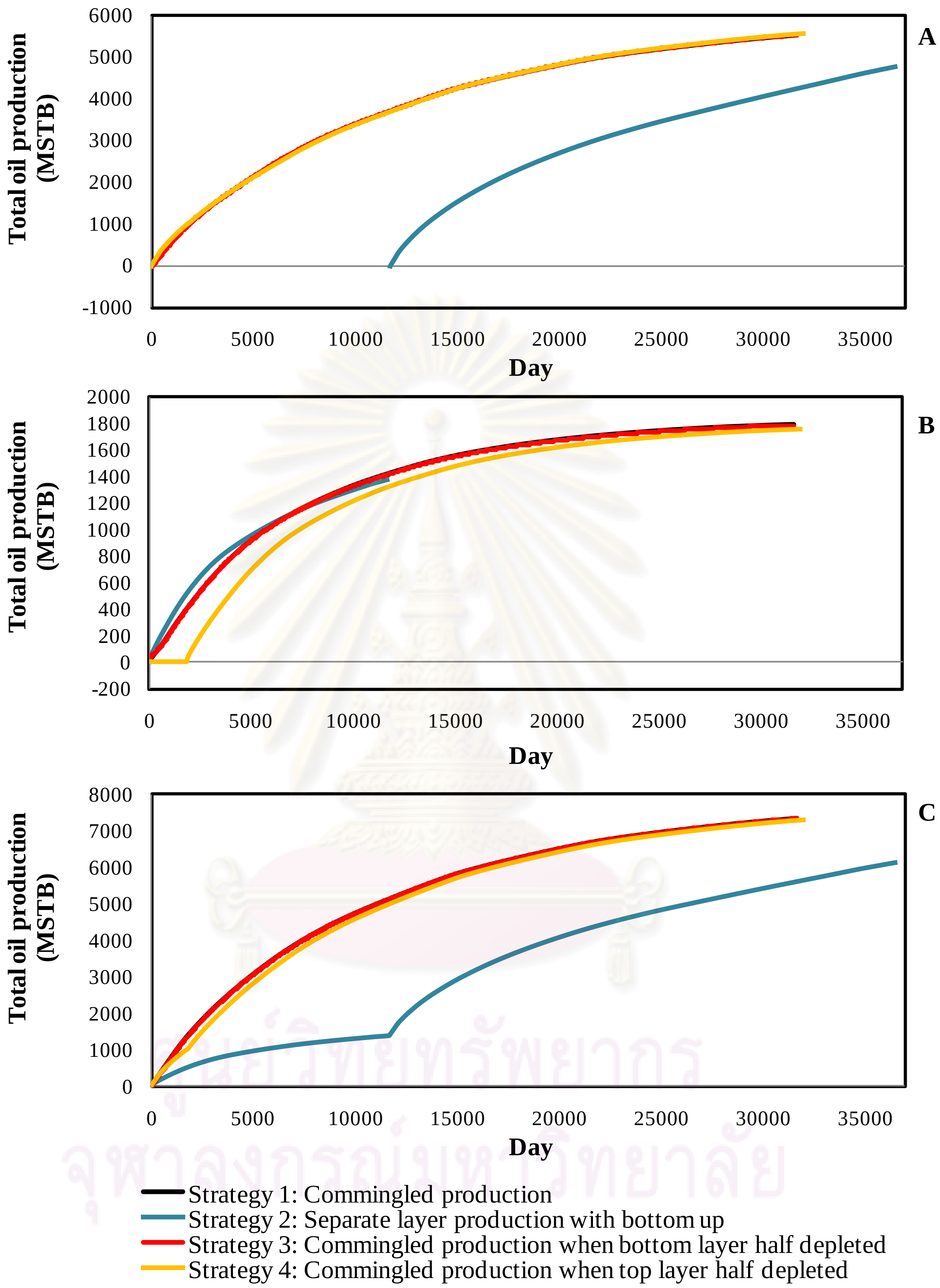

Figure 5.99: Total oil production of Case 15: O&W – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

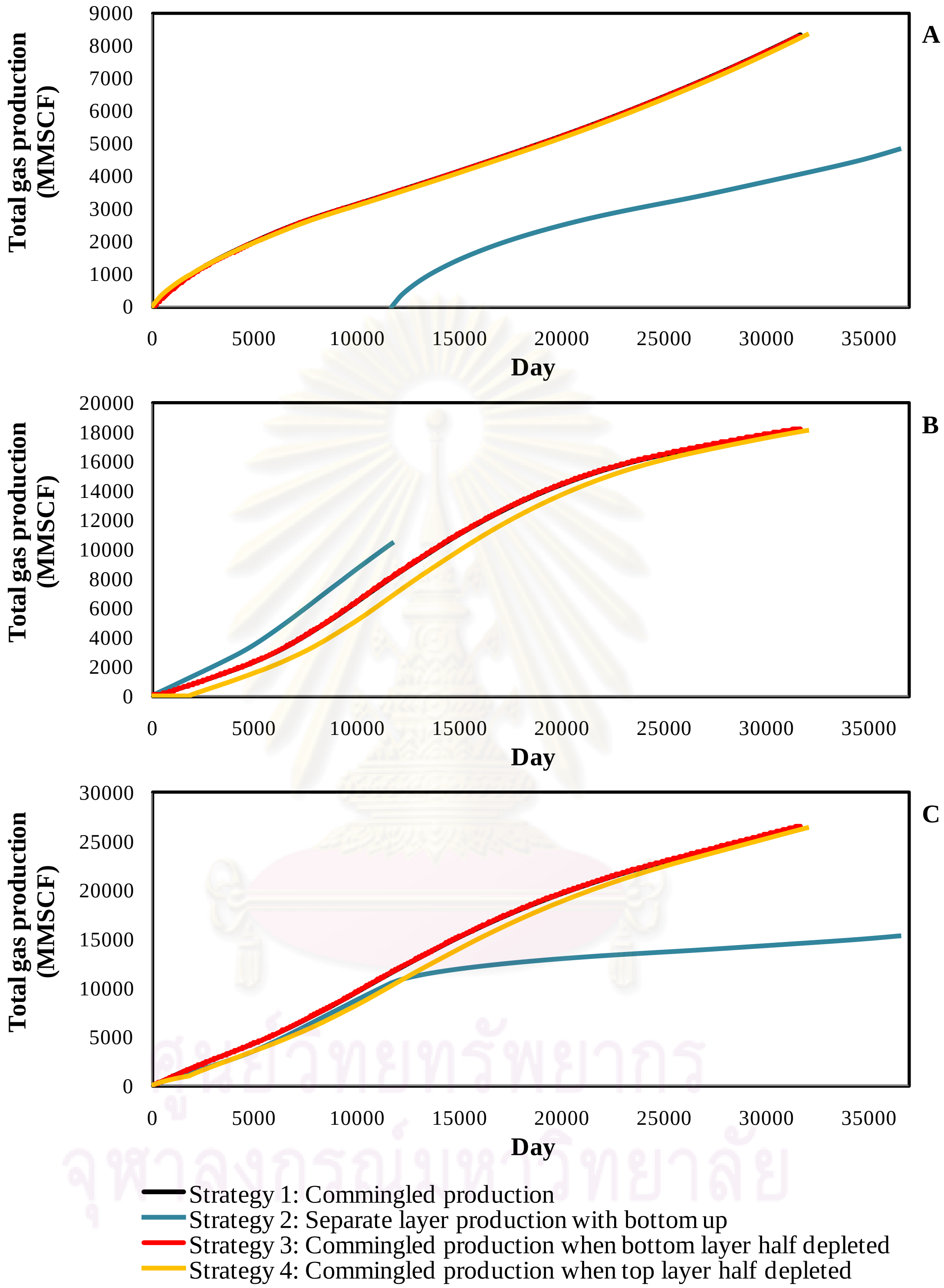

Figure 5.100: Total gas production of Case 15: O&W – G&O&W at (A) the top layer, (B) the bottom layer and (C) both layers

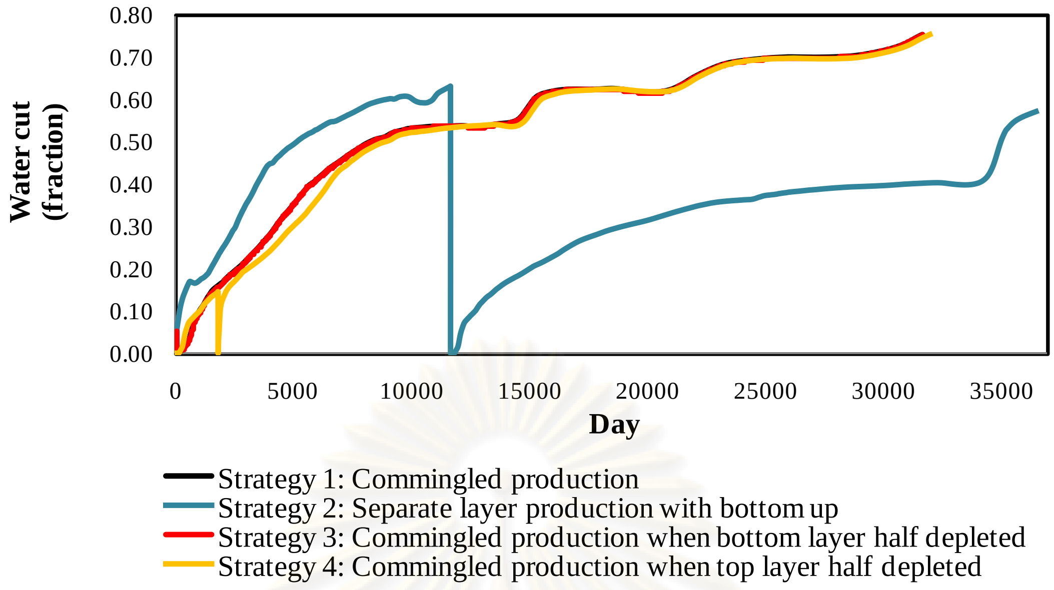

Figure 5.101: Water Cut of Case 15: O&W – G&O&W

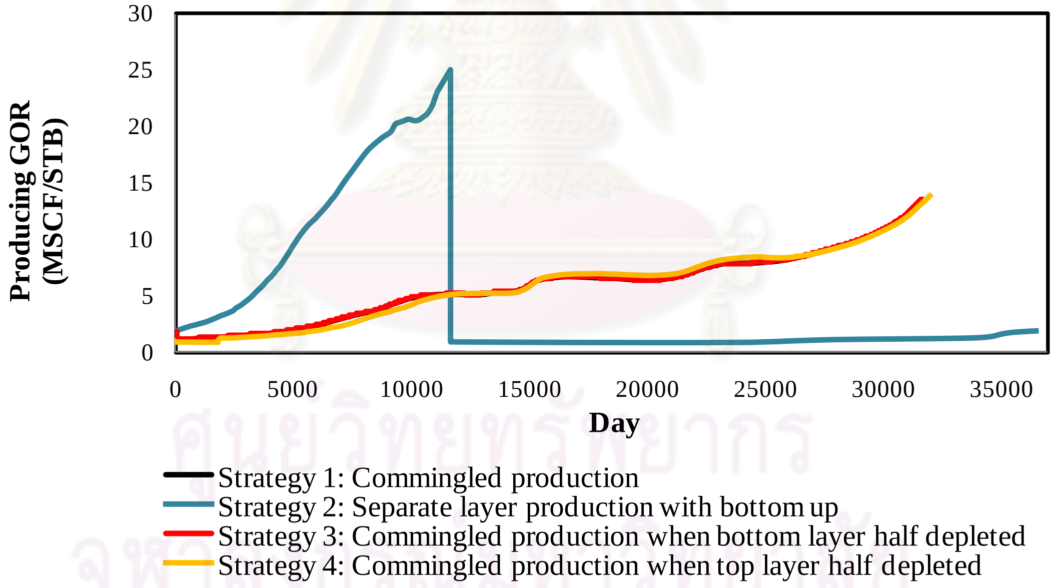

Figure 5.102: Producing GOR of Case 15: O&W – G&O&W

CHAPTER VI

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The different production strategies used in the study in order to achieve the highest ultimate recovery give some clues of which strategies stand out for the highest oil and gas recovery. The results obtained indicated that no single strategy appears to consistently deliver the highest ultimate hydrocarbon recovery.

Excellent strategy for each case is summarized in Table 6.1.

Table 6.1: Excellent strategy for each case

Case	Best strategy for oil production	Best strategy for gas production	Best strategy in term of BOE
Case 1: G – O	2	4	2
Case 2: G – G&O	2	4	4
Case 3: O – G&O	1 and 3	1 and 3	1 and 3
Case 4: O – O&W	3	3	3
Case 5: G – G&W	N/A	1	N/A
Case 6: G – O&W	2	2	2
Case 7: O – G&W	1 and 4	4	4
Case 8: G – G&O&W	1 and 3	1, 3 and 4	1 and 3
Case 9: O – G&O&W	1 and 3	1 and 3	1 and 3
Case 10: G&O – G&W	1 and 4	1 and 4	1 and 4
Case 11: G&O – O&W	3	3	3
Case 12: G&W – O&W	2 and 3	2 and 3	2
Case 13: G&O – G&O&W	1 and 3	1 and,3	1 and 3
Case 14: G&W – G&O&W	1, 2 and 3	2	2
Case 15: O&W – G&O&W	1 and 3	1 and 3	1 and 3

We attempt to group the cases which have similar configuration of fluid and similar results. As a result, a guideline for production strategy selection is presented in this chapter in order to maximize the ultimate recovery of hydrocarbon. Excellent strategy for different conditions of multilayer reservoirs is described as follows:

6.1.1 Two-layered reservoirs with oil present in both the top and bottom layers with *a gas cap* in the bottom layer

When multilayer reservoirs have oil present in both the top and bottom layers with a gas cap presents in the bottom layer, i.e., case 3: O – G&O, case 9: O – G&O&W, case 13: G&O – G&O&W, and case 15: O&W – G&O&W, the excellent production strategies are strategies 1 and 3. The major reason is that oil reservoir from both layer are produced simultaneously. Therefore, the oil producing rate is contributed from both layers. As a result of low oil production rate from each individual layer, we can prevent the flow of gas in the oil zone as well as early water loading, resulting in an increase in ultimate oil recovery.

Since the difference in recovery factor between the two strategies is not much. Therefore, strategy 1 may be more attractive since only one batch of perforation is needed while strategy 3 needs two perforation runs.

6.1.2 Two-layered reservoirs with oil present in both the top and bottom layers with *an aquifer* in the bottom layer

When multilayer reservoirs have oil present in both the top and bottom layers with an aquifer at the bottom layer, i.e., case 4: O – O&W and case 11: G&O – O&W, the excellent production strategy is strategy 3. This is because strategy 3 produces oil from a water-drive reservoir at the bottom layer separately. During this period, the reservoir can take more advantage from water-drive mechanism which is the best one to maximize the oil recovery.

6.1.3 Two-layered reservoirs with gas present in the top layer and oil present in the bottom layer

When multilayer reservoirs have gas present in the top layer and oil present in the bottom layer, i.e., case 1: G – O, case 2: G – G&O, case 6: G – O&W, case 12: G&W – O&W, and case 14: G&W – G&O&W, the excellent production strategy is strategy 2. The major reason is that no crossflow takes place between the two layers since gas and oil reservoirs have a large difference in pressure drawdown when we produce two layers simultaneously.

There is an acceptation for case 8: G – G&O&W which has gas present in the top layer and oil present in the bottom layer, but the excellent production strategies are strategies 1and 3. Although no crossflow takes place for strategy 2, but this strategy does not deliver the best performance because the reservoir is produced one layer at a time. Hence, less energy support due to separate production may be the possible reason.

6.1.4 Two-layered reservoirs with oil present in the top layer and gas present in the bottom layer

When multilayer reservoirs have oil present in the top layer and gas present in the bottom layer, i.e., case 7: O – G&W, and case 10: G&O – G&W, the excellent production strategies are strategies 1 and 4. These two strategies yield excellent outcomes for oil recovery since no crossflow of oil takes place between the two layers. This is because the pressure difference between the layers of these strategies is not as much since the gas reservoir is not produced separately at the early time.

Although strategy 4 delivers slightly better results than strategy 1 because water production is delayed, but strategy 1 may be more attractive since only one batch of perforation is needed while strategy 4 needs two perforation runs.

6.1.5 Two-layered reservoirs with gas present in both the top and bottom layers and *there is no oil* in the system

When multilayer reservoirs have no oil present but gas present in both the top and bottom layers, i.e., case 5: G – G&W, the excellent production strategy is strategy 1 because the bottom layer is produced in a commingled fashion with depletion-drive reservoir at the top layer. Generally, the depletion-drive mechanism is the best for gas reservoirs. Therefore, gas production from the depletion-drive reservoir induces a larger pressure drop at the bottom layer and resulting in an increase in ultimate gas recovery.

6.2 Recommendation

In this study, we investigate the impact of different production strategies on the production performance and ultimate recovery. However, the conclusions are made from simulation results which come from a hypothetical model. Since the reservoir model is assumed to be very large with dimensions of 5,000 ft x 5,000 ft and a thickness of 500 ft, the difference in performance between the strategies cannot be seen obviously since the production period is very long. Therefore, future work should reduce the size of model to get better comparative results and should perform economic analysis for different strategies.

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VITAE

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