PETROLEUM PRODUCTION EFFICIENCY IN CARBONATE ROCK BY SIMULATION MODEL

Miss Manward Kangkun

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Geotechnology

Suranaree University of Technology

Academic Year 2002

ISBN 974-533-120-1

ประสิทธิภาพการผลิตปิโตรเลียมจากหินคาร์บอเนต
โดยใช้แบบจำลองคอมพิวเตอร์

นางสาว แม้นวาด แข่งขัน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตร์มหาบัณฑิต
สาขาวิชาเทคโนโลยีธรณี
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2545

ISBN 974-533-120-1

Thesis title

PETROLEUM PRODUCTION EFFICIENCY IN CARBONATE ROCK BY SIMULATION MODEL

Suranaree University of Technology Council has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

Thesis examining committee

Chongpan Chonglakmani

....

(Chongpan Chonglakmani, Ph.D.)

Chairman

Kriangkrai Trisarn

....

(Asst. Prof. Kriangkrai Trisarn, M.Sc)

Thesis advisor and Member

....

(Jirawat Chewaroungroaj, Ph.D.)

Member

....

(Assoc. Prof. Tawit Chitsomboon, Ph.D.)

Vice Rector for Academic Affairs

V. Khompis

....

(Assoc. Prof. Vorapot Khompis, Ph.D.)

Dean of Institute of Engineering

แม้นวาด แข่งขัน: ประสิทธิภาพการผลิตปิโตรเลียมจากหินคาร์บอเนต โดยใช้แบบจำลองคอมพิวเตอร์ (PETROLEUM PRODUCTION EFFICIENCY IN CARBONATE ROCK BY SIMULATION MODEL) อาจารย์ที่ปรึกษา: ผศ. เกรียงไกร ไตรสาร, 107 หน้า.

ISBN 974-533-120-1

การศึกษาวิจัยมีวัตถุประสงค์เพื่อ วิเคราะห์และคำนวณหาประสิทธิภาพของแหล่งกักเก็บปิโตรเลียมที่เป็นหินปูน ในปัจจุบันนี้การประมาณหาประสิทธิภาพของหินปูนในภาคตะวันออกเฉียงเหนือของไทยยังไม่แม่นยำและเพียงพอสำหรับการหาปริมาณสำรองที่แท้จริงยิ่งไปกว่านั้นข้อมูลจากผู้รับสัมปทานมีจำกัดและเป็นความลับ ไม่สามารถเปิดเผยได้ดังนั้นจึงมีความจำเป็นที่จะศึกษาถึงการกระจายตัวของข้อมูลความพรุนและความซึมผ่านได้ของหินปูน โดยใช้โปรแกรมคอมพิวเตอร์ที่ใช้ในการนี้โดยเฉพาะกระบวนการในการศึกษามีขั้นตอนดังต่อไปนี้ 1)ประมวลผลข้อมูลความพรุนและความซึมผ่านได้จากข้อมูลของผู้รับสัมปทาน 2)วิเคราะห์ข้อมูลหลุมเจาะเพื่อนำมาประกอบในการศึกษา 3)เก็บตัวอย่างหินปูนประมาณ 18 ตัวอย่าง เพื่อนำไปวัดค่าความพรุน (Porosity) และค่าความซึมผ่านได้(Permeability) ที่ห้องทดลอง 4)สร้างแบบจำลองที่มีขนาดประมาณ 3.1x6.2x0.2 ลูกบาศก์กิโลเมตรประกอบด้วยชั้นทั้งหมด 10 ชั้น แต่ละชั้นมี 200 เซลล์ 5)ประยุกต์และบ่งชี้ค่า ความดัน ความอิ่มตัวของน้ำ ค่าสัมประสิทธิ์ประสิทธิภาพการผลิต ค่าความพรุน และค่าความซึมผ่านได้ในแบบจำลอง 6)ประมวลผลจากแบบจำลองเพื่อตรวจสอบค่าตัวแปร กำหนดและปรับค่าต่างๆ เพื่อทำ History matching ผลการศึกษาแหล่งก๊าซธรรมชาติที่จะค้นพบในภาคตะวันออกเฉียงเหนือมีปริมาณก๊าซ 225 พันล้านลูกบาศก์ฟุต ผลการวิเคราะห์ทางเศรษฐกิจมีอัตราเสี่ยงในการลงทุนร้อยละสิบ เมื่อพบแล้วมีการพัฒนาแหล่งก๊าซธรรมชาติแหล่งนี้จะสามารถผลิตก๊าซได้นาน 20 ปี อัตราการคืนทุนร้อยละ 20 ผลการทำแบบจำลองคอมพิวเตอร์ (Reservoir simulation) แหล่งก๊าซจะผลิตอัตราเริ่มต้นประมาณ 90 ล้านลูกบาศก์ฟุตต่อวัน ผลิตถึง 2 ปี อัตราการผลิตลดลงปีละ ประมาณร้อยละ16 จนถึงปีที่ 20 จึงหยุดผลิต ประโยชน์ที่ได้รับจากการศึกษาครั้งนี้เพื่อนำไปปรับปรุงความรู้ในการทำแบบจำลอง รวมถึงความสามารถในการใช้โปรแกรมละมุนภัณฑ์ในการประเมินศักย ภาพการผลิตปิโตรเลียมในภาคตะวันออกเฉียงเหนือของไทย

สาขาวิชาเทคโนโลยีธรณี	ลายมือชื่อนักศึกษา...
ปีการศึกษา 2545	ลายมือชื่ออาจารย์ที่ปรึกษา.......................................

MANWARD KANGKUN: PETROLEUM PRODUCTION EFFICIENCY IN CARBONATE ROCK BY SIMULATION MODEL

THESIS ADVISOR: ASST.PROF. KRIANGKRAI TRISARN, M.S. 107 PP.

ISBN 974-533-120-1

CARBONATE ROCK/POROSITY/PERMEABILITY/SIMULATION MODEL

The objective of the research is to analyze and to estimate the petroleum production efficiency in carbonate rock reservoir. At present, the estimation of petroleum production efficiency in carbonate rock of northeastern Thailand is not accurate and sufficient enough including its actual reserve. The data from the concessionaire is limited and confidential. Therefore, it is necessary to study the porosity and permeability distribution of carbonate rock by using computer software specifically, the reservoir simulation model. The methodologies for this study are as follows: 1) to compile the porosity and permeability data from the concessionaire results, the technical, and research papers, 2) to analyze the well data using in this study, 3) to collect the carbonate rock sample about 18 samples and measure their porosity and permeability values at the laboratory, 4) to create the simulation model by reproducing model size approximately 3.1x6.2x0.2 km^3 composing of 10 layers with 200 cells for each layer, 5) to apply and identify pressure, water saturation, recovery factor, formation volume factor, porosity and permeability in each cell of simulation model, 6) to run the simulation model for checking all parameters and adjusting them for history matching. The result of this study is 225 BCF of gas reserve. The economic analysis result is 10% investment risk with 20% interest rate of return. The developed reservoir is produced gas along 20 years starting with 92 MMCF/D of the production rate and declining at 16% per year until 20th year that gas production ceased. The benefit of this study will improve the knowledge of reservoir simulation model including the ability to use the software for approximating the efficiency of petroleum production in the northeastern Thailand.

สาขาวิชาเทคโนโลยีธรณี	ลายมือชื่อนักศึกษา..
ปีการศึกษา 2545	ลายมือชื่ออาจารย์ที่ปรึกษา......................................

Acknowledgements

The author would like to express appreciation to her thesis committee members, Dr. Chongpan Chonglakmani, Mr. Kriangkrai Trisarn and Dr. Jirawat Chewaroungroaj.

Grateful acknowledgements are extended to The Exxonmobil Exploration and Production Khorat Inc. and Department of Mineral Resources of Thailand (DMR) for the permission to study the confidential data.

Special acknowledgements are due to Mr. Somchai Phumim and his staffs for their assistance and valuable suggestions.

The author is particularly indebted to her thesis advisor, Mr. Kriangkrai Trisarn who assisted in the selection of her thesis topics, effectively and patiently steered her to the right path and Miss Siree Nasakul who directed, taught and made many helpful suggestion in Black Oil Simulation of Petroleum WorkBench program.

The author would also like to thank Miss Supharaporn Sakulphakdee for laboratory guidance, Mr. Varodome Ratchanekhornkrilat who gave technical help in sample preparation and supported the laboratory testing and Mr. Komsan Taisup and Mr. Prasittichai Damnoentitikij who are the consultant of the Auto CAD program.

Finally, sincerest thanks to her family, for encouragement, patience and understanding they rendered throughout this undertaking.

Miss Manward Kangkun

TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS (Continued)

PAGE

TABLE OF CONTENTS (Continued)

PAGE

LIST OF TABLES

TABLE **PAGE**

LIST OF FIGURES

FIGURE **PAGE**

LIST OF FIGURES (Continued)

FIGURE **PAGE**

LIST OF FIGURES (Continued)

FIGURE **PAGE**

LIST OF ABBREVIATIONS

A	=	Annual cash flow
A or A_x	=	Cross sectional area of plug
Atm / sec	=	Atmosphere per second
B	=	Barrel
BCF	=	Billion cubic feet
BHP	=	Bottom hole pressure
BP	=	Barometric pressure in the atmosphere unit
BPD	=	Barrel per day
BTU	=	British thermal unit
BV	=	Bulk volume
B_g	=	Gas formation volume factor
B_o	=	Oil formation volume factor
B_w	=	Water formation volume factor
B_1, B_2	=	Collections of terms that include saturation, PVT terms and production terms
B_1^n	=	Collections of terms that include saturation, PVT terms and production terms at level n
B_2^{n+1}	=	Collections of terms that include saturation, PVT terms and production terms at level n+1
CAPEX	=	Capital cost
cp	=	Centipoise
C	=	Isothermal compressibility factor = negative annual cash flow value
$^{\circ}C$	=	Degree in Celsius unit
D	=	Diameter
D	=	Day
ESCAL	=	Escalation

Fac.	=	Facility		
GD	=	Grain density		
Gth	=	Gross thickness		
GOR	=	Gas oil ratio		
GV	=	Grain volume		
h	=	Height		
HTOP	=	High of top structure		
I	=	Assumed value		
i	=	Discount rate		
Inc.Tax	=	Income tax		
IRR	=	Internal rate of return		
K_{gas}	=	Overburden permeability		
k_g	=	Gas permeability		
k_o	=	Oil permeability		
k_w	=	Water permeability		
km	=	Overburden permeability	=	Kilometer
L	=	Length		
M	=	Month		
MM	=	Million		
MMSCF / D	=	Million standard cubic feet per day		
MSL	=	Mean sea level		
m^3	=	Cubic meter		
mm	=	Millimeter		
mm^3	=	Cubic millimeter		
NPV	=	Net present value		
NTh	=	Net thickness		
n	=	Amount of year		
OPEC	=	Operating cost		

LIST OF ABBREVIATIONS (Continued)

P	=	Pressure
P^n	=	Pressure at this time step
P^{n+1}	=	Pressure at the next time step
P_b	=	Billet equilibrated pressure
P_{cg}	=	Gas capillary pressure
P_{cw}	=	Water capillary pressure
P_f	=	Chamber equilibrated pressure
P_g	=	Gas pressure
P_o	=	Oil pressure
P_{ob}	=	Reference billet equilibrated pressure
P_{of}	=	Reference chamber pressure
P_{os}	=	Reference chamber with helium pressure
P_s	=	Chamber with helium equilibrated pressure
P_w	=	Water pressure
P_1	=	Upstream pressure
Psi	=	Pound per square inch
Phi	=	Porosity
PIR	=	Profit to investment ratio
PV	=	Pore volume
Q	=	Flow rate
q_g	=	Gas rate
r	=	Radius
RHS_i	=	Result of the multiplication equation on the left hand side
SCF	=	Standard cubic foot
sq.km	=	Square-kilometer
S_g	=	Gas saturation
S_o	=	Oil saturation
S_w	=	Water saturation

LIST OF ABBREVIATIONS (Continued)

t	=	Time
T	=	Temperature
US$	=	United State dollar
Re v	=	Revenue
RV	=	Reference volume
R_{so}	=	Oil saturation resistivity
R_{sw}	=	Water saturation resistivity
V	=	Velocity
V_{bil}	=	Volume of billet removed
V_{bil}^{2}	=	Volume of billets
Δx	=	Distance in x-direction
Δy	=	Distance in y-direction
Δz	=	Distance in z-direction
%	=	Percent
π	=	Constant value equal to 3.1416
Φ_g, Φ_o, Φ_w	=	Flux or phase potential of gas, oil and water
ϕ	=	Porosity
ϕ_g	=	Gas porosity
ϕ_o	=	Oil porosity
ϕ_w	=	Water porosity
ρ_g	=	Gas density
ρ_o	=	Oil density
ρ_w	=	Water density
λ_g	=	Gas mobility
λ_o	=	Oil mobility
λ_w	=	Water mobility
μ_{air} or μ_{N2}	=	Gas viscosity which varies with temperature

LIST OF ABBREVIATIONS (Continued)

μ_g	=	Gas viscosity
μ_o	=	Oil viscosity
μ_w	=	Water viscosity
υ	=	Velocity

CHAPTER 1

INTRODUCTION

1.1 Problem and rationale

The petroleum energy is the most important factor for economic development in developing the country. The exploration and development of the petroleum reservoirs in Thailand are successful moderately. Now, we can produce petroleum up to 40% of petroleum consumption in our country. We can reduce the petroleum import from abroad. We can form the stability of the energy supply for the economic and social development of our country. Future oil and gas production in the country is depended upon reservoir characterization technologies and reservoir simulation. Intense computer simulation is essential for effective reservoir management. The reservoir management is to determine the optimum conditions needed to maximize the economic recovery of hydrocarbons from a prudently operated field (John, 1997). The petroleum reservoir simulation is an important component in the development of more efficient techniques in oil recovery. Current simulators, used routinely in industry, are fundamentally limited in the size and complexity of the problems that they can handle (Borns, 2001). Significant advances in data and the detailed description of the gas reservoirs are essential in simulation. Ideally, all available information describing reservoir heterogeneity and a large number of important fluid and rock properties should be used in the simulators.

On the other hand, the exploration and development of the petroleum reservoirs in the northeast Thailand are still not successful enough. According to only one gas field is discovered and produced in the northeastern at Amphoe Nam Phong, Khon Kean province (Assavarittiprom, 1995) comparing this reservoir with many other structures that distribute in overall area of the northeastern. There are fewer reservoirs. The most reservoirs in the northeastern are located in carbonate rock (Prадidtan, 1995). It is not obviously in understanding about porosity and permeability of the carbonate rock, so that we cannot estimate the production efficiency closely with the actual performance. Furthermore the analytical data of ESSO who is the concessionaire of gas reservoir is limited and confidential.

1.2 Research objectives

Study, experiment and analyze carbonate rock to find porosity, permeability, reserve and production efficiency of Permian carbonate rock in the northeastern of Thailand. Compare the results between the experiment calculation and computer simulation.

1.3 Scope and limitations of the study

The scope and limitations is regulated on the rock formation in areas of the exposed outcrops and drilled cores by concessionaire in the northeastern Thailand. The reservoir simulation is done and limited at the data availability and some reasonable assumption.

1.4 Expected results

a. The results of the study is the ability to calculate gas in place, reserve, production rate, production efficiency from the discovered gas reservoirs and other reservoirs that are carbonate reservoirs in the northeastern of Thailand.

b. The results of laboratory are

1) The average porosity is 3% in limestone and 4% in dolomite.

2) The average permeability is less than 2 mD.

c. The results of simulation are

1) The gas production wells are 5.

2) The total gas production rate of five wells is started at 85-95 MMSCF/D and produced with constant rate along 2-4 years. Total gas production rate is declined at 4th year at declined rate about 15-20% per year until the end of the production at the 20th year.

3) The final production gas rate at the last production year is 5 MMSCF/D.

d. The results of economic evaluation are

1) Internal rate of return should be more than the discounted factor at the time being (more than 7.25%).

2) Profit investment ratio is in the range of 0.8-1.

3) Payback period will be at the 2nd or 3rd year of production.

1.5 The benefits of the study

a. The data is useful in planning to predict and discover the energy resource for industrial and economic development in the northeastern Thailand.

b. Experiences in term of programming application, simulation model, testing, including equipment in laboratory and software utilization.

c. Earning the experience in developing the simulation model, testing apparatus in laboratory and software computer.

d. Knowing how to do reservoir description.

e. Getting more details in the reservoir properties.

1.6 Methodology

a. Collect the data relevant to the characteristics of carbonate rock that had been studied, experimented and researched.

b. Collect data concerning the results of petroleum exploration and petroleum production in the northeastern Thailand.

c. Analyze the data for using in this study.

d. Collect rock samples, about 18-20 specimens, from Saraburi, Phetchabun and Lopburi provinces.

e. Analyze porosity and permeability of rock samples are analyzed from laboratory.

f. Compile the porosity and permeability data from the concessionaire results and the research papers.

g. Create the simulation model by reducing model size approximately 3.1x6.2x0.2 km^3 composing of 10 layers with 200 cells for each layer.

h. Apply pressure, water saturation, recovery factor, formation volume factor, porosity and permeability and identify in each cell of simulation model (Henry, 1997).

i. Run the simulation model for checking all parameters and adjusting them for history matching.

j. Calculate the internal rate of return from cash flow table by using 1 exploration well, 3 appraisal wells and 2 development wells.

k. Evaluate, conclude and write the final report in the last step of the methodology.

CHAPTER 2

LITERATURE REVIEW

2.1 Reservoir efficiency determination by using the tank model.

Reservoir efficiency determination by using the tank model is written by Mr. Kriangkrai Trisarn (Kriangkri, 1987). The method uses the simulation model to determine the energy production and predict the production rate of wells at the interested area in the northeastern of Thailand. The well model has 2 km^2 and 1 $mile^2$ in drainage area. His model assumption is beginning with production rate equal to 22 MMSCF/D and 25 MMSCF/D. The results of simulation run are 63 BCF and 70 BCF of gas production with the constant rate along 8.4 years and 8.2 years. The rate will decline until 20^{th} year of production. The flow rates are 2.8 and 5.1 MMSCF/D. Gas in places are 123 and 158 BCF and total gas productions are 105 and 128 BCF. Mathematics of each well is constructed based on actual data and relationship of equations by using the computer to calculate the production capacity of each well. The drainage areas are 640 acre and 2979 feet in radius. The characteristic of formation and gas quantity can be determined by using exploration and well test data.

Mr. Kriangkrai Trisarn uses the tank model to calculate the efficiency by using the model simulation in state of radial flow. Radial model of Mr. Kriangkrai Trisarn was based on the geologic interpretations and the buildup analysis. Simulation method differs from his study in term of flow regime which is linear flow from cells to cells. The model is based on FASPU program that has different variation in verifying the efficiency and potential of the model and resulted the most likely gas in place of 255 BCF. This study starts with total gas production rate at 92 MMSCF/D of five wells. The reserve of simulation run is 225 BCF and gas in place is 250 BCF.

2.2 Improved oil recovery in carbonate reservoirs

The project of improved oil recovery in Mississippian carbonate reservoirs of Kansas is written by Bhattacharya, S., et al of the University of Kansas center for research Inc. The project target improves the reservoir performance of mature oil fields located in shallow shelf carbonate reservoirs (Bhattacharya, S., 1999). The focus of this project is development and demonstration of cost-effective reservoir description and management technologies to extend the economic life of mature reservoirs in Kansas and the mid-continent. The project introduced a number of potentially useful technologies, and demonstrated these technologies in actual oil field operations. Included in this report is a summary of significant project results at the demonstration site (Schaben Field, Ness County, Kansas). The value of cost-effective techniques for reservoir characterization and simulation at Schaben Field were demonstrated to independent operators. At the Schaben demonstration site, the additional locations resulted in incremental production increases of 200 BOPD from a smaller number of wells. In Kansas, the majority of Mississippian production occurs at or near the top just below a regional unconformity. Production from Mississippian reservoirs accounts for approximately 43% of total annual production, and cumulative production exceeds 1 billion barrels. The objective of project was to characterize and simulate a typical oil field producing from a Mississippian reservoir by using tools that are modern and cost-effective for small independent producers operating mature fields. General application of PC-based simulators such as BOAST3 to large-scale or full-field simulation has been restricted by hardware and software limitations. Integrated reservoir characterization forms the foundation for the development of a descriptive reservoir model and provides the framework for simulation. The descriptive reservoir model integrated existing and newly acquired well. Simulation input parameters were generated from the reservoir model and used to simulate the reservoir performance of the Schaben field from discovery to 1996. The reservoir model is composed of dolomite, packstone and wackstone. Analysis of the reservoir performance and the distribution of the remaining mobile oil in place led to the identification of regions with potential for incremental oil recovery. The simulator was used to predict the performance of potential infill wells drilled in these areas. It is hoped that this study will provide a model for improving field management of similar reservoirs in Kansas and in the mid-continent. The major premise of this simulation study was to enter eleven years of historical data and have the simulator predict and match the next 23 years of known field production data. At the field level, a good match between simulated and observed was obtained for both oil and water production rates during the 34 years encompassed by the historical and predictive periods.

The project of improved oil recovery in carbonate reservoir in Mississippian carbonate reservoirs of Kansas differs from this study. The project is simulated on oil reservoir but this study is simulated on gas reservoir. The model of the project is composed of dolomite, packstone and wackstone but this study is composed of limestone and dolomite. The simulator was used in the project is BOAST3. The Work Bench is the software program being used as simulator in this study.

CHAPTER 3

LABORATORY EXPERIMENT

3.1 Objective

The objective is to determine porosity and permeability of specimens. Porosity is determined by using the porosimeter. Permeability is determined from the overburden poro-perm cell instrument.

3.2 Sample collection

Eighteen rock samples had been collected randomly from many fields where the prospect areas are such as Saraburi, Lopburi and Phetchabun provinces. Most of interested carbonate rocks in the areas occur in Permian era. Limestone samples were collected from Saraburi, Phetchabun provinces and khao Somposhn. Dolomite samples were collected from the area near khao Somposhn.

3.3 Sample preparation

The samples had been prepared into a proper size by using coring machine that is shown in Figure 3.1. The coring samples are called specimens. The shape of specimen is cylinder. The specimen size is two inches (51.17 millimeters) in length and one and a half inches (38.55 millimeters) in diameter. The specimens were heated in the oven with low temperature about 50-60 ^{0}C along 24 hours or until they were dried. The examples of specimen are shown in Figure 3.2.

3.4 Porosity measurement

The porosimeter is the instrument for identifying the porosity of specimen. The porosimeter is shown in Figure 3.3. Porosity in clean and dried specimens is determined by a combination of three physical properties that are grain volume, bulk volume and pore volume. Grain volume can be determined from helium injection by passing helium through the specimen.

Figure 3.1 Coring Machine is the instrument that used for drilling the rock samples with cylinder shape.

Figure 3.2 The specimen shape is cylinder. The specimen size is two inches long and one and a half inches diameter.

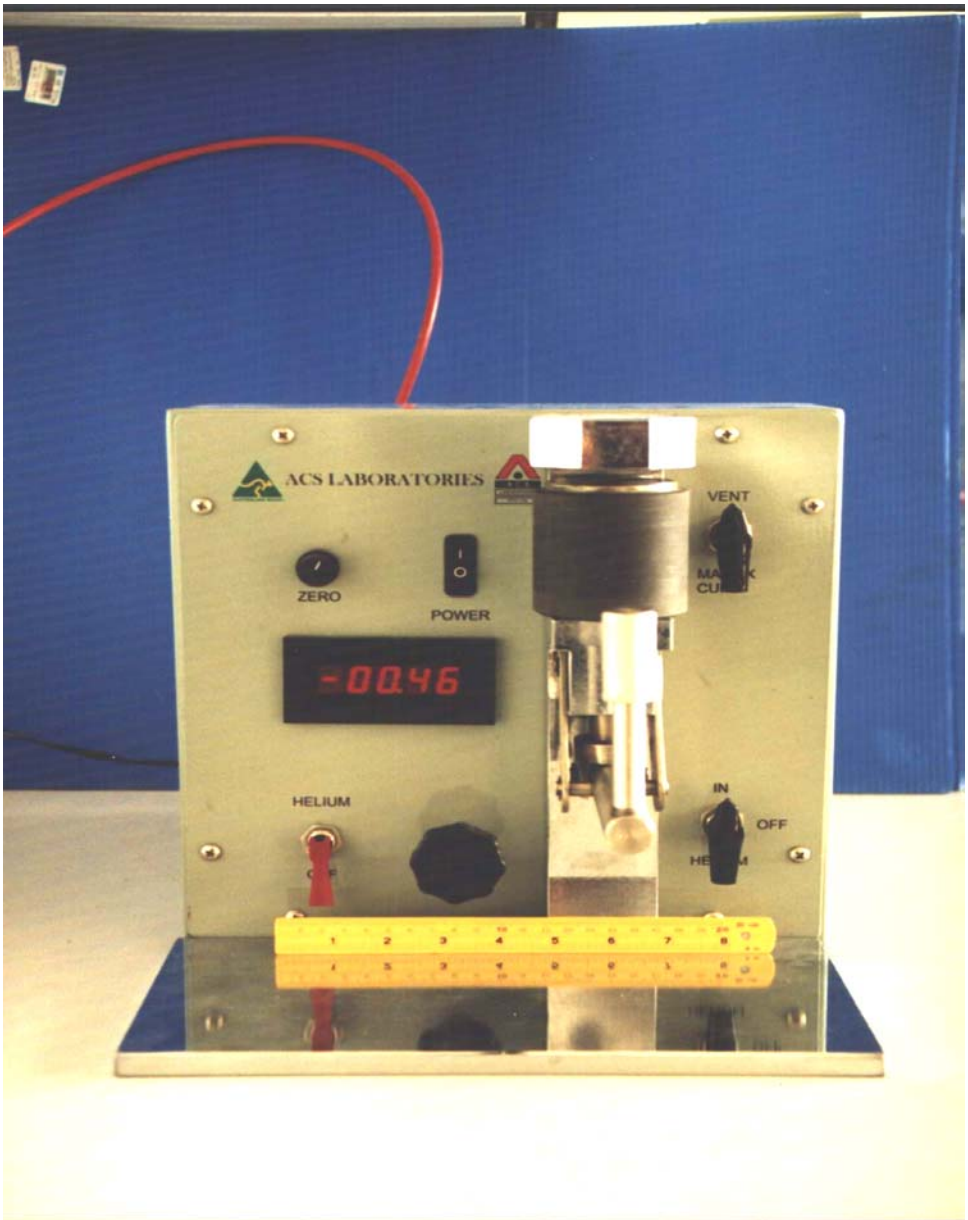


Figure 3.3 The porosimeter instrument is used for measuring the porosity of the specimens.

Helium is an inert gas. The small molecular size of helium allows it to penetrate micro-pores more readily than other gases. Helium does not react with, nor does the specimen absorb it. It does not affect the instrument. It is suitable for using in the test. The specimen has inserted to the schematic cell. The relationship of reference pressure, billet pressure, billet volume and specimen volume are received after injecting helium to the schematic cell. It is used for determining grain volume. Bulk volume is calculated from the relationship between length and diameter of the specimen. Pore volume is the different value of bulk volume and grain volume. Porosity is the ratio of pore volume to bulk volume. Porosity unit is in percentage.

The processes of porosimeter operation

a. The helium gas connection is supplied to the port at the rear of the instrument.

b. The instrument should be set up in a constant temperature environment. The pressure transducer should be calibrated and equipment leak checked on set up and checked periodically after that.

c. The electronic is turned on and allowed to warm up (5-10 minutes).

d. The digital readout set to be zero.

e. The helium position is pointed to “off” position and the top value in “vent” position. The zero potentiometer is adjusted to a point where the digital readout reads 0.00.

f. The helium supply at the botton of the porosimeter is turned on (red toggle value).

g. Pressuring up and down several times warms up the transducer.

h. The reference volume of the reference chamber (RV) is determined by following steps this:

1) The matrix cup with billets and seal of the cup is filled into the porosimeter. The matrix cup must be the same position for each reading (for reference and grain volume measurements) to ensure that there is no change in volume.

2) The reference chamber with helium is filled to 100.00 psig. The reference pressure always uses 100.00 psig. The pressure is record as P_{of}.

3) The reference chamber is opened to the sample chamber. The equilibrated pressure is recorded as P_f.

4) The appropriate billet is removed from the sample chamber. The volume of the billet removed should be approximately equal to the pore volume of the samples being tested

(typically billet 1 for porous carbonate rock). The volume of the billet removed is recorded as V_{bil} (cm^3). The billets are shown in the figure 3.4.

5) The step 2) and 3) are repeated. The reference chamber pressure and the equilibrated pressure of the sample chamber are recorded as P_b .

6) Repeat steps 2) and 3), however, this time records the reference chamber pressure as P_{ob} . These pressure measurements are repeated until three consecutive identical readings are obtained. The RV is obtained at the start of each sample run and then at 18 sample intervals. Reference volume calculations is follow this:

$$RV = \frac{V_{bil}}{\frac{P_{ob}}{P_b} - \frac{P_{of}}{P_f}} \tag{3.1}$$

or if P_{ob} and P_{of} = 100.00 psi

$$RV = \frac{P_b V_{bil}\left(\frac{P_f}{100}\right)}{P_f - P_b} \tag{3.2}$$

i. Grain volume (GV) is determined by following this:

1) The clean and dried core sample is placed in the matrix cup. If the sample is short, then fill the excess space with a billet(s). The identification number of the billets that left out of the cup is recorded. The volume of these billets ($V_{bil}{}^2$) is used in the calculation and found in matrix cup billet volumes that shown in Table 3.1. The cup is sealed atmospheric conditions and is isolated from the atmosphere.

2) The reference chamber with helium is filled 100.00 psig. The pressure is record as P_{os} .

3) The helium is introduced into the matrix cup and the pressure is allowed to stabilize. The stabilized pressure is recorded as P_s .

4) Through knowledge of the previously determined RV. The P_s is used to calculate the grain volume.

$$GV = V_{bil}{}^2 + RV\left(\frac{P_{of}}{P_f} - \frac{P_{os}}{P_s}\right) \tag{3.3}$$

j. Sample weight is determined by using the weight balance for measuring the dry weight of specimens. The sample is weighed to 2 decimal places.

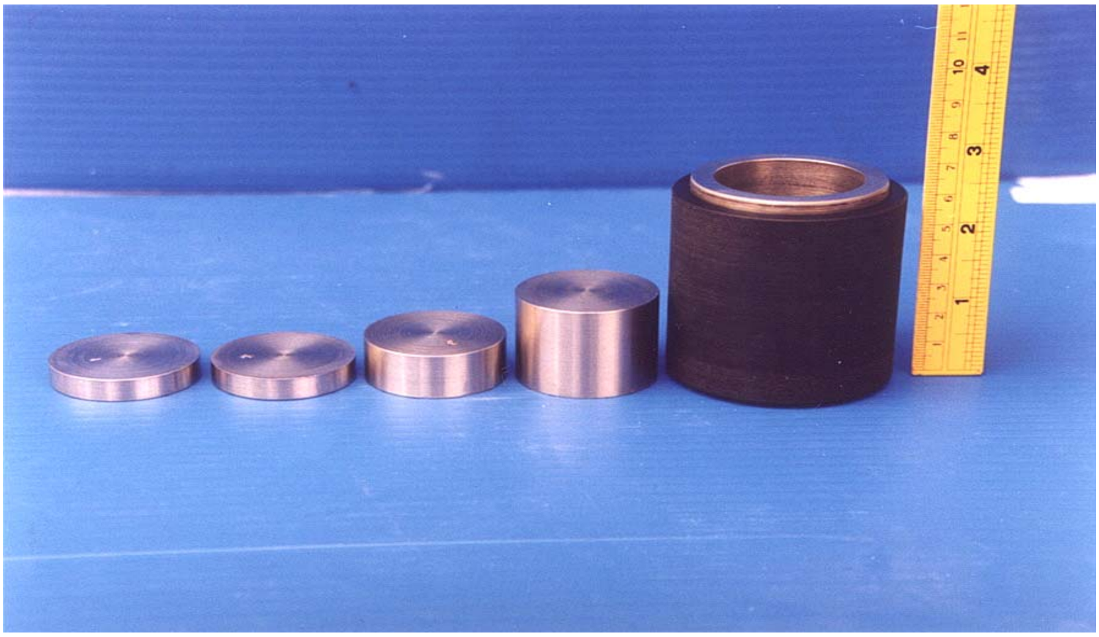


Figure 3.4 Billets are put in the chamber. When testing the specimen, specimen is put into the chamber then billet number 1 is filled up in the chamber. Billet number 1 is the representation of the pore volume of carbonate rock.

Table 3.1 The volumes of the matrix cup billets that are used with the porosimeter. The volume of the billet removed should be approximately equal to the pore volume of the samples test.

1" Billets	Billet Number	Volume (cm^3)
	1	4.63
	2	4.59
	3	9.22
	4	18.49
1 1/2 " Billets	Billet Number	Volume (cm^3)
	1	10.18
	2	10.2
	3	20.39
	4	40.74

k. Bulk volume (BV) is calculated from the relationship of length and diameter as follows;

$$BV = \pi L \left(\frac{D}{2} \right)^2 \tag{3.4}$$

l. Pore volume determination

$$PV = BV - GV \tag{3.5}$$

m. Porosity

$$\phi\% = \frac{PV}{BV} \times 100 \tag{3.6}$$

The porosity results that were calculated by using the parameters from porosimeter instrument are shown in the Table 3.2.

3.5 Permeability measurement

The overburden poro-perm cell is the instrument for testing the specimens to find permeability. The overburden poro-perm cell is shown in Figure 3.5. The overburden poro-perm cell has been designed to perform porosity and permeability measurements on specimens under simulated reservoir overburden conditions. It uses an air actuated hydraulic pump to achieve a simulated reservoir confining pressure on the specimen.

The permeability determination of specimen is used air (or nitrogen) which specified initial pressure (upstream pressure) let flow through the length of specimen. The specimen is sealed along its length so that no air can leak from the specimen. The flow rate of air from the other end of specimen is measured. The permeability of the sample is calculated by using the upstream pressure and flow rate during the test, the atmospheric pressure, viscosity of air and the length and cross sectional area of specimen. The relationship of time, viscosity, flow rate and cross sectional area are used for determining permeability. This study uses the overburden poro- perm cell for testing specimens to find only permeability. Permeability is the indicator of the ability of a porous medium to transmit fluids. The measurement of permeability of a porous rock is a measurement of the fluid conductivity of the particular material. Measuring permeability is expressed in mD.

The overburden poro-perm cell operations

a. The overburden poro - perm cell should be set up in a constant temperature environment.

Table 3.2 Porosity results are calculated by using parameters from porosimeter instrument.

Sample Number	Field Location	Rock Type	Vol. Billet Removed (mm^3)	P_f (psia)	P_b (psia)	Dry Weight (mm)	P_{os} (psia)	P_s (psia)	Volume Removed (mm^3)	Temp. (^oC)	Length (mm)	Diameter (mm)	RV (mm^3)	GV (mm^3)	BV (mm^3)	PV (mm^3)	ϕ (%)	GD (g/cc)
1	1	Limestone	10.18	88.74	72.57	157.29	100.00	68.97	71.33	16	51.17	38.55	40.54	58.24	59.72	2.91	4.9	2.701
2	1	Limestone	10.18	88.74	72.57	158.87	100.02	69.76	71.33	16	51.02	38.53	40.54	58.89	59.49	2.26	3.8	2.698
3	1	Limestone	10.18	88.74	72.57	158.13	100.00	69.32	71.33	16	51.00	38.50	40.54	58.54	59.37	2.61	4.4	2.701
4	1	Limestone	10.18	88.74	72.57	159.38	100.00	70.15	71.33	16	51.15	38.57	40.54	59.23	59.76	1.92	3.2	2.691
5	1	Limestone	10.18	88.74	72.57	160.76	100.01	70.75	71.33	16	51.20	38.55	40.54	59.71	59.76	1.44	2.4	2.692
6	1	Limestone	10.18	88.74	72.57	160.66	100.02	70.75	71.33	16	51.10	38.55	40.54	59.71	59.64	1.44	2.4	2.691
7	1	Limestone	10.18	88.74	72.57	159.06	100.01	69.93	71.33	16	51.65	38.63	40.54	59.04	60.54	2.11	3.5	2.694
8	1	Limestone	10.18	88.74	72.57	159.86	100.03	70.32	71.33	16	51.60	38.53	40.54	59.35	60.16	1.80	3.0	2.694
9	1	Limestone	10.18	88.74	72.57	153.57	100.02	70.01	71.33	16	51.12	38.60	40.54	59.10	59.82	2.05	3.4	2.598
10	1	Limestone	10.18	88.74	72.57	151.98	100.00	70.02	71.33	16	51.07	38.85	40.54	59.12	60.54	2.03	3.4	2.571
11	2	Dolomite	10.18	87.65	72.46	166.94	100.00	70.41	71.33	18	52.17	38.40	42.56	59.44	60.42	1.71	2.8	2.808
12	2	Dolomite	10.18	87.65	72.46	167.83	100.00	70.87	71.33	18	51.97	38.43	42.56	59.84	60.28	1.31	2.2	2.805
13	2	Dolomite	10.18	87.65	72.46	165.26	100.01	69.63	71.33	18	51.30	38.27	42.56	58.76	59.01	2.39	4.0	2.812
14	2	Dolomite	10.18	87.65	72.46	169.13	100.00	71.30	71.33	18	52.47	38.33	42.56	60.20	60.55	0.95	1.6	2.810
15	2	Dolomite	10.18	87.65	72.46	165.68	100.03	69.87	71.33	18	51.27	38.40	42.56	58.96	59.38	2.19	3.7	2.810
16	2	Dolomite	10.18	87.65	72.46	160.88	100.02	67.66	71.33	18	52.07	38.40	42.56	56.98	60.30	4.17	6.9	2.824
17	2	Dolomite	10.18	87.65	72.46	164.04	100.02	69.15	71.33	18	50.70	38.37	42.56	58.33	58.62	2.82	4.8	2.812
18	2	Dolomite	10.18	87.65	72.46	163.05	100.01	68.53	71.33	18	52.57	38.40	42.56	57.78	60.88	3.37	5.5	2.822

Remark: In the field location block, number 1 is the area of Saraburi, Phetchabun provinces and khao Somposhn. Number 2 is the area near khao Somposhn.

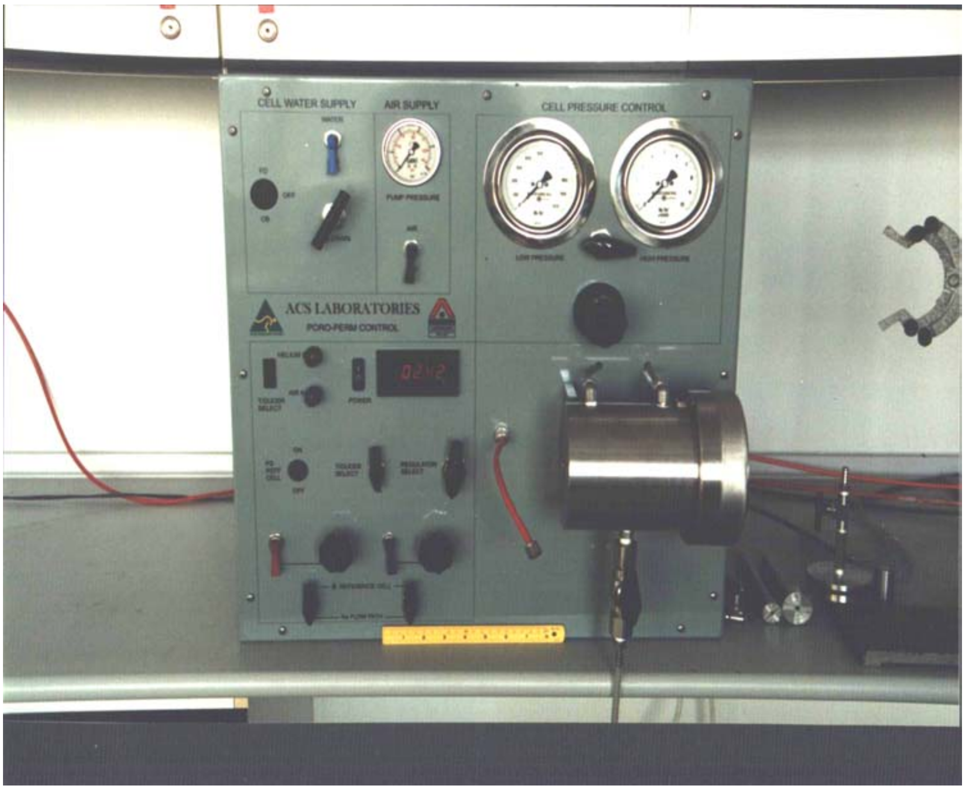


Figure 3.5 The overburden poro-perm cell instrument is used for testing the specimens to find permeability value.

The pressure transducers should be calibrated and the equipment leak checked on installation. The transducers calibration should be checked from time to time and re-calibrated as needed.

b. External helium, air and water supplies are connected to the entry ports at the rear of the instrument.

c. The water drain port is connected to an external drain line.

The sample loading and cell pressuring operations

d. The thick walled rubber sleeve places over the platen end of the down stream end piece and secure with retaining ring.

e. The right cylinder sample insert into the thick walled rubber sleeve, ensuring the sample is butted neatly up against the platen.

f. The upstream platen insert into the rubber sleeve end, ensuring the platen is butted neatly up against the sample, and secure with retaining ring.

g. The sample holder is inserted into the hydrostatic cell, to a point where the base of the downstream end platen is flush with the lip of the cell.

h. The cell is secured by screwing on the end cap.

i. Pressure up hydrostatic cell by following this

1) The "OB DRAIN" valve is opened and the "WATER" supply valve is turned on (blue toggle valve).

2) The drain valve at the bottom of the hydrostatic cell is closed.

3) " OB DRAIN " valve is closed when the cell is full. A full cell will be evidenced by the noise of water draining though the drain hose at the back of the equipment.

4) The "AIR SUPPLY" valve is turned on (black toggle valve).

5) The correct "CELL PRESSURE CONTROL" gauge is selected to cover the pressure you intend to go up to.

6) The "CELL PRESSURE CONTROL" air supply regulator is turned in a clockwise direction until the desired pressure is obtained.

7) The cell is now pressured up and you are ready to perform your porosity or permeability tests.

The cell depressuring and sample unloading operations

a. De-pressure the hydrostatic cell

1) Completely back off the "CELL PRESSURE CONTROL" air supply regulator in an anti-clockwise direction and turn off the "AIR" supply valve (black toggle valve).

2) The "WATER" supply valve is turned off (blue toggle valve).

3) The pressure is release in the cell by opening the drain valve on the bottom of the cell.

4) The "OB DRAIN" valve is opened to allow the water to drain from the cell.

b. Once the water is completely drained from the hydrostatic cell, unscrew the cell end cap and remove the sample holder from the cell.

c. The retainer rings and the end platens are removed from the rubber sleeve and extract the sample. It is important to have a towel handy at this point to wipe excess water from the sample holder as you remove the sample to stop the sample getting wet.

The details of the overburden poro-perm cell equipment are following this:

a. Air and water supply plumbed into the instrument. Overburden poro-perm cell - equipped with a hydrostatic cell with necessary pressure gauges. An air driven hydraulic is pumped to allow permeability measurements to be made at high confining pressures. It includes the following components:

1) Valves to control and direct gas and water flow.

2) Regulator to control gas pressure.

3) Stainless steel hydrostatic cell to withstand 10,000 psi.

4) An air driven hydraulic pumps to pressure up the cell.

5) Pressure gauges to monitor cell pressure.

6) Rubber sleeve and stainless steel end pieces to hold the sample in the cell.

b. A series of calibrated flow tubes of different volumes to monitor the flow rate of air through the plug (unit - cm^3/sec).

c. Stop Watch.

d. Vernier calipers to measure the plug dimensions (unit-cm).

e. Thermometer.

The permeability measurement procedures

a. The plug sample is measured the dimensions. The sample must be a right cylinder. The length and diameter of the plug are taken several measurements of with vernier calipers. The average length (L) and diameter (D) of the sample are recorded in centimeters to two decimal places.

b. The external air and water supply are turned on.

c. The electronics "POWER" switch is turned on and warm up 5 -10 minutes.

d. "TRANSDUCER SELECT" switch is switched to "AIR Ka"

e. "TRANSDUCER SELECT" valve is switched to "Ka"

f. "REGULATOR SELECT" valve is switched to "Ka"

g. The digital readout to be zero by adjusting the "AIR Ka" potentiometer.

h. The sample is loaded into the sample holder assembly and load into the hydrostatic cell.

i. The hydrostatic cell is filled with water; ensure the correct "CELL PRESSURE CONTROL" gauge is selected.

j. Pressure up to the desired overburden pressure.

k. The supply tube is connected and is tighten to the upstream side of the cell.

l. The vent valve is opened on the down streamside of the cell.

m. With the valves on either side of the "Ka FLOW PATH" open, turn on the air supply valve (black toggle valve).

n. The bubble tube and via a rubber hose are attached to the down stream end of the hydrostatic cell, that is the downstream end of the sample. The bubble tube must be clean and wet before a measurement is made. The rubber hose must be checked regularly during testing to ensure it is not partially blocked with water from the bubble tube or sand from friable samples.

o. The "AIR" regulator (upstream pressure -P_1) is adjusted to obtain the desired flow rate. A very high flow rate causes turbulence in the airflow that leads to inaccurate results. Ideally the upstream pressure and flow tube should be chosen in conjunction to achieve a repeatable flow rate measurement of around 20 second, (e.g. 1 psig upstream pressure / flow volume of 100 cm^3 / flow time of 20 seconds).

p. Once a stabilized flow-rate is established record the following;

1) Upstream Pressure – psig
2) Flow Volume - cm^3
3) Flow Time – second
4) Barometric Pressure – atmosphere
5) Temperature - ^0C

q. On completion of the test, the "AIR" supply valve is turned off, the supply tube is disconnected from the upstream side of the hydrostatic cell and disconnect the flow tube on the down stream side of the cell.

r. The hydrostatic cell is depressurized. The cell is allowed to drain. The sample holder is removed and the sample removed from the sample holder.

s. Overburden permeability can be determined at numerous confining pressures by increasing the confining pressure prior to each flow measurement.

The overburden permeability calculations

The following equation (a form of Darcy's law) is used to calculate permeability. All pressures need to be in unit of atmosphere (atm):

$$K_{gas} = \frac{2000 \times BP \times \mu_{gas} \times Q \times L}{[(P_1 \times 0.06805 + BP)^2 - (BP)^2] \times A} \tag{3.7}$$

$$K_{gas}\,(\text{actual}) = K_{gas}\,(\text{apparent}) \times 0.9716 \tag{3.8}$$

Where:

BP is barometric pressure in the atmosphere unit (BP millibar x 0.0009869 = BP atmosphere).

μ_{air} or μ_{N2} is the viscosity of gas which varies with temperature. The unit is centipoise.

Q is flow rate that measured from flow volume (cm^3) divided by flow time (sec).

L is the length of plug. The unit is centimeter (cm).

P_1 is the upstream pressure. The unit is psig.

0.6805 = conversion factor for psi to atmosphere

A is an cross sectional area of plug. It is calculated from $\pi(D/2)^2$

0.9716 = conversion factor for the expansion of air due to saturation with water vapour in the bubble tube.

$$\mu_{air} = -8 \times 10^{-7}\,T^2 + 8 \times 10^{-5}\,T + 0.0171 \tag{3.9}$$

$$\mu_{N2} = -8 \times 10^{-7}\,T^2 + 8 \times 10^{-5}\,T + 0.0158 \tag{3.10}$$

T is the temperature. The unit is Celsius (°C).

3.6 Conclusion

Eighteen rock samples were collected from Saraburi, Phetchabun and Lopburi provinces. They are limestone and dolomite. The porosity of specimen was determined by using the porosimeter at laboratory. The specimens had average porosity about 3.44% in limestone and

3.95% in dolomite. The permeability values cannot be measured from the poro-perm cell because the specimens are so tight and have very low permeability. The poro-perm cell is used to test the specimen based on the low-pressure measurement. It cannot measure permeability of specimen that has low permeability and dense as limestone and dolomite, but it can measure permeability from sandstone that has higher permeability than limestone and dolomite. The permeability range that the poro-perm cell can measure is 1 mD up. The permeability values used in simulator are come from assumption, well test data, collection data in reference papers and simulation history match. The average permeability is 0.6 mD.

CHAPTER 4
RESERVOIR SIMULATION

4.1 Theory

Reservoir simulation applies the concepts and techniques of mathematical modeling to the analysis of the behavior of petroleum reservoir systems. The simulation is a collection of computer program that implement the mathematical model on a particular computing, machine and refer only to the dynamics of flow within the reservoir.

Numerical reservoir simulators are used widely, primarily because they can solve problems that cannot be solved in any other way. Simulation is the only way to describe quantitatively the flow of multiple phases in a heterogeneous reservoir having a production schedule determined not only by the properties of the reservoir, but also by market demand, investment strategy, and government regulations. However, the usefulness of numerical models extends beyond solving difficult problems; even on simple problems, simulation is often the best solution method because it may be faster, cheaper, or more reliable than other methods.

4.1.1 Classification of reservoir simulation

Reservoir simulator is divided to:

a. Single phase reservoir simulator (liquid or gas)

b. Multiphase reservoir simulator is divided to black-oil reservoir simulator and compositional simulator

4.1.2 Black oil simulation application overview

The Petroleum WorkBench Black Oil reservoir simulator solves problems in which one, two, or three fluid phases are flowing in one, two, or three dimensions.

The black oil simulator is used the FORTRAN for writing the data details input the simulator. Black-oil simulator was the first type developed and still the most frequently used. The simulator can model the flow of water, oil, and gas. Simulator can account for pressure-dependent solubility of gas in oil, but it cannot model changes in oil or gas composition. When modern black - oil simulator is used properly, the user can be confident that the calculations will give realistic answers if the input data are complete and reasonably accurate.

4.1.3 Fundamental of reservoir simulation

a. Single-phase flow

Combining the following develops the equation governing the single-phase flow of a fluid through a porous medium:

1) Conservation of mass
2) Rate equation
3) Equation of state

Conservation of mass

An element of a reservoir is considered through which a single phase is flowing in the x-direction. Than at any instant:

Mass rate in – mass rate out = mass rate of accumulation

$$\left(\upsilon_x \ \rho_x \Delta y \Delta z\right) - \left(\upsilon_{x+\Delta x} \rho_{x+\Delta x} \Delta y \Delta z\right) = \left(\Delta x \Delta y \Delta z\right) \phi \frac{\left(\rho_{t+\Delta t} - \rho_t\right)}{\Delta t} \tag{4.1}$$

Dividing Eq. (4.1) by $\Delta x \Delta y \Delta z$:

$$-\frac{\left(\upsilon_{x+\Delta x} \rho_{x+\Delta x}\right) - \left(\upsilon_x \rho_x\right)}{\Delta x} = \frac{\phi\left(\rho_{t+\Delta t} - \rho_t\right)}{\Delta t} \tag{4.2}$$

Take the limit as $\left\{ \begin{matrix} \Delta x \\ \Delta t \end{matrix} \right\}$ go to zero simultaneously:

$$\frac{\partial(\upsilon\rho)}{\partial x} = -\phi \frac{\partial \rho}{\partial t} \tag{4.3}$$

This is the continuity equation in linear system. Similar:

$$\frac{\partial(\upsilon\rho)}{\partial y} = -\phi \frac{\partial \rho}{\partial t} \tag{4.4}$$

$$\frac{\partial(\upsilon\rho)}{\partial z} = -\phi \frac{\partial \rho}{\partial t} \tag{4.5}$$

Then for three-dimensional flow:

$$\frac{\partial(\upsilon\rho)}{\partial x} + \frac{\partial(\upsilon\rho)}{\partial y} + \frac{\partial(\upsilon\rho)}{\partial z} = -\phi \frac{\partial \rho}{\partial t} \tag{4.6}$$

Rate Equation

Darcy's law relates the velocity to the pressure gradient:

$$\upsilon = -\frac{k}{\mu}\frac{\partial p}{\partial x} \tag{4.7}$$

Then, substituting Eq. (4.7) into Eq. (4.3):

$$\frac{\partial\left(-\frac{k}{\mu}\frac{\partial P}{\partial x}\rho\right)}{\partial x} = -\phi\frac{\partial \rho}{\partial t} \tag{4.8}$$

Equation of state

The equation of state is needed to express the density in terms of pressure. Most of oil field liquid systems are considered to be slightly compressible. In this case, the equation of state is:

$$\rho = \rho_o e^{C\left(P - P_o\right)} \tag{4.9}$$

where ρ = density at pressure P

ρ_o = density at pressure P_o

C = isothermal compressibility factor

$$C \equiv -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

b. Multiphase Flow

The fluid flow in the multiphase is use the derivation of multiphase flow equations. The flow for each phase is developed identically to that scheme outlined for a single-phase fluid. The fluid phase is divided to 3 types that are oil, gas and water. Gas is used in this study. A mass balance on the gas phase must include all possible sources of gas. For a linear system we can write:

Mass rate in - mass rate out = mass rate of accumulation.

Each of the sources of gas as indicated in figure 4.1 is incorporated in the mass rate term. Thus:

$$\left[-A\left(\frac{k_g}{\mu_g B_g} + \frac{R_{so} k_o}{\mu_o B_o} + \frac{R_{sw} k_w}{\mu_w B_w}\right)\frac{\partial P}{\partial x}\right]_x - \left[-A\left(\underset{\substack{\text{Free}\\\text{Gas}}}{\frac{k_g}{\mu_g B_g}} + \underset{\substack{\text{Gas}\\\text{in}\\\text{oil}}}{\frac{R_{so} k_o}{\mu_o B_o}} + \underset{\substack{\text{Gas}\\\text{in}\\\text{water}}}{\frac{R_{sw} k_w}{\mu_w B_w}}\right)\frac{\partial P}{\partial x}\right]_{x+\Delta x}$$

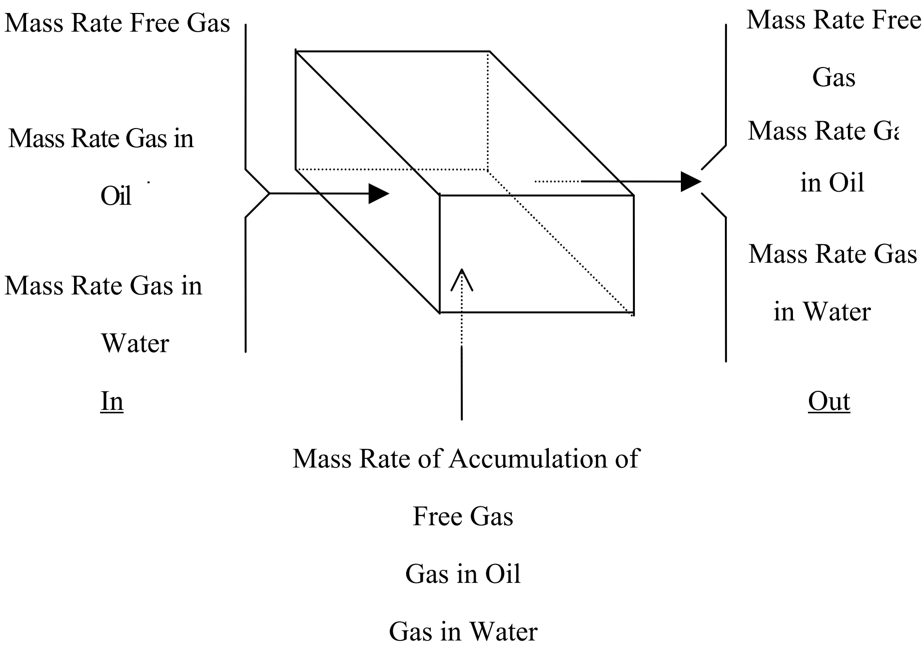


Figure 4.1 A mass balance on the gas phase is shown the detail about mass in, mass out and mass accumulation.

$$= V \left[\frac{\phi \left(\frac{S_g}{B_g} + \frac{R_{so} S_o}{B_o} + \frac{R_{sw} S_w}{B_w} \right)^{n+1} - \left(\frac{S_g}{B_g} + \frac{R_{so} S_o}{B_o} + \frac{R_{sw} S_w}{B_w} \right)^{n}}{\Delta t} \right] \qquad (4.10)$$

which becomes in the limit:

$$\frac{\partial}{\partial x} \left[\left(\frac{k_g}{\mu_g B_g} + \frac{R_{so} k_o}{\mu_o B_o} + \frac{R_{sw} k_W}{\mu_w B_w} \right) \frac{\partial P}{\partial x} \right] = \frac{\partial}{\partial t} \left[\phi \left(\frac{S_g}{B_g} + \frac{R_{so} S_o}{B_o} + \frac{R_{sw} S_w}{B_w} \right) \right] \qquad (4.11)$$

For a radial system the following equation is obtained:

$$\frac{1}{r} \frac{\partial}{\partial r} \left[r \left(\frac{k_g}{\mu_g B_g} + \frac{R_{so} k_o}{\mu_o B_o} + \frac{R_{sw} k_w}{\mu_w B_w} \right) \frac{\partial P}{\partial r} \right] = \frac{\partial}{\partial t} \left[\phi \left(\frac{S_g}{B_g} + \frac{R_{so} S_o}{B_o} + \frac{R_{sw} k_w}{B_w} \right) \right] \qquad (4.12)$$

The generalized multiphase flow equation for the unsteady-state flow of oil, combining the three single-phase flow equations into one basic equation develops gas and water in a porous medium. To do this several other observations are made. First, for all phase the following is true:

$$S_o + S_g + S_w = 1 \qquad (4.13)$$

Thus:

$$\frac{\partial}{\partial t} \left[S_o + S_g + S_w \right] = 0 \qquad (4.14)$$

Pressure gradients are assumed small and the square of this term is neglected:

$$\left(\frac{\partial P}{\partial t} \right)^2 \approx 0 \qquad (4.15)$$

The gas equation (4.12) is multiplied by Bg and expanded as above:

$$\frac{B_g}{r} \left\{ r \left(\frac{R_{so} k_o}{\mu_o B_o} + \frac{R_{sw} k_w}{\mu_w B_w} + \frac{k_g}{\mu_g B_g} \right) \frac{\partial^2 P}{\partial r^2} + r \frac{\partial P}{\partial r} \left[\frac{k_0}{\mu_0} \left(\frac{1}{B_0} \frac{\partial R_{so}}{\partial P} \frac{\partial P}{\partial r} - \frac{R_{so}}{B_0^{\,2}} \frac{\partial B_0}{\partial P} \frac{\partial P}{\partial r} \right) \right. \right.$$

$$\left. + \frac{k_w}{B_w} \left(\frac{1}{B_w} \frac{\partial R_{sw}}{\partial P} \frac{\partial P}{\partial r} - \frac{R_{sw}}{B_w^{\,2}} \frac{\partial B_w}{\partial P} \frac{\partial P}{\partial r} \right) - \frac{k}{\mu_g} \left(\frac{1}{B_g^{\,2}} \frac{\partial B_g}{\partial P} \frac{\partial P}{\partial r} \right) \right]$$

$$\left. + \frac{\partial P}{\partial r} \left(\frac{R_{so} k_o}{\mu_o B_o} + \frac{R_{sw} k_w}{\mu_w B_w} + \frac{k_g}{\mu_g B_g} \right) \right\}$$

$$=\phi B_g\left(\frac{S_o}{B_o}\frac{\partial R_s}{\partial P}\frac{\partial P}{\partial t}+\frac{R_{so}}{B_o}\frac{\partial S_o}{\partial t}-\frac{R_{so}S_o}{B_o^2}\frac{\partial P}{\partial t}+\frac{S_w}{B_w}\frac{\partial R_{sw}}{\partial P}\frac{\partial P}{\partial t}+\frac{R_{sw}}{B_w}\frac{\partial S_w}{\partial t}\right.$$

$$\left.-\frac{R_{sw}S_w}{B_w^2}\frac{\partial B_w}{\partial P}\frac{\partial P}{\partial t}+\frac{1}{B_g}\frac{\partial S_g}{\partial t}-\frac{S_g}{B_g^2}\frac{\partial B_g}{\partial P}\frac{\partial P}{\partial t}\right) \tag{4.16}$$

Collecting terms:

$$\left(\frac{k_o}{\mu_o}\frac{R_{so}B_g}{B_o}+\frac{k_w}{\mu_w}\frac{R_{sw}B_g}{B_w}+\frac{k_g}{\mu_g}\right)\frac{\partial^2 P}{\partial r^2}+\frac{k_o}{\mu_o}\frac{B_g}{B_o}\frac{\partial R_{so}}{\partial P}\left(\frac{\partial P}{\partial r}\right)^2+\frac{k_w}{\mu_w}\frac{B_g}{B_w}\frac{\partial R_{sw}}{\partial P}\left(\frac{\partial P}{\partial r}\right)^2$$

$$-\frac{k_o}{\mu_o}\frac{R_{so}}{B_o^2}\frac{\partial B_o}{\partial P}\left(\frac{\partial P}{\partial r}\right)^2-\frac{k_w}{\mu_w}\frac{B_g}{B_w^2}\frac{\partial B_w}{\partial P}\left(\frac{\partial P}{\partial r}\right)^2-\frac{k_g}{\mu_g}\frac{1}{B_g}\frac{\partial B_g}{\partial P}\left(\frac{\partial P}{\partial r}\right)^2$$

$$+\left(\frac{k_o}{\mu_o}\frac{R_{so}B_g}{B_o}+\frac{k_w}{\mu_w}\frac{R_{sw}B_g}{B_w}+\frac{k_g}{\mu_g}\right)\frac{1}{r}\frac{\partial P}{\partial r}$$

$$=\phi\left(\frac{S_oB_g}{B_o}\frac{\partial R_{so}}{\partial P}-\frac{R_{so}S_oB_g}{B_o^2}\frac{\partial B_o}{\partial P}+\frac{S_wB_g}{B_w}\frac{\partial R_{sw}}{\partial P}-\frac{R_{sw}S_wB_g}{B_w^2}\frac{\partial B_w}{\partial P}-\frac{S_g}{B_g}\frac{\partial B_g}{\partial P}\right)\frac{\partial P}{\partial t}$$

$$+\phi\left(\frac{B_gR_{so}}{B_o}\frac{\partial S_o}{\partial t}+\frac{R_{sw}B_g}{B_w}\frac{\partial S_w}{\partial t}+\frac{\partial S_g}{\partial t}\right) \tag{4.17}$$

Neglecting $\left(\frac{\partial P}{\partial r}\right)^2$ terms in the above equation:

$$\left(\frac{k_o}{\mu_o}\frac{R_{so}B_g}{B_o}+\frac{k_w}{\mu_w}\frac{R_{sw}B_g}{B_w}+\frac{k_g}{\mu_g}\right)\left(\frac{\partial^2 P}{\partial r^2}+\frac{1}{r}\frac{\partial P}{\partial r}\right)$$

$$=\phi\left(\frac{S_oB_g}{B_o}\frac{\partial R_s}{\partial P}-\frac{R_{so}S_oB_g}{B_o^2}\frac{\partial B_o}{\partial P}+\frac{S_wB_g}{B_w}\frac{\partial R_{sw}}{\partial P}-\frac{R_{sw}S_wB_g}{B_w^2}\frac{\partial B_w}{\partial P}-\frac{S_g}{Bg}\frac{\partial B_g}{\partial P}\right)\frac{\partial P}{\partial t}$$

$$+\phi\left(\frac{R_{so}B_g}{B_o}\frac{\partial S_o}{\partial t}+\frac{R_{sw}B_g}{B_w}\frac{\partial S_w}{\partial t}+\frac{\partial S_g}{\partial t}\right) \tag{4.18}$$

4.1.4 IMPES method

The Implicit Pressure – Explicit Saturation method (IMPES method) is the one of the solution of the simulation equation. It combines the single- phase equations into a single multiphase equation based on pressure, and then solves the pressure equation implicitly for the pressure distribution. The saturation distribution is explicit calculated for each point. The IMPES process is formulated as follows,

a. An each single- phase equation in a single dimension

$$A_x \frac{\partial}{\partial x}\left(\frac{k_o}{\mu_o B_o}\frac{\partial \phi_o}{\partial x}\right) + q_o = V_R \frac{\partial}{\partial t}\left(\frac{\phi S_o}{B_o}\right) \quad \text{Oil} \tag{4.19}$$

$$A_x \frac{\partial}{\partial x}\left(\frac{k_w}{\mu_w B_w}\frac{\partial \phi_w}{\partial x}\right) + q_w = V_R \frac{\partial}{\partial t}\left(\frac{\phi S_w}{B_w}\right) \text{Water} \tag{4.20}$$

$$A_x \frac{\partial}{\partial x}\left(\frac{k_g}{\mu_g B_g}\frac{\partial \phi_g}{\partial x} + \frac{R_{so} k_o}{\mu_o B_o}\frac{\partial \phi_o}{\partial x} + \frac{R_{sw} k_w}{\mu_w B_w}\frac{\partial \phi_w}{\partial x}\right) + q_g$$

$$= V_R \frac{\partial}{\partial t}\left[\phi\left(\frac{S_g}{B_g} + \frac{R_{so}}{B_o} + \frac{R_{sw} S_w}{B_w}\right)\right] \text{Gas} \tag{4.21}$$

Equations (4.19), (4.20), and (4.21) are combined to yield a single equation relating the behavior of all phases in the reservoir. In order to make this transformation, the following additional definitions are required. The potential terms are defined as:

$$\text{Oil} \quad \Phi_o = P_o + \rho_o gh \tag{4.22}$$

$$\text{Gas} \quad \Phi_g = P_g + \rho_g gh \tag{4.23}$$

$$\text{Water} \quad \Phi_w = P_w + \rho_w gh \tag{4.24}$$

The capillary pressure terms are:

$$P_{cw} = P_o - P_w \tag{4.25}$$

$$P_{cg} = P_g - P_o \tag{4.26}$$

Equation (4.22) through (4.26) can be combined using in addition, the saturation equation (4.14) to obtain:

$$A_x \frac{\partial}{\partial x}\left(\lambda_T \frac{\partial P_o}{\partial x}\right) + A_x \frac{\partial}{\partial x}\left(\lambda_g \frac{\partial P_{cg}}{\partial x} - \lambda_w \frac{\partial P_{cw}}{\partial x}\right) + A_x \frac{\partial}{\partial x}\left[\lambda_g \frac{\partial(\rho_g gh)}{\partial x}\right.$$

$$\left. + \lambda_o \frac{\partial(\rho_o gh)}{\partial x} + \lambda_w \frac{\partial(\rho_w gh)}{\partial x}\right] = B_1 \frac{\partial P_o}{\partial t} + B_2 \tag{4.27}$$

$$A_x \frac{\partial}{\partial x}\left(\lambda_T^{\,n} \frac{\partial P_o^{\,n+1}}{\partial x}\right) + A_x \frac{\partial}{\partial x}\left(\lambda_g \frac{\partial P_{cg}}{\partial x} - \lambda_w \frac{\partial P_{cw}}{\partial x}\right)^n + A_x \frac{\partial}{\partial x}\left[\lambda_g^{\,n} \frac{\partial(\rho_g gh)}{\partial x}\right.$$

$$+\lambda_o^{\ n}\frac{\partial(\rho_o gh)}{\partial x}+\lambda_w^{\ n}\frac{\partial(\rho_w gh)}{\partial x}\Bigg]=B_1^{\ n}\frac{\partial P_o^{\ n+1}}{\partial t}+B_2^{\ n+1} \tag{4.28}$$

where the λ-variables are mobility terms, B_1-variables are functions of PVT (pressure-volume-temperature) terms, and B_2-variables are production terms. For two-dimensional flow, equation (4.28) is expanded to include the y-coordinate terms. The summarize IMPES processes are shown in the figure 4.2 through 4.5.

4.1.5 Benefits of reservoir simulation

a. All data are compiled pertinent to a reservoir into one compact database.

b. Opportunity provides to produce the reservoir before commencing actual production.

c. The reservoir can produce several times to examine alternatives.

d. The management tool can be utilized for selecting development plan and operational changes.

e. Present a common ground between companies and regulatory agencies that deal with petroleum resources.

4.2 Data preparation of reservoir simulation

The groups of data generally required in making a simulation run are as following:

a. Fluid Data

The reservoir fluids have properties that must be evaluated many times during the simulation of a reservoir under depletion or under some secondary or tertiary mechanism.

The pressure-dependent fluid properties are;

1) Formation volume factors

2) Fluid viscosity

3) Solution gas-oil ratio

These properties are generally obtained from laboratory studies of samples of the reservoir fluid. Regardless of the data entry methods you use, you must use the oil data (for black oil system only), gas data and water options on the basic menu to entry:

1) The under-saturated oil compressibility (black oil system only)

2) The under-saturated oil viscosity slope (black oil system only)

<u>Start Time Step:</u>

Time = t Step1

Old Pressure Distribution Old Saturation Distribution

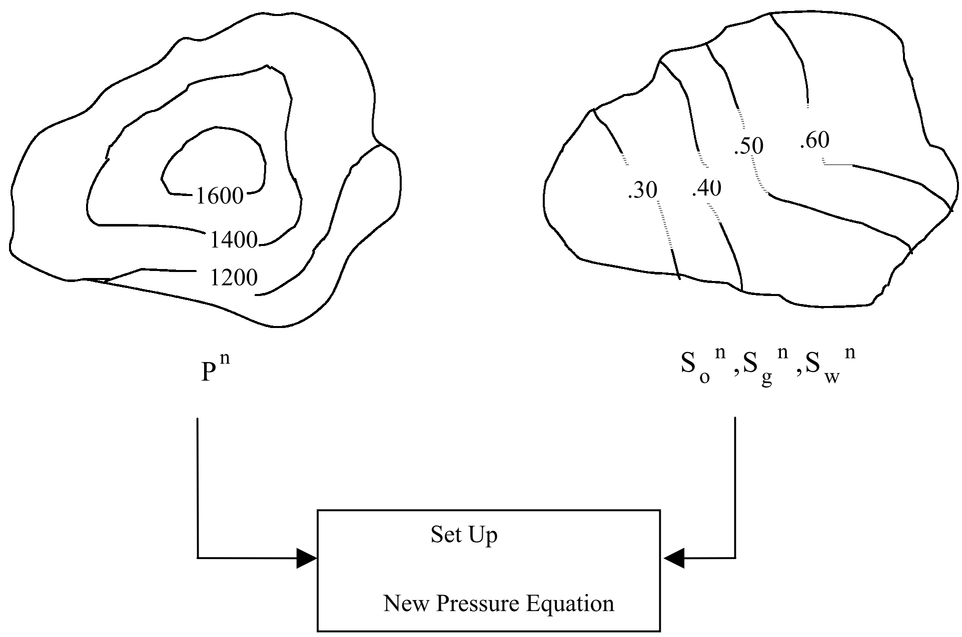
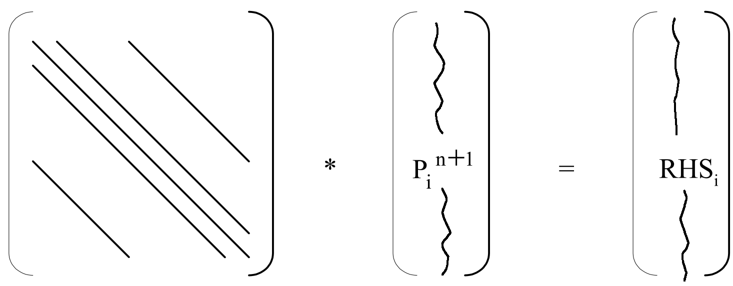


Figure 4.2 Setting up pressure equations at the time step1.

<u>Time = t</u>

Step 2



Solve For New Pressure : P^{n+1}

<u>Time = t+Δt</u>

Step 3

Calculate New Saturations Using The New Pressure Gradients

$\rightarrow S_o^{n+1}, S_g^{n+1}, S_w^{n+1}$

Figure 4.3 At the time step 2 is used the matrix for solving new pressure (implicit pressure).

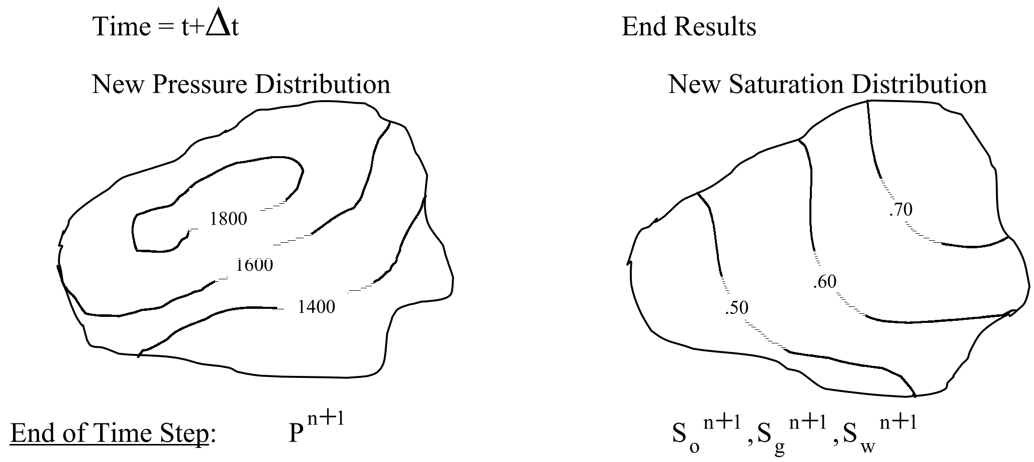


Figure 4.4 Results at end of time step are the saturation that solve by substitute new pressure in the equation (explicit saturation).

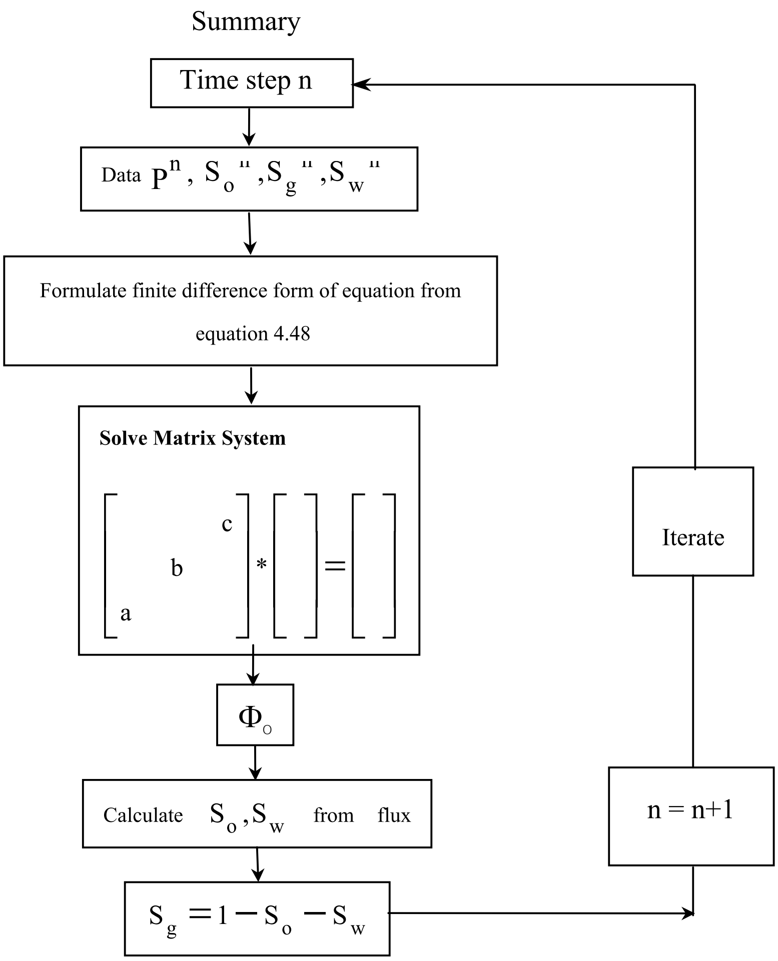


Figure 4.5 IMPES Summary

3) Bubble point pressure (black oil system only)

4) Gravity (black oil and gas-water system)

5) Water viscosity (black oil and gas-water system)

6) Water Formation volume factor (black oil and gas-water system)

b. Rock Data

The various parameters needed to determine the physical extent of the reservoir end to evaluate the transmissibility, during the simulation run must input some form. The required data are:

1) Permeability, can be obtained from several sources;
   - Pressure build up data (drill stem test)
   - Pressure fall off data
   - Interference tests
   - Initial potential test
   - Regression analysis (case history approach)
   - Laboratory measurements

2) Porosity, is usually obtained from;
   - Logging data in the form of sonic/acoustic logs
   - Laboratory measurements
   - Published correlation

3) Formation Thickness, are obtained from;
   - Gross isopach map (must simulations usually use)
   - Net isopach map

4) Formation elevations, source, log data, drilling records

5) Compressibility, sources; laboratory analyses, Published correlations

6) Relative Permeability, can be obtained from one of five means;
   - Laboratory measurements using steady-state displacement process
   - Laboratory measurements using unsteady-state displacement process
   - Calculation from capillary pressure data
   - Calculation from field data
   - Calculation from published correlation

7) Formation fluid saturations, in a reservoir there are two possible planes of interest that can be used to evaluate saturations of reservoir fluids; the gas/oil contact and

water/oil contact. The saturations are generally computed from the locations of the contact within a cell. Connate water can be evaluated from

- Core data
- Electric logs
- Capillary pressure data

8) Capillary pressure, is usually determined from laboratory data

c. Production Data

The information required is obtained from well production records. The following is required for each well:

1) Oil production vs. time.
2) Water production vs. time.
3) Gas production vs. time.
4) Any measured pressure vs. time.

d. Flow rate Data

Flow rate data are required by the simulator to compute producing capacity of a well within the system. These data are generally based on the following:

1) Productivity index.
2) Injectivity Index.
3) Optimum flow rates.
4) Maximum allowable drawdowns.

Flowing well and gas well generally show some rate sensitivity to gas-oil ratio (GOR), bottom hole pressure (BHP), and flow rate. A surface fit of following bottom hole pressure versus flow rate and GOR is necessary to determine the flow parameters in the well bore during simulation

4.3 Input data for this simulation model

The simulation model was designed for 255 BCF gas in place according to the FASPU program running in the northeast of Thailand. The exploration risk was evaluated at 10% risk of the field to be discovered. It was recommended that there would be one discovery for 10 exploration wells. The field with five wells has been producing for several years. Input data consists of general data, rock and fluid data, well data, grid data and production data. Available reservoir and production data are given below:

a. Field data

- Production area = 19.22 km^2 = 4,750 acres
- Depth to top of structure (below MSL) = -8,500 feet
- Initial pressure = 6,500 psia
- Initial temperature = 213 °F
- Base date for simulation @ 01-01-04 (DD-MM-YY).
- Input unit: English - SPE Standard.
- Output unit: English - SPE Standard.

b. Rock properties data

- Gross thickness = 65 feet
- Net thickness = 20 feet
- Irreducible water saturation = 0.1 fraction
- Critical gas saturation = 0.05 fraction
- Relative permeability to gas @ irreducible water saturation = 1.0 fraction
- Pore size distribution index = 0.8
- Capillary entry pressure - G/W = 1.0 psia
- Constant compressibility for matrix rock = 6×10^{-6} psi^{-1}

c. Fluid data

1) Gas property
   - Gas gravity = 0.59
2) Water property
   - Density @ standard conditions = 62.4 lb/cu.ft
   - Water compressibility = 3×10^{-6} psi^{-1}
   - Viscosity = 0.5 cp
   - Formation volume factor @ initial reservoir pressure =1.001 RB/STB
   - Standard pressure = 14.65 psia
   - Standard temperature = 60 °F
   - Maximum pressure current = 7,000 psia

d. Grid

-	Number of layers to model	=	10	layers
-	X-origin on map	=	0	
-	Y-origin on map	=	0	
-	Grid angle (X-axis)	=	0	
-	Number of X-increments	=	10	cells
-	Size of X-increments	=	1,017.05	feet
-	Number of Y-increments	=	20	cells
-	Size of Y-increments	=	1,017.05	feet

e. Equilibrium

-	Reference elevation	=	-9,000	feet
-	Pressure @ reference elevation	=	6,500	psia
-	Elevation of G-W contact	=	-9,500	feet
-	G-W capillary pressure @ constant elevation	=	0	psia

f. Wells

The initial production rate is an input value for each well, then the simulator will calculate the production rate with time. The production rate of each well is shown in table 4.1.

4.4 Simulation model

Reservoir modeling is separated three types following this:

1. Physical models

The models are constructed to duplicate pressures that are physically similar to the original scaled-down reproductions of the original.

2. Analog models

The models use similarities between the phenomenon of fluid flows through porous media and physical phenomena to simulate reservoir performance.

3. Mathematical models

The models use mathematical equations or set of equations describing the physical behavior of the process under investigation. The reservoir model is a representation of fluid flow through porous media. A model can be abstract mathematical description of a process or a

Table 4.1 The gas production rates of each well are started at 1st year production and stopped at 20th year production.

Date	Gas production rate (MSCF/D)				
	Well 1	Well 2	Well 3	Well 4	Well 5
7-Jul-04	20000	30000	22000	10000	10000
10-Jan-05	20000	30000	22000	10000	10000
15-Jul-05	20000	29646	22000	10000	10000
18-Jan-06	20000	24939	22000	10000	10000
24-Jul-06	20000	21266	19622	10000	10000
27-Jan-07	20000	18212	16783	10000	10000
2-Aug-07	19176	15608	14389	10000	10000
5-Feb-08	16429	13526	12380	10000	10000
11-Aug-08	14231	11785	10659	10000	10000
14-Feb-09	12445	10339	9167	9875	10000
19-Aug-09	10965	9145	7957	8342	10000
22-Feb-10	9666	8104	6941	7116	10000
28-Aug-10	8561	7201	6073	6122	8472
3-Mar-11	7626	6428	5340	5314	7265
6-Sep-11	6844	5788	4743	4676	6327
12-Mar-12	6130	5227	4229	4125	5549
15-Sep-12	5524	4688	3776	3663	4906
20-Mar-13	4970	4250	3377	3256	4341
23-Sep-13	4484	3850	3031	2914	3867
29-Mar-14	4105	3502	2755	2643	3494
2-Oct-14	3744	3216	2505	2401	3168
7-Apr-15	3444	2951	2299	2195	2895
11-Oct-15	3181	2725	2118	2013	2656
16-Apr-16	2946	2526	1954	1826	2406
20-Oct-16	2692	2343	1780	1678	2208
24-Apr-17	2486	2163	1640	1537	2016
28-Oct-17	2288	1994	1505	1409	1843
3-May-18	2108	1840	1385	1298	1692
6-Nov-18	1947	1702	1277	1199	1560
12-May-19	1808	1579	1184	1111	1444
15-Nov-19	1686	1471	1103	1033	1344
21-May-20	1575	1374	1032	973	1268
24-Nov-20	1477	1286	969	913	1193
29-May-21	1396	1208	917	864	1129
2-Dec-21	1326	1143	872	820	1071
7-Jun-22	1263	1087	830	779	1019
11-Dec-22	1204	1036	792	742	970
16-Jun-23	1149	990	755	707	924
31-Dec-23	1095	944	719	670	876

laboratory scale experiment. A reservoir model is use to analyze characteristics and behavior of a reservoir process that cannot be conveniently observed. A reservoir model is base on geological, petrophysical and production data. Almost all models use to simulate reservoir behavior are mathematical in nature. Laboratory scale physical models are primarily used to study specific oil and gas reservoir recovery process. The results from physical models are then incorporated into reservoir scale mathematical models for engineering design process. The simulation model in this study has approximate size 3.1×6.2×0.2 cubic-kilometers. It covers area about 20 square kilometers. It composes of 10 layers. Each cell of a layer is called one grid block (Fanchi, 1997) which 310×310×20 cubic-meters. The details of each layer are shown in table 4.2. The reservoir area of each layer is divided into number of grid blocks follows the table 4.3. The total grid block of model is accounted to 1,097 grid blocks. The model has five vertical wells. Each well is located at the middle of the assigned grid block. The gross thickness of five wells in each layer is 65 feet (20 meters) and the net thickness varies in the interval of 20-26 feet. The top structure of model is started at the depth of 8,500 feet and the end of bottom structure at the depth of 9,150 feet (below MSL). Simulation model shape of reservoir with three dimensions is shown in figure 4.6. In each layer of reservoir model is randomly divided to limestone and dolomite that shown in figure 4.7. Limestone is red and dolomite is blue. The permeability and porosity distributions are shown in figure 4.8 and 4.9.

4.5 Simulator procedure

Menus drive the simulator as follows:

a. Edit menu

It is the first menu displayed when the simulation is started. It creates or opens projects and cases through file menu, and specifies the fluid system, reference, and input and output units through system menu. The step of edit menu follows this.

1) Create a new or open project

File →Project →New

2) Set system

System data → Fluid type (oil-gas-water)

Reference (table)

Base date (table)

Table 4.2 Details of each layer are composed of layer number, well number, coordinate (x,y), structure top, gross thickness, net thickness, porosity, water saturation and permeability.

Layer	Well	X	Y	HTOP (ft)	GTh (ft)	NTh (ft)	Phi	Sw	k
1	1	4576.7	13730.2	-8500	65	20	0.060	0.198	0.60
1	2	5593.8	15764.2	-8500	65	20	0.055	0.220	0.70
1	3	4576.7	10679.0	-8500	65	20	0.050	0.201	0.43
1	4	4576.7	8644.9	-8500	65	20	0.047	0.300	0.35
1	5	5593.8	6610.8	-8500	65	26	0.045	0.300	0.75
2	1	4576.7	13730.2	-8565	65	20	0.059	0.199	0.59
2	2	5593.8	15764.2	-8565	65	20	0.054	0.221	0.68
2	3	4576.7	10679.0	-8565	65	20	0.049	0.202	0.42
2	4	4576.7	8644.9	-8565	65	20	0.046	0.301	0.34
2	5	5593.8	6610.8	-8565	65	26	0.044	0.301	0.73
3	1	4576.7	13730.2	-8630	65	20	0.058	0.200	0.58
3	2	5593.8	15764.2	-8630	65	20	0.053	0.222	0.66
3	3	4576.7	10679.0	-8630	65	20	0.048	0.203	0.41
3	4	4576.7	8644.9	-8630	65	20	0.045	0.302	0.32
3	5	5593.8	6610.8	-8630	65	26	0.043	0.302	0.72
4	1	4576.7	13730.2	-8695	65	26	0.057	0.201	0.90
4	2	5593.8	15764.2	-8695	65	20	0.052	0.223	0.64
4	3	4576.7	10679.0	-8695	65	20	0.047	0.204	0.40
4	4	4576.7	8644.9	-8695	65	20	0.044	0.303	0.30
4	5	5593.8	6610.8	-8695	65	26	0.042	0.303	0.71
5	1	4576.7	13730.2	-8760	65	26	0.056	0.202	0.85
5	2	5593.8	15764.2	-8760	65	20	0.051	0.224	0.62
5	3	4576.7	10679.0	-8760	65	20	0.046	0.205	0.38
5	4	4576.7	8644.9	-8760	65	26	0.043	0.304	0.67
5	5	5593.8	6610.8	-8760	65	26	0.041	0.304	0.68
6	1	4576.7	13730.2	-8825	65	26	0.055	0.203	0.82
6	2	5593.8	15764.2	-8825	65	26	0.050	0.222	0.90
6	3	4576.7	10679.0	-8825	65	26	0.045	0.206	0.70
6	4	4576.7	8644.9	-8825	65	26	0.042	0.305	0.65
6	5	5593.8	6610.8	-8825	65	26	0.040	0.305	0.67
7	1	4576.7	13730.2	-8890	65	26	0.054	0.204	0.80
7	2	5593.8	15746.2	-8890	65	20	0.049	0.223	0.58
7	3	4576.7	10679.0	-8890	65	26	0.044	0.207	0.68
7	4	4576.7	8644.9	-8890	65	26	0.041	0.306	0.63
7	5	5593.8	6610.8	-8890	65	26	0.039	0.306	0.65

Table 4.2 Details of each layer are composed of layer number, well number, coordinate (x,y), structure top, gross thickness, net thickness, porosity, water saturation and permeability. (continued)

Layer	Well	X	Y	HTOP (ft)	GTh (ft)	NTh (ft)	Phi	Sw	k
8	1	4576.7	13730.2	-8955	65	26	0.053	0.205	0.78
8	2	5593.8	15764.2	-8955	65	26	0.048	0.224	0.92
8	3	4576.7	10679.0	-8955	65	26	0.043	0.208	0.66
8	4	4576.7	8644.9	-8955	65	26	0.040	0.307	0.60
8	5	5593.8	6610.8	-8955	65	26	0.038	0.307	0.64
9	1	4576.7	13730.2	-9020	65	26	0.052	0.206	0.76
9	2	5593.8	15764.2	-9020	65	26	0.047	0.225	0.88
9	3	4576.7	10679.0	-9020	65	26	0.042	0.209	0.64
9	4	4576.7	8644.9	-9020	65	26	0.039	0.308	0.58
9	5	5593.8	6610.8	-9020	65	26	0.037	0.308	0.62
10	1	4576.7	13730.2	-9085	65	26	0.051	0.207	0.74
10	2	5593.8	15764.2	-9085	65	20	0.046	0.226	0.52
10	3	4576.7	10679.0	-9085	65	26	0.041	0.210	0.58
10	4	4576.7	8644.9	-9085	65	26	0.038	0.309	0.56
10	5	5593.8	6610.8	-9085	65	26	0.036	0.309	0.60

Table 4.3 The reservoir area is related with amount of grid blocks in each layer from 1st layer to 10th layer.

Layer number	Amount of grid block
1	30
2	44
3	60
4	78
5	98
6	120
7	144
8	153
9	180
10	190

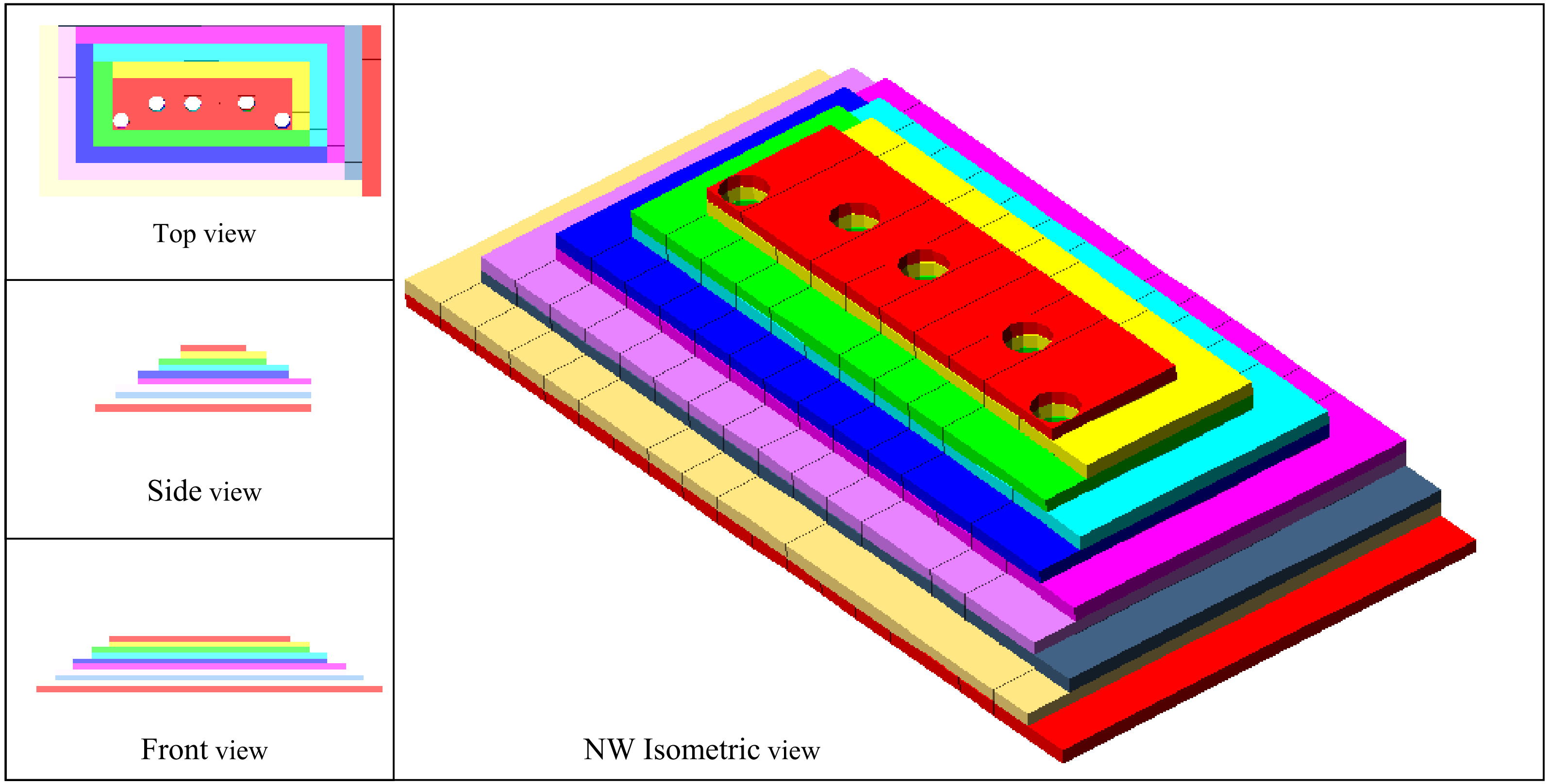


Figure 4.6 The reservoir model with other views that shown in top view, side view, front view, and NW Isometric view.

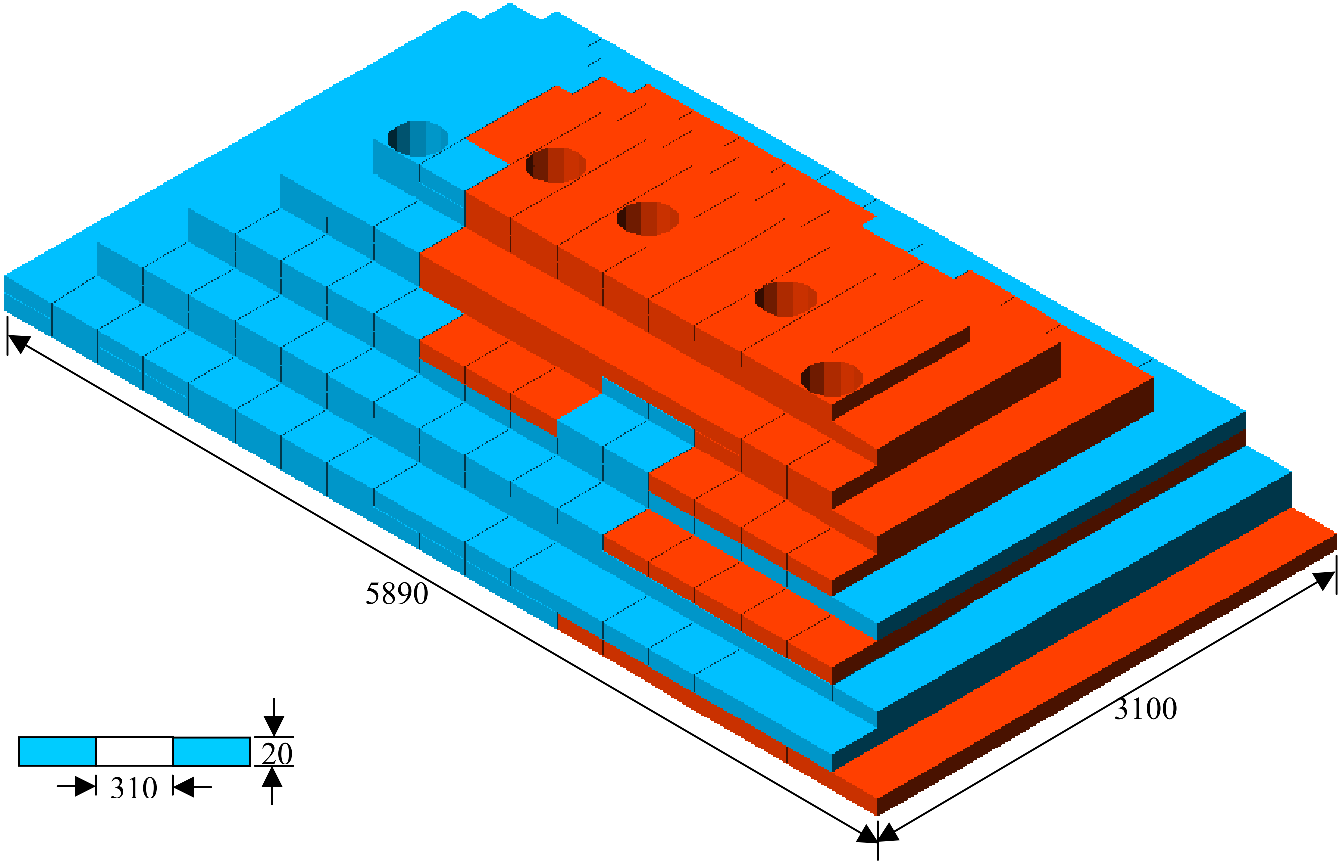


Figure 4.7 The reservoir model is divided in two zone that composed of limestone (red) and dolomite (blue).

.70	.50	.40	.40	.40	.40	.30	.30	.70	**.75**
.50	.50	**.60**	.40	.40	**.43**	.30	**.35**	.30	.70
.50	.50	.40	.40	.40	.40	.30	.30	.30	.70

a

.48	**.68**	.48	.39	.39	.39	.39	.38	.29	.69	**.73**
.48	.48	.48	**.59**	.39	.39	**.42**	.38	**.34**	.29	.69
.48	.48	.48	.39	.39	.39	.39	.38	.29	.29	.69
.48	.48	.48	.39	.39	.39	.39	.38	.29	.29	.69

b

.47	.47	.47	.38	.38	.38	.38	.28	.28	.68	.68	.68
.47	**.66**	.47	.38	.38	.38	.38	.28	.28	.68	**.72**	.68
.47	.47	.47	**.58**	.38	.38	**.41**	.28	**.32**	.28	.68	.68
.47	.47	.47	.38	.38	.38	.38	.28	.28	.28	.68	.68
.47	.47	.47	.38	.38	.38	.38	.28	.28	.28	.68	.68

c

.45	.45	.45	.45	.80	.80	.36	.36	.36	.26	.65	.65	.65
.45	.45	**.64**	.45	.80	.80	.36	.36	.36	.26	.65	**.71**	.65
.45	.45	.45	.45	**.90**	.80	.36	**.40**	.36	**.30**	.26	.65	.65
.45	.45	.45	.45	.80	.80	.36	.36	.36	.26	.26	.65	.65
.45	.45	.45	.45	.80	.80	.36	.36	.36	.26	.26	.65	.65
.45	.45	.45	.45	.80	.80	.36	.36	.36	.26	.26	.65	.65

d

.44	.44	.44	.44	.80	.80	.34	.34	.33	.63	.63	.63	.63	.63
.44	.44	.44	.44	.80	.80	.34	.34	.33	.63	.63	.63	.63	.63
.44	.44	**.62**	.44	.80	.80	.34	.34	.33	.63	.63	**.68**	.63	.63
.44	.44	.44	.44	**.85**	.71	.34	**.38**	.33	**.67**	.63	.63	.63	.63
.44	.44	.44	.44	.71	.71	.34	.34	.33	.63	.63	.63	.63	.63
.44	.44	.44	.44	.71	.71	.34	.34	.33	.63	.63	.63	.63	.63
.44	.44	.44	.44	.71	.71	.34	.34	.33	.63	.63	.63	.63	.63

e

Figure 4.8 The permeability values distribute in each grid block from the 1st layer until the 10th layer that showed in figure a to j.

.78	.78	.78	.78	.78	.78	.78	.62	.62	.62	.62	.62	.62	.62	.62
.78	.78	.78	.78	.78	.78	.78	.62	.62	.62	.62	.62	.62	.62	.62
.78	.78	.78	**.90**	.78	.78	.78	.62	.62	.62	.62	.62	**.67**	.62	.62
.78	.78	.78	.78	.78	**.82**	.78	.62	**.70**	.62	**.65**	.62	.62	.62	.62
.78	.78	.78	.78	.78	.70	.70	.62	.62	.62	.62	.62	.62	.62	.62
.78	.78	.78	.78	.70	.70	.70	.62	.62	.62	.62	.62	.62	.62	.62
.78	.78	.78	.78	.70	.70	.70	.62	.62	.62	.62	.62	.62	.62	.62
.78	.78	.78	.78	.70	.70	.70	.62	.62	.62	.62	.62	.62	.62	.62

f

.48	.48	.48	.48	.48	.76	.76	.61	.61	.61	.61	.60	.60	.60	.60	.60
.48	.48	.48	.48	.48	.76	.76	.61	.61	.61	.61	.60	.60	.60	.60	.60
.48	.48	.48	.48	.48	.76	.76	.61	.61	.61	.61	.60	.60	.60	.60	.60
.48	.48	.48	**.58**	.48	.76	.62	.61	.61	.61	.61	.60	**.65**	.60	.60	.60
.48	.48	.48	.48	.48	**.80**	.62	.61	**.68**	.61	**.63**	.60	.60	.60	.60	.60
.48	.48	.48	.48	.48	.62	.62	.61	.61	.61	.61	.60	.60	.60	.60	.60
.48	.48	.48	.48	.48	.62	.62	.61	.61	.61	.61	.60	.60	.60	.60	.60
.48	.48	.48	.48	.48	.62	.62	.61	.61	.61	.61	.60	.60	.60	.60	.60
.48	.48	.48	.48	.48	.62	.62	.61	.61	.61	.61	.60	.60	.60	.60	.60

g

.76	.76	.76	.76	.76	.75	.75	.60	.60	.60	.57	.57	.59	.59	.59	.59	.59
.76	.76	.76	.76	.76	.75	.75	.60	.60	.60	.57	.57	.59	.59	.59	.59	.59
.76	.76	.76	.76	.76	.75	.75	.60	.60	.60	.57	.57	.59	.59	.59	.59	.59
.76	.76	.76	.76	**.92**	.75	.75	.60	.60	.60	.57	.57	.57	**.64**	.59	.59	.59
.76	.76	.76	.76	.76	.75	**.78**	.60	.60	**.66**	.57	**.60**	.57	.59	.59	.59	.59
.76	.76	.76	.76	.76	.75	.60	.60	.60	.60	.57	.57	.57	.59	.59	.59	.59
.76	.76	.76	.76	.76	.75	.60	.60	.60	.60	.57	.57	.57	.59	.59	.59	.59
.76	.76	.76	.76	.76	.75	.60	.60	.60	.60	.57	.57	.57	.59	.59	.59	.59
.76	.76	.76	.76	.76	.75	.60	.60	.60	.60	.57	.57	.57	.59	.59	.59	.59

h

.72	.72	.72	.72	.72	.72	.58	.58	.58	.58	.54	.54	.54	.58	.58	.58	.58	.58
.72	.72	.72	.72	.72	.72	.58	.58	.58	.58	.54	.54	.54	.58	.58	.58	.58	.58
.72	.72	.72	.72	.72	.72	.58	.58	.58	.58	.54	.54	.54	.58	.58	.58	.58	.58
.72	.72	.72	.72	.72	.72	.58	.58	.58	.58	.54	.54	.54	.58	.58	.58	.58	.58
.72	.72	.72	.72	**.88**	.72	.58	.58	.58	.58	.54	.54	.54	**.62**	.58	.58	.58	.58
.72	.72	.72	.72	.72	.72	**.76**	.58	.58	**.64**	.54	.58	.54	.58	.58	.58	.58	.58
.72	.72	.72	.72	.72	.72	.58	.58	.58	.58	.54	.54	.54	.58	.58	.58	.58	.58
.72	.72	.72	.72	.72	.72	.58	.58	.58	.58	.54	.54	.54	.58	.58	.58	.58	.58
.72	.72	.72	.72	.72	.72	.58	.58	.58	.58	.54	.54	.54	.58	.58	.58	.58	.58
.72	.72	.72	.72	.72	.72	.58	.58	.58	.58	.54	.54	.54	.58	.58	.58	.58	.58

i

Figure 4.8 The permeability values distribute in each grid block from the 1st layer until the 10th layer that showed in figure a to j. (continued)

.50	.50	.50	.50	.50	.50	.50	.56	.56	.56	.56	.52	.52	.56	.56	.56	.56	.56	.56
.50	.50	.50	.50	.50	.50	.50	.56	.56	.56	.56	.52	.52	.56	.56	.56	.56	.56	.56
.50	.50	.50	.50	.50	.50	.50	.56	.56	.56	.56	.52	.52	.56	.56	.56	.56	.56	.56
.50	.50	.50	.50	.50	.50	.50	.56	.56	.56	.56	.52	.52	.56	.56	.56	.56	.56	.56
.50	.50	.50	.50	.50	**.52**	.50	.56	.56	.56	.56	.52	.52	.56	**.60**	.56	.56	.56	.56
.50	.50	.50	.50	.50	.50	.50	**.74**	.56	.56	**.58**	.52	**.56**	.56	.56	.56	.56	.56	.56
.50	.50	.50	.50	.50	.50	.50	.56	.56	.56	.56	.52	.52	.56	.56	.56	.56	.56	.56
.50	.50	.50	.50	.50	.50	.50	.56	.56	.56	.56	.52	.52	.56	.56	.56	.56	.56	.56
.50	.50	.50	.50	.50	.50	.50	.56	.56	.56	.56	.52	.52	.56	.56	.56	.56	.56	.56
.50	.50	.50	.50	.50	.50	.50	.56	.56	.56	.56	.52	.52	.56	.56	.56	.56	.56	.56

j

Figure 4.8 The permeability values distribute in each grid block from the 1st layer until the 10th layer that showed in figure a to j. (continued)

.055	.052	.052	.052	.045	.045	.045	.045	.060	**.065**
.052	.052	**.060**	.052	.045	**.050**	.045	**.047**	.045	.060
.052	.052	.052	.052	.045	.045	.045	.045	.045	.060

a

.051	**.054**	.051	.051	.051	.044	.044	.044	.044	.059	**.064**
.051	.051	.051	**.059**	.051	.044	**.049**	.044	**.046**	.044	.059
.051	.051	.051	.051	.051	.044	.044	.044	.044	.044	.059
.051	.051	.051	.051	.051	.044	.044	.044	.044	.044	.059

b

.050	.050	.050	.050	.050	.043	.043	.043	.043	.058	.058	.058
.050	**.053**	.050	.050	.050	.043	.043	.043	.043	.058	**.063**	.058
.050	.050	.050	**.058**	.050	.043	**.048**	.043	**.045**	.043	.058	.058
.050	.050	.050	.050	.050	.043	.043	.043	.043	.043	.058	.058
.050	.050	.050	.050	.050	.043	.043	.043	.043	.043	.058	.058

c

.049	.049	.049	.049	.049	.049	.042	.042	.042	.042	.057	.057	.057
.049	.049	**.052**	.049	.049	.049	.042	.042	.042	.042	.057	**.062**	.057
.049	.049	.049	.049	**.057**	.049	.042	**.047**	.042	**.044**	.042	.057	.057
.049	.049	.049	.049	.049	.049	.042	.042	.042	.042	.042	.057	.057
.049	.049	.049	.049	.049	.049	.042	.042	.042	.042	.042	.057	.057
.049	.049	.049	.049	.049	.049	.042	.042	.042	.042	.042	.057	.057

d

.048	.048	.048	.048	.048	.048	.041	.041	.041	.049	.056	.056	.056	.056
.048	.048	.048	.048	.048	.048	.041	.041	.041	.049	.056	.056	.056	.056
.048	.048	**.051**	.048	.048	.048	.041	.041	.041	.049	.056	**.061**	.056	.056
.048	.048	.048	.048	**.056**	.048	.041	**.046**	.041	**.053**	.049	.056	.056	.056
.048	.048	.048	.048	.048	.048	.041	.041	.041	.049	.049	.056	.056	.056
.048	.048	.048	.048	.048	.048	.041	.041	.041	.049	.049	.056	.056	.056
.048	.048	.048	.048	.048	.048	.041	.041	.041	.049	.049	.056	.056	.056

e

Figure 4.9 The porosity values distribute in each grid block from the 1st layer until the 10th layer that showed in figure a to j.

.047	.047	.047	.047	.047	.047	.047	.040	.040	.040	.048	.055	.055	.055	.055
.047	.047	.047	.047	.047	.047	.047	.040	.040	.040	.048	.055	.055	.055	.055
.047	.047	.047	**.050**	.047	.047	.047	.040	.040	.040	.048	.055	**.060**	.055	.055
.047	.047	.047	.047	.047	**.055**	.047	.040	**.045**	.040	**.052**	.048	.055	.055	.055
.047	.047	.047	.047	.047	.047	.047	.040	.040	.040	.048	.048	.055	.055	.055
.047	.047	.047	.047	.047	.047	.047	.040	.040	.040	.048	.048	.055	.055	.055
.047	.047	.047	.047	.047	.047	.047	.040	.040	.040	.048	.048	.055	.055	.055
.047	.047	.047	.047	.047	.047	.047	.040	.040	.040	.048	.048	.055	.055	.055

f

.046	.046	.046	.046	.046	.046	.046	.039	.039	.039	.047	.054	.054	.054	.054	.054
.046	.046	.046	.046	.046	.046	.046	.039	.039	.039	.047	.054	.054	.054	.054	.054
.046	.046	.046	.046	.046	.046	.046	.039	.039	.039	.047	.047	.054	.054	.054	.054
.046	.046	.046	**.049**	.046	.046	.046	.039	.039	.039	.047	.054	**.059**	.054	.054	.054
.046	.046	.046	.046	.046	**.054**	.046	.039	**.044**	.039	**.051**	.047	.054	.054	.054	.054
.046	.046	.046	.046	.046	.046	.046	.039	.039	.039	.047	.047	.054	.054	.054	.054
.046	.046	.046	.046	.046	.046	.046	.039	.039	.039	.047	.047	.054	.054	.054	.054
.046	.046	.046	.046	.046	.046	.046	.039	.039	.039	.047	.047	.054	.054	.054	.054
.046	.046	.046	.046	.046	.046	.046	.039	.039	.039	.047	.047	.054	.054	.054	.054

g

.045	.045	.045	.045	.045	.045	.045	.045	.038	.038	.038	.046	.053	.053	.053	.053	.053
.045	.045	.045	.045	.045	.045	.045	.045	.038	.038	.038	.046	.053	.053	.053	.053	.053
.045	.045	.045	.045	.045	.045	.045	.045	.038	.038	.038	.046	.053	.053	.053	.053	.053
.045	.045	.045	.045	**.048**	.045	.045	.045	.038	.038	.038	.046	.053	**.058**	.053	.053	.053
.045	.045	.045	.045	.045	.045	**.053**	.045	.038	**.043**	.038	**.050**	.046	.053	.053	.053	.053
.045	.045	.045	.045	.045	.045	.045	.045	.038	.038	.038	.046	.046	.053	.053	.053	.053
.045	.045	.045	.045	.045	.045	.045	.045	.038	.038	.038	.046	.046	.053	.053	.053	.053
.045	.045	.045	.045	.045	.045	.045	.045	.038	.038	.038	.046	.046	.053	.053	.053	.053
.045	.045	.045	.045	.045	.045	.045	.045	.038	.038	.038	.046	.046	.053	.053	.053	.053

h

.044	.044	.044	.044	.044	.044	.044	.044	.037	.037	.037	.045	.052	.052	.052	.052	.052	.052
.044	.044	.044	.044	.044	.044	.044	.044	.037	.037	.037	.045	.052	.052	.052	.052	.052	.052
.044	.044	.044	.044	.044	.044	.044	.044	.037	.037	.037	.045	.052	.052	.052	.052	.052	.052
.044	.044	.044	.044	.044	.044	.044	.044	.037	.037	.037	.045	.052	.052	.052	.052	.052	.052
.044	.044	.044	.044	.047	.044	.044	.044	.037	.037	.037	.045	.052	.057	.052	.052	.052	.052
.044	.044	.044	.044	.044	.044	.052	.044	.037	.042	.037	.049	.045	.052	.052	.052	.052	.052
.044	.044	.044	.044	.044	.044	.044	.044	.037	.037	.037	.045	.045	.052	.052	.052	.052	.052
.044	.044	.044	.044	.044	.044	.044	.044	.037	.037	.037	.045	.045	.052	.052	.052	.052	.052
.044	.044	.044	.044	.044	.044	.044	.044	.037	.037	.037	.045	.045	.052	.052	.052	.052	.052
.044	.044	.044	.044	.044	.044	.044	.044	.037	.037	.037	.045	.045	.052	.052	.052	.052	.052

i

Figure 4.9 The porosity values distribute in each grid block from the 1st layer until the 10th layer that showed in figure a to j. (continued)

.043	.043	.043	.043	.043	.043	.043	.043	.043	.036	.036	.036	.044	.051	.051	.051	.051	.051	.051
.043	.043	.043	.043	.043	.043	.043	.043	.043	.036	.036	.036	.044	.051	.051	.051	.051	.051	.051
.043	.043	.043	.043	.043	.043	.043	.043	.043	.036	.036	.036	.044	.051	.051	.051	.051	.051	.051
.043	.043	.043	.043	.043	.043	.043	.043	.043	.036	.036	.036	.044	.051	.051	.051	.051	.051	.051
.043	.043	.043	.043	.043	**.046**	.043	.043	.043	.036	.036	.036	.044	.051	**.056**	.051	.051	.051	.051
.043	.043	.043	.043	.043	.043	.043	**.051**	.043	.036	**.041**	.036	**.048**	.044	.051	.051	.051	.051	.051
.043	.043	.043	.043	.043	.043	.043	.043	.043	.036	.036	.036	.044	.044	.051	.051	.051	.051	.051
.043	.043	.043	.043	.043	.043	.043	.043	.043	.036	.036	.036	.044	.044	.051	.051	.051	.051	.051
.043	.043	.043	.043	.043	.043	.043	.043	.043	.036	.036	.036	.044	.044	.051	.051	.051	.051	.051
.043	.043	.043	.043	.043	.043	.043	.043	.043	.036	.036	.036	.044	.044	.051	.051	.051	.051	.051

j

Figure 4.9 The porosity values distribute in each grid block from the 1st layer until the 10th layer that showed in figure a to j. (continued)

Input units (English-SPE)

3) Output units (English-SPE)

b. Jump → Fluids menu

Fluids menu uses to enter laboratory or simulator generated fluid property data. The step of fluid menu follows this.

1) Input basic data

Basic data → Oil data (table)

Gas data (table)

Default all (used for correlation)

Equation to Use (used for correlation)

2) Input oil properties by keying in table

Edit → Edit data → Key in (table)

Plots → Oil plots (oil PVT display)

3) Input gas properties by keying in table

Plots → Gas plots

Edit →Edit data →Key in (table)

Plots → Gas plots (gas PVT display)

Edit → Validate (fluid data)

4) Optionally oil & gas properties by importing tables

c. Jump →Rocks

To enter laboratory or simulator generated water-oil and gas-oil relative permeability and capillary pressure data. The step of rocks menu follows this.

1) Input basic data

Basic data → Compressibility (table)

Default all (optional for correlation)

2) Input oil/water relative permeability

Edit → Edit data → Key in (table)

Plots → Water oil K_r (display)

Plots → Gas liquid K_r

Edit → Edit data → Key in (table)

Edit → Validate (rock date)

d. Jump → Mapping

To handle map information, girding system, well location, property data, i.e., structure, thickness, porosity and permeability. The step of mapping menu follows this.

1) Define simulation grid

Grid → Create grid → Regular grid → Grid by form (table)

View →Zoom → Scale to grid

2) Enter reservoir data

Edit maps → Constant by layer (table)

3) Add a well

Edit maps → Wells →Add wells

Select well symbol

Enter well name

Pick well location

4) Build Arrays

Grid →Build arrays → Full build

Answer "Yes"

5) View → Display items (simulation grid)

6) Verify the arrays for thickness, porosity, permeability, etc. by selecting each property for each layer

View → Layer up

Layer down

Select layer - Layer1

- Layer2

View → Property → Select property → Structure tops

Vertical gross thickness

Porosity

X (R) permeability

Y (T) permeability

Z permeability

e. Jump Wells

To enter well definition, completion, production/injection, production control data, and time points.

1) Enter well Information

Define → Completions → Define completion

Add completion locations: Yes

Calculate Kh: Yes

Well history → Rates (rate table)

Plots (display)

2) Enter well controls

Controls → Minimum rate

Maximum water cut

Maximum GOR

BHP limites

THP limlts

- - -

All Wells

f. Jump → Equilibrium

The following steps of equilibrium show how to enter equilibrium data. The equilibrium data that input into the equilibrium menu are the reference elevation, the elevation of gas- water contact, the pressure value at the reference elevation and the gas- water capillary pressure. The steps of equilibrium menu are followed this.

Enter equilibrium data

Equilibrium (table)

g. Jump → Run

1) Initialize and build deck

Initialize → Build deck

Run

Initial in-place water, oil, solution gas, free gas, average pressures are shown.

2) Create time points

Time points → Define points (table)

3) Set history Matching Option

Simulate → Options → History matching (yes)

4) Simulate

Simulate → Build deck

Simulate → Sumbit

5) Monitor progress of the simulation

Simulate → Monitor

h. Jump →Results

To display results in tables x, y plots and maps.

1) Load results

File → Simulation result → Load results

Clear prior results (yes)

Delete interface file (yes)

2) View results

Plots → Wells → Plots

Plots → Wells → Copy history

Plots → Wells → Plots

Plots → Wells → Observed pressures

Enter pressure into the screen

i. Jump → Run

Rebuild the simulation deck and then submit the run

j. Look at results: Jump → Results

Load results and view the well plot

k. Prediction run:

1) Jump → Run

Time points → edit time points

Enter end date and desired increment

2) Jump → Well

Control → field minimum

3) Jump → Run

Build the simulation deck and submit the run

4) Jump → Results

Load results and view the well plots.

The other menu

Jump menu

To change edit, fluids, rocks, mapping, wells, aquifer, equilibrium, run and result menus.

Tools menu

To check completeness of the input data, specify display, mapping, and hard copy options, display an on-screen calculator, change colors used for display, system of units used for input and output data, and specify the type of model to be used to create a mathematical model of input data.

Help menu

To display software version, and turn on the help system.

View menu

To view specific types of data in each main menu. Some sub menus and options are repeated from main menu to main menu. All main menus, for example, have a file menu, a Jump menu, a tools menu, and a help menu, and most have a view menu. The options associated with the sub menus may differ slightly from main menu to main menu, but the menu options themselves have the same general functions.

4.6 Result of reservoir simulation

a. Total field.

- Initial Gas In Place	=	250	BCF
- Initial Water In Place	=	15	MMSTB
- Initial Average Pressure	=	6,492	Psia
- Field Matrix Pore Volume	=	149	MMRB

b. Total field at the end of time step.

- Fluid In Place

Total Gas	=	24.9	BCF
Water	=	14.9	MMSTB
- Cumulative Production			
Gas	=	225	BCF
Water	=	0	MSTB

c. Each well.

The pressure decline of five wells summary is shown in the figure 4.10. The production rate of five wells summary is shown in the figure 4.11. The pressure distribution of each well is shown in appendix B.

d. Time step summary

The time steps summary has shown the production rates of total field that decline when the time is elapse. Time step summary is shown in table 4.4.

4.7 Discussion

In this thesis, the reservoir simulation is useful for determination of the energy production and estimating the production rate. The model size is 3.1x6.2x0.2 cubic-kilometers. It is started at 8500 feet of depth. The production rate is started at 92 MMSCF/D that comes from the reservoir that is divided in to 10 layers with 65 feet (20 meters) of gross thickness in each layer. The model produces gas with constant rate two years. The gas production is equal to 67 BCF. After that rate declines 16% in each year until 19^{th}year. The final production rate is 4.3 MMSCF/D. The total gas production is 225 BCF. Gas in place is 250 BCF. If permeability value in each grid block is changed, the pressure values will rapidly decline when permeability increases. Vice versa if permeability values decrease then the pressure values decline slowly.

The input data

a. Reserve

The reserve is resulted from FASPU program running for 255 BCF gas in place. It is 225 BCF. The model is created based on the reserve value. It has five vertical wells with 10 layers. Each layer is divided into dolomite and limestone. The model has equally top structure in each layer. The model lay out is set as one contour of one layer and contour interval of structural

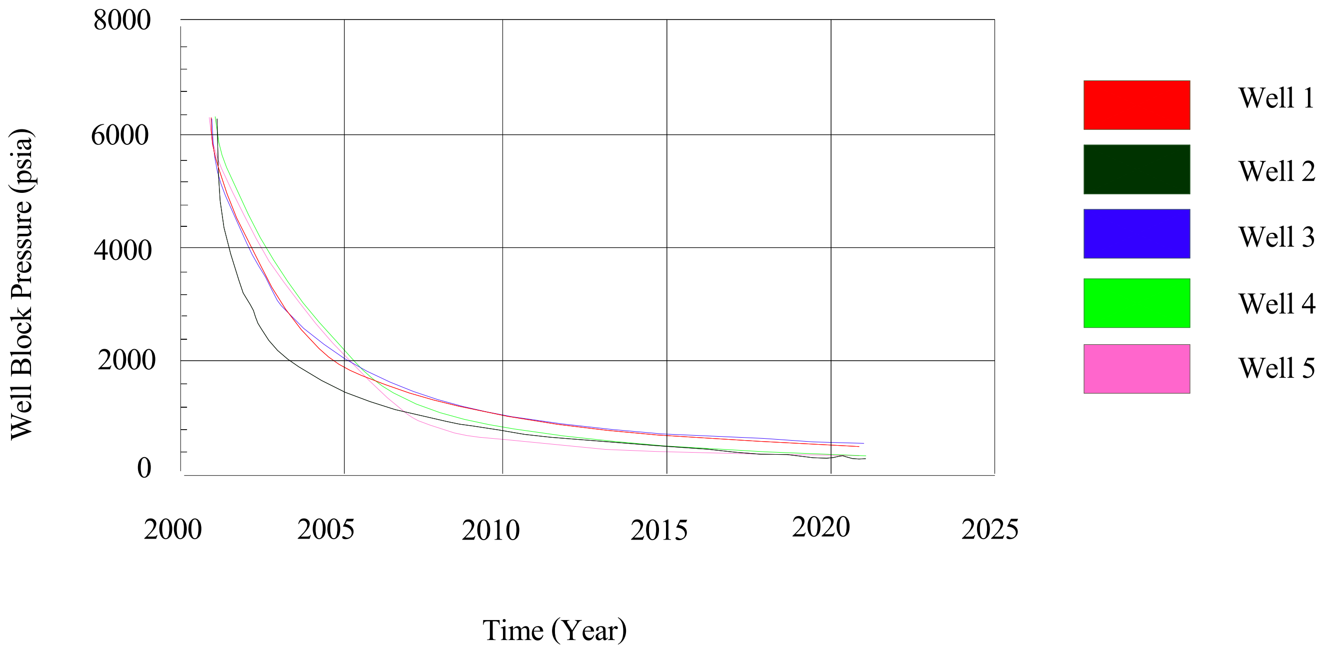


Figure 4.10 The relationship between pressures of each well & time. Maximum pressure is 6,480 psia and minimum pressure is 641 psia.

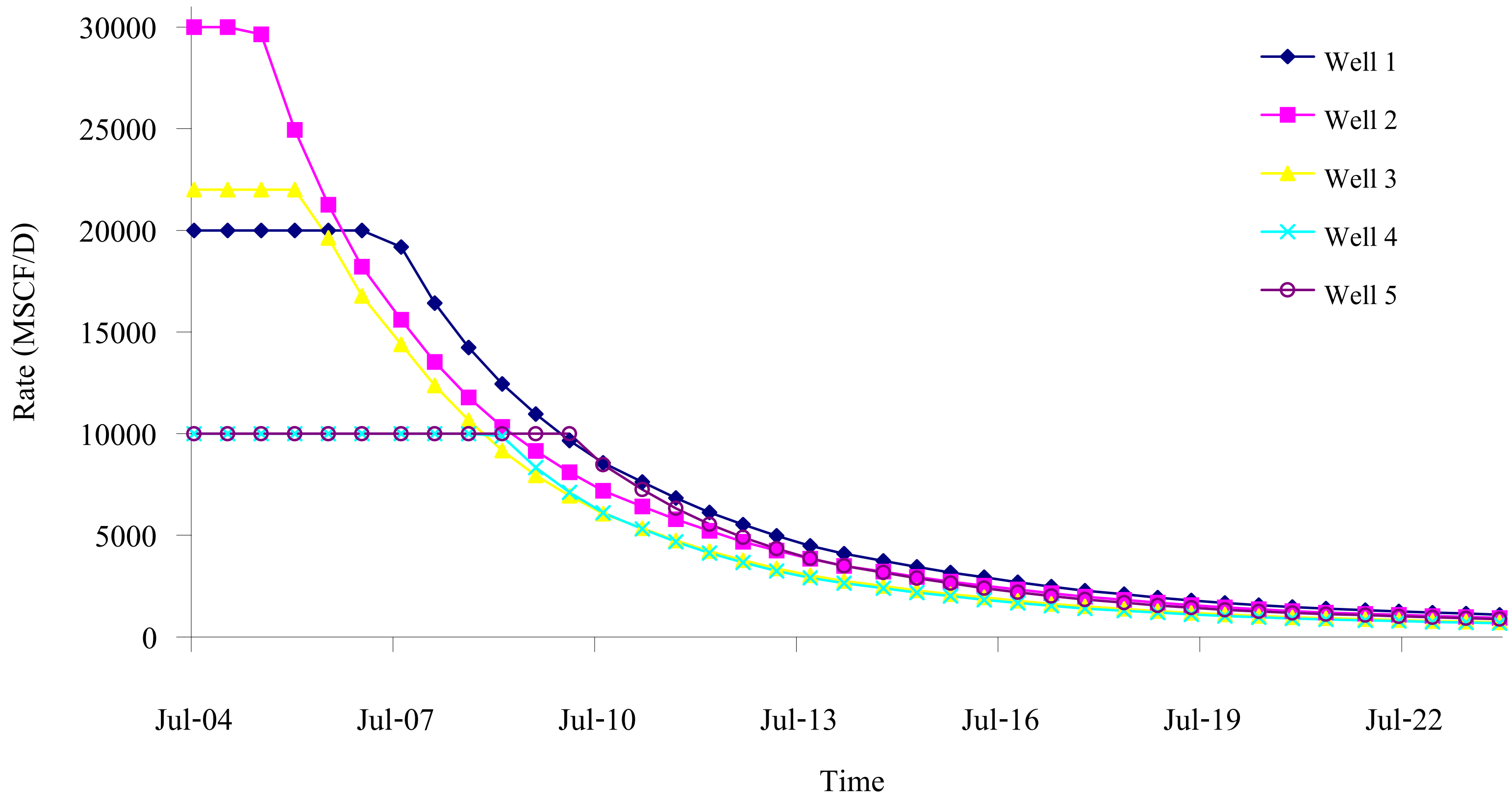


Figure 4.11 The relationship between the production rates of each well & time.

Table 4.4 The time step summary. The production rates of total field that decline when the time is elapse.

Time		Production		Max
Step	Day	Gas (MSCF/D)	Water (STB/D)	Pressure (PSI)
1	2	92,000	0	6,480
2	6	92,000	0	6,466
3	13	92,000	0	6,439
4	21	92,000	0	6,403
5	33	92,000	0	6,354
6	49	92,000	0	6,287
7	73	92,000	0	6,192
8	106	92,000	0	6,062
9	152	92,000	0	5,886
10	187	92,000	0	5,753
11	276	92,000	0	5,432
12	374	92,000	0	5,101
13	477	92,000	0	4,775
14	561	92,000	0	4,528
15	715	92,000	0	4,123
16	748	91,000	0	4,042
17	935	87,000	0	3,634
18	1,122	74,994	0	3,283
19	1,309	69,173	0	2,982
20	1,496	62,335	0	2,724
21	1,683	56,675	0	2,298
22	1,870	51,825	0	2,122
23	2,057	46,409	0	1,965
24	2,244	41,828	0	1,830
25	2,431	36,429	0	1,830
26	2,618	31,972	0	1,711
27	2,805	28,378	0	1,605
28	2,992	25,259	0	1,512
29	3,179	22,556	0	1,429
30	3,366	20,193	0	1,354
31	3,553	18,146	0	1,286

Table 4.4 The time step summary. The production rates of total field that decline when the time is elapse. (continued)

Time		Production		Max
Step	Day	Gas (MSCF/D)	Water (STB/D)	Pressure (PSI)
32	3,740	16,499	0	1,223
33	3,927	15,035	0	1,165
34	4,114	13,785	0	1,114
35	4,301	12,691	0	1,067
36	4,488	11,657	0	1024
37	4,675	10,701	0	984
38	4,862	9,841	0	946
39	5,049	9,039	0	910
40	5,236	8,323	0	876
41	5,423	7,684	0	844
42	5,610	7,126	0	815
43	5,797	6,637	0	788
44	5,984	6,221	0	764
45	6,171	5,839	0	743
46	6,358	5,515	0	723
47	6,545	5,232	0	704
48	6,732	4,978	0	687
49	6,919	4,744	0	671
50	7,106	4,524	0	656
51	7,304	4,304	0	641

contour map is 65 feet. The top layer has the smallest reservoir area. The underneath layers have increased area according to depth until the bottom layer, that is the biggest reservoir area.

b. Permeability

The permeability values are the assumed values. The results of actual reservoir history matching testing at the department of mineral resource are satisfied. It is the confidential data that is not permitted by the ESSO company to reveal data in this study. So the permeability values that put in simulation model are the assumed values. The result of simulation program running is the result of the prospect reservoir not actual reservoir. The permeability of the original rock may not be good enough to produce gas. It is good effective value for producing gas after the acidizing treatment process is performed.

c. Porosity

The porosity values are measured from specimens by using the porosimeter at the SUT laboratory. The porosity values are shown in the table 3.2.

d. Other data

The other input data such as field data, rock property data, fluid data etc., are shown in the data preparation of simulation.

The output data

The output data of prospect reservoir from simulation running result are following this:

a. Reserve that is calculated from simulation program running is 225 BCF. Gas in place is 250 BCF.

b. The prospect reservoir area covers around 19.22 square kilometers (4750 acres).

c. The gross thickness is 65 feet and net thickness is 20 feet in each layer.

d. The prospect reservoir has average permeability about 0.6 mD and average porosity about 0.03.

e. The total production rate of five wells is 92 MMSCF/D with constant rate since 2004 until 2005, after that the rate come to decline 16% in each year which is started from 2005-2023 that produced along 19 years. The final production rate at 23^{th}year is 4.3 MMSCF/D.

f. The production efficiency is calculated by using cumulative gas production divided by gas in place (225 BCF/250 BCF) equal to 89%.

CHAPTER 5

PROSPECT ECONOMIC EVALUATION

5.1 Objective

The objective is to study and calculate the pay back period, net present value, profit investment ratio and internal rate of return for analyzing and estimating the investment options.

5.2 Exploration and production regulation

The period of natural gas exploration and production plan under petroleum acts is divided into three years of exploration period that can be continued for another three years and 20 years of production period that can be continued for another 10 years (start at the end of exploration period).

5.3 The exploration and production work plan

The total exploration and production period is 24 years that is divided into four years for exploration and 20 years for production. The work plan is as following

1^{st} year @ 2000	: 2-D seismic investigation 300 kilometers
	: Geological survey
2^{nd} year @ 2001	: 3-D seismic investigation 30 square kilometers
	: Drill one exploration wells
3^{rd} year @ 2002	: First phase gas pipeline (four kilometers)
	: Drill three appraisal wells
4^{th} year @ 2003	: Drill two development wells
	: Second phase gas pipeline (three kilometers)
	: Installing processing facility
5^{th} year @ 2004	: Starting economic production and stop at the end of 24^{th} year.

Amount of production wells are 5. The total production rate of 5 wells that receives from simulation process (chapter 4) is shown in Table 5.1. The gas production is started at 5^{th} year with the rate of 92 MMCF/D for 2 year then decreased continuously and ended at the 20^{th} year

Table 5.1 Total production rate of five wells is received from simulation process in the chapter 4.

Year	Prod. Rate (MMSCF/D)
1	92.0
2	92.0
3	80.0
4	68.0
5	55.5
6	46.0
7	36.0
8	27.0
9	22.0
10	17.5
11	15.6
12	12.5
13	10.5
14	8.8
15	7.6
16	6.5
17	5.8
18	5.2
19	4.7
20	4.3

of production. The production rate decline is shown in figure 5.1.

The recoverable reserve of this study is 225 BCF that derived from complying FASPU (Fast Appraisal System for Petroleum Universal) program. The FASPU program is an evaluated program of potential oil and gas reservoir that will be discovered. This program is used the principle of lognormal distribution by assigning the calculation of reservoir size distribution. This program calculates mean values and variance of oil and gas accumulative size. The FASPU program estimation is divided into groups under the same condition such as same geological characteristic and play attributes. The geological attributes consist of play attributes, prospect attributes and hydrocarbon volume. The play and prospect attributes characteristic are used for analyzing the geological characteristic. Hydrocarbon volume analyzes the hydrocarbon accumulation. The play attributes consist of 1) hydrocarbon source 2) timing period during trapping and sealing occurred that include the properly duration of hydrocarbon migration and 3) the hydrocarbon migration is considered along the volume of hydrocarbon that migrates till deposit at least 1 accumulation in specific case. Lastly, potential reservoir facies mean the characteristics of reservoir include porosity and permeability that control the potential of reservoir. The prospect attributes consist of trapping mechanism, effective porosity and hydrocarbon accumulation. The hydrocarbon volume consists of closure area, reservoir thickness, reservoir depth, hydrocarbon saturation, percent trap fill and number of drillable prospects. The probability distribution of each attribute is calculated by using the cumulative distribution function at seventh fractile (100^{th} 75^{th} 50^{th} 25^{th} 5^{th} 0^{th}). The play analysis uses seventh fractile for calculating the hydrocarbon volume attributes.

5.4 Assumptions of economic study

The petroleum economic study under the concession system and petroleum economics evaluation of Thailand III (Department of Mineral Resource, 1999) has assumptions and details that divided into basic cost assumptions and other cost assumptions.

5.4.1 Basic cost assumptions

a.	Number of exploration well	1
	Number of appraisal well	3
	Number of development well	2

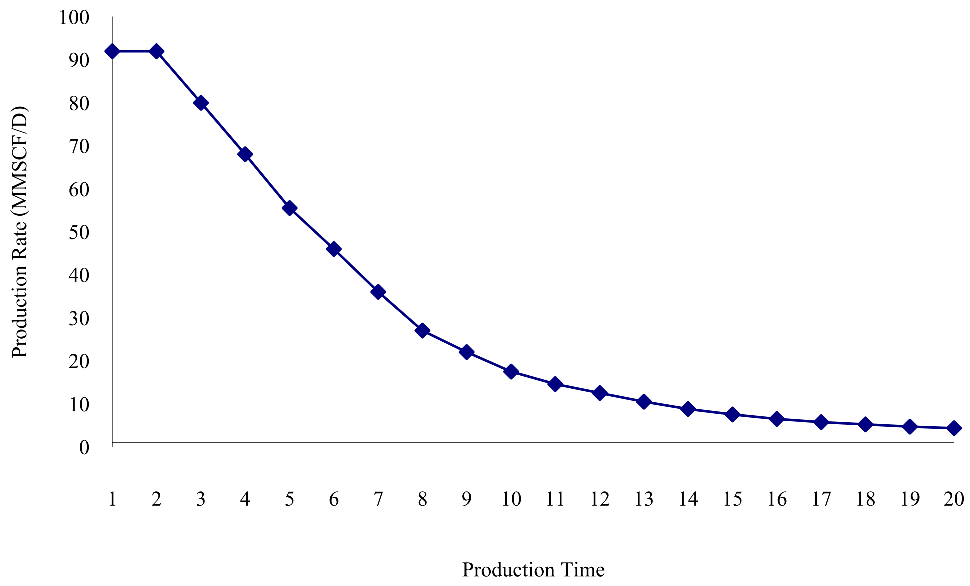


Figure 5.1 The relationship between production rates and time. The total production rate starts at 92 MMSCF/D and declines from the 2nd production year until 20th year.

b. Sale gas reserve (BCF) 225

c. Gas heating value (BTU/SCF) 1,000

d. Exchange rate (Bath to US$) 40

e. Income tax (%) 50

f. Escalation factor (%) 2

g. Discount rate (%) 7.25

h. Tangible cost (%) 20

i. Intangible cost (%) 80

j. Depreciation of tangible cost (%) 20

k. Sliding Scale royalty (%) 5, 6.25

Monthly sale volume (BCF)	Rate (%)
0 - 600	5.00
600 – 1,500	6.25
1,500 – 3,000	10.00
3,000 – 6,000	12.50
> 6,000	15.00

Monthly sale volume levels are calculated from production rate level of oil that relate with block by block basic:

Production Level (BPD)	Rate (%)
0-2,000	5.00
2,000-5,000	6.25
5,000-10,000	10.00
10,000-20,000	12.50
> 20,000	15.00

The gas production levels are calculated by using gas and oil heating value condition. One standard cubic foot of gas has heating value equal to 1000 BTU and a generous conversion factor of 10 million BTU gas to one barrel oil is provided, for example

2000BPD$\rightarrow$(2000B/D) x (30D/M) x (10x10^{6}BTU/1B) x (1 SCF/1000BTU) = 600 MMSCF/M.

5.4.2 Other cost assumptions

a. The gas price is constant over the contract.

b. Increasing rate of capital expenditure comes from the price increasing of machineries and other equipments used in oil industries, and given to two percent per year.

c. Discount rate of money is 7.25 percent (Siam Commercial Bank, April 2002)

d. Operating cost is escalated 2 percent each year forward.

e. The first production is conducted in the five years of work plan.

f. The expenses used in cash flow analysis are estimated as follow:

1) Capital cost

- 2- D seismic investigation (US$ / line km)	1,000
- 3-D seismic investigation (US$ / line sq. km)	5,000
- Well drilling & completion exploration well (MMUS$ / well)	10
- Well drilling & completion appraisal well (MMUS$ / well)	10
-Well drilling & completion development well (MMUS$ / well)	10
- Pipeline (MMUS$ / km)	0.5
- Processing production facilities (MMUS$)	70
- Geological survey (MMUS$)	0.1
- Special bonus (MMUS$)	2
2) Operating cost (US$ / MMSCF)	400
3) Petroleum price	
- Gas price (US$ / MMBTU)	2.52

5.5 Cash flow table explanations

a. The cash flow table is shown in the table 5.2. The cash flow table detail of each block is explained as follow:

Column		Detail
A	=	Year
B	=	Gas production per day (MMSCF/D)
C	=	Gas production per month (MMSCF/M)
D	=	Gas production per year (MMSCF/Y)
E	=	Gas price (US$ / MMBTU) constant over the contact

Table 5.2 The cash flow table that calculates the pay back period, net present value, profit investment ratio and internal rate of return.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
YEAR	GAS PRODUCTION			GAS PRICE	GROSS REV. SALE INCOME	ROYALTY SLIDING SCALE	2% ESCAL FACTOR	INVESTMENT COST							TOTAL COST
								SEISMIC 2D	SEISMIC 3D	DRILLING INTANG	DRILLING TANG	PIPELINE	PROCESSING FACILITY	OPER. COST	
	MMSCF/D	MMSCF/M	MMSCF/Y	US$/MMBTU	MM US$	MM US$		MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$
2000	0.00	0.00	0.00	2.52	0.00	0.00	1.0000	2.40						0.00	2.40
2001	0.00	0.00	0.00	2.52	0.00	0.00	1.0200		0.15	8.00	2.00			0.00	10.15
2002	0.00	0.00	0.00	2.52	0.00	0.00	1.0404			24.00	6.00	2.00		0.00	32.00
2003	0.00	0.00	0.00	2.52	0.00	0.00	1.0612			16.00	4.00	1.50	70.00	0.00	91.50
2004	92.00	1104.00	33580.00	2.52	84.62	5.29	1.0824							13.43	13.43
2005	92.00	1104.00	33580.00	2.52	84.62	5.29	1.1041							13.70	13.70
2006	80.00	960.00	29200.00	2.52	73.58	4.60	1.1262							12.15	12.15
2007	68.00	816.00	24820.00	2.52	62.55	3.91	1.1487							10.54	10.54
2008	55.50	666.00	20257.50	2.52	51.05	3.19	1.1717							8.77	8.77
2009	46.00	552.00	16790.00	2.52	42.31	2.12	1.1951							7.42	7.42
2010	36.00	432.00	13140.00	2.52	33.11	1.66	1.2190							5.92	5.92
2011	27.00	324.00	9855.00	2.52	24.83	1.24	1.2434							4.53	4.53
2012	22.00	264.00	8030.00	2.52	20.24	1.01	1.2682							3.76	3.76
2013	17.50	210.00	6387.50	2.52	16.10	0.80	1.2936							3.05	3.05
2014	14.60	175.20	5329.00	2.52	13.43	0.67	1.3195							2.60	2.60
2015	12.50	150.00	4562.50	2.52	11.50	0.57	1.3459							2.27	2.27
2016	10.50	126.00	3832.50	2.52	9.66	0.48	1.3728							1.94	1.94
2017	8.80	105.60	3212.00	2.52	8.09	0.40	1.4002							1.66	1.66
2018	7.55	90.60	2755.75	2.52	6.94	0.35	1.4282							1.45	1.45
2019	6.50	78.00	2372.50	2.52	5.98	0.30	1.4568							1.28	1.28
2020	5.75	69.00	2098.75	2.52	5.29	0.26	1.4859							1.15	1.15
2021	5.20	62.40	1898.00	2.52	4.78	0.24	1.5157							1.06	1.06
2022	4.70	56.40	1715.50	2.52	4.32	0.22	1.5460							0.98	0.98
2023	4.30	51.60	1569.50	2.52	3.96	0.20	1.5769							0.91	0.91
Total	616.40		224986.00		566.96	32.80		2.40	0.15	48.00	12.00	3.50	70.00	98.59	234.64

Table 5.2 The cash flow table that calculates the pay back period, net present value, profit investment ratio and internal rate of return. (continued)

Q										R	S	T	U	V
DEPRECIATION(20%) TANGIBLE EXPENSE										WRITE OFF	TOT.ALLOW EXPENSE	TAXABLE INCOME	CUMULATIVE TAXABLE INCOME	INCOME TAX (50%)
2000	2001	2002	2003	2004	2005	2006	2007	2008	TOTAL					
MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$
0.00									0.00	2.40	2.40	-2.40	-2.40	0.00
	0.40								0.40	8.15	8.55	-8.55	-10.95	0.00
		2.00							2.00	24.00	26.00	-26.00	-36.95	0.00
			17.10						17.10	16.00	33.10	-33.10	-70.05	0.00
				17.10					17.10	18.72	35.82	48.80	-21.25	0.00
					17.10				17.10	18.99	36.09	48.53	27.28	13.64
						16.70			16.70	16.75	33.45	40.13	67.42	20.07
							15.10		15.10	14.44	29.54	33.00	100.42	16.50
								0.00	0.00	11.96	11.96	39.09	139.50	19.54
									0.00	9.53	9.53	32.78	172.29	16.39
									0.00	7.57	7.57	25.54	197.82	12.77
									0.00	5.77	5.77	19.06	216.89	9.53
									0.00	4.78	4.78	15.46	232.35	7.73
									0.00	3.86	3.86	12.24	244.59	6.12
									0.00	3.27	3.27	10.16	254.75	5.08
									0.00	2.84	2.84	8.65	263.40	4.33
									0.00	2.43	2.43	7.23	270.63	3.62
									0.00	2.07	2.07	6.03	276.66	3.01
									0.00	1.80	1.80	5.14	281.80	2.57
									0.00	1.58	1.58	4.40	286.20	2.20
									0.00	1.42	1.42	3.87	290.07	1.94
									0.00	1.30	1.30	3.48	293.56	1.74
									0.00	1.20	1.20	3.13	296.68	1.56
									0.00	1.11	1.11	2.84	299.53	1.42
									85.50	181.94	267.44	299.53		149.76

Table 5.2 The cash flow table that calculates the pay back period, net present value, profit investment ratio and internal rate of return. (continued)

W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH
YEAR	GAS PRODUCTION		GAS PRICE	CASH FLOW SUMMARY						DISCOUNTED	7.25%
				GROSS REVERNUE	CAPEX	OPEX	GOVERNMENT TAKE		ANNUAL CASH FLOW	CASH FLOW (NPV@7.25%)	DISC FACTOR
							ROYALTY	INC.TAX			
	MMSCF/D	MMSCF/Y	US$/MMBTU	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	MM US$	
2000	0.0	0.0	2.5	0.0	2.4	0.0	0.0	0.0	-2.4	-2.4	1.000
2001	0.0	0.0	2.5	0.0	10.3	0.0	0.0	0.0	-10.3	-9.6	0.932
2002	0.0	0.0	2.5	0.0	33.2	0.0	0.0	0.0	-33.2	-28.9	0.869
2003	0.0	0.0	2.5	0.0	97.1	0.0	0.0	0.0	-97.1	-78.7	0.810
2004	92.0	33580.0	2.5	84.6	0.0	13.4	5.2	0.0	65.9	49.8	0.755
2005	92.0	33580.0	2.5	84.6	0.0	13.7	5.2	13.6	51.9	36.6	0.704
2006	80.0	29200.0	2.5	73.5	0.0	12.1	4.6	20.0	36.7	24.1	0.657
2007	68.0	24820.0	2.5	62.5	0.0	10.5	3.9	16.5	31.6	19.3	0.612
2008	55.5	20257.5	2.5	51.0	0.0	8.7	3.1	19.5	19.5	11.1	0.571
2009	46.0	16790.0	2.5	42.3	0.0	7.4	2.1	16.3	16.3	8.7	0.532
2010	36.0	13140.0	2.5	33.1	0.0	5.9	1.6	12.7	12.7	6.3	0.496
2011	27.0	9855.0	2.5	24.8	0.0	4.5	1.2	9.5	9.5	4.4	0.463
2012	22.0	8030.0	2.5	20.2	0.0	3.7	1.0	7.7	7.7	3.3	0.431
2013	17.5	6387.5	2.5	16.1	0.0	3.0	0.8	6.1	6.1	2.4	0.402
2014	14.6	5329.0	2.5	13.4	0.0	2.6	0.6	5.0	5.0	1.9	0.375
2015	12.5	4562.5	2.5	11.5	0.0	2.2	0.5	4.3	4.3	1.5	0.350
2016	10.5	3832.5	2.5	9.6	0.0	1.9	0.4	3.6	3.6	1.1	0.326
2017	8.8	3212.0	2.5	8.0	0.0	1.6	0.4	3.0	3.0	0.9	0.304
2018	7.5	2755.7	2.5	6.9	0.0	1.4	0.3	2.5	2.5	0.7	0.283
2019	6.5	2372.5	2.5	5.9	0.0	1.2	0.3	2.2	2.2	0.5	0.264
2020	5.7	2098.7	2.5	5.2	0.0	1.1	0.2	1.9	1.9	0.4	0.246
2021	5.2	1898.0	2.5	4.7	0.0	1.0	0.2	1.7	1.7	0.4	0.230
2022	4.7	1715.5	2.5	4.3	0.0	0.9	0.2	1.5	1.5	0.3	0.214
2023	4.3	1569.5	2.5	3.9	0.0	0.9	0.2	1.4	1.4	0.2	0.199
Total	616.4	224986.0		566.9	143.1	98.5	32.8	149.7	142.6	55.0	
								PIR=	1.0	IRR=	18.90%

F	=	Gross revenue sale income (MMUS$)
	=	[(1000 * D* E)] / 1,000,000
G	=	Royalty sliding scale 6.25 or 5 percent of gross revenue (MMUS$)
	=	F*0.0625 or 0.05
H	=	2% escalation factor
I	=	(2-D seismic investigation cost * distances of 2-D seismic) + geologic survey+ special bonus
J	=	3-D seismic investigation cost * area of 3-D
I,J	=	Investment is intangible cost 100 percent
K	=	Number of well * Intangible cost 80 percent * well cost
L	=	Number of well * Tangible cost 20 percent * well cost
K,L	=	Investment cost is divided to tangible cost 20 percent and intangible cost 80 percent
M	=	Pipeline cost * pipeline length
N	=	Processing production facilities
M,N	=	Investment cost is tangible cost 100 percent
O	=	Operating cost
	=	[D*400/1,000,000] * escalation factor 2% for each year
P	=	Total cost = I+J+K+L+M+N+O
Q	=	Depreciation rate 20 percent of tangible cost (straight forward 5 years)
	=	(L+M+N)*0.20
R	=	Write off (MMUS$) = G+I+J+K+O
S	=	Total allow expense = (Total Q) + R
T	=	Taxable income (MMUS$) = F-S
	=	Gross revenue - Total allow expense
U	=	Cumulative taxable income (MMUS$)
V	=	Income tax (MMUS$) = U*0.50
W	=	Year
X	=	Gas production per day (MMSCF/D)
Y	=	Gas production per year (MMSCF/Y)
Z	=	Gas price (US$/MMBTU)

AA = Gross revenue = F

AB = Capital cost (MMUS$)

= (I+J+K+L+M+N) * (2% escalation factor)

AC = Operation cost (MMUS$) = O

AD = Royalty = G

AE = Income tax. (MMUS$) = V

= U*0.5 (50 percent of taxable income accounted when the project start getting profit

AF = Annual cash flow = AA-AB-AC-AD-AE

AG = Discounted cash flow (NPV @ 7.25%)

= AE* discounted factor each year

AH = Discounted factor

Note: The glossary of evaluation terms show in appendix.

b. Cash inflow and cash outflow analysis is considering the money annual project that specified the cash status of annual economic process.

c. Pay back period analysis consider at the first year of the cumulative taxable income is the positive value.

d. Income tax is calculated from net profit.

e. Net profit after tax is equal to cash flow is minuses by tangible cost.

f. Tangible cost is equal to depreciation-sunk cost including the operating cost.

g. Depreciation sunk cost is 20 percent of depreciation.

h. Net present value, profit investment ratio and interest rate of return calculate same as below example.

1) Net present value (NPV)

Assume; NPV at 24th year (2023) calculated backward to 1st year (2000) @ i = 7.25%

$$NPV = A(1+i)^{-n}$$

$$= 1.42\,(1+0.0725)^{-23}$$

$$= 0.28 \text{ MMUS\$}$$

Where A is the annual cash flow

n is the amount of year

i is the discount rate.

2) Profit Investment Ratio (PIR)

PIR is the ratio of sum of annual cash flow divided by sum of CAPEX

PIR $= \sum$ (Annual cash) / $\sum$ (CAPEX)

= 142.67/143.15

= 1.00

3) Internal Rate of return (IRR)

- Using trial & error to find **I** value. **I** value make the lower equation to be zero or nearby when replace **I** in the equation.

$0 = (-C)+A(1+\mathbf{I})^{-1}+A(1+\mathbf{I})^{-2}+...+A(1+\mathbf{I})^{-n}$

Where C is negative annual cash flow value

A is annual cash flow value

I is the assumed value

Assume; **I** = 0.1889, the result when replace **I** in upper equation is NPV that equal to 0.01

I = 0.1891, the result when replace **I** in upper equation is NPV that equal to -0.01

-Using interpolate method to find IRR.

IRR $= [(NPV_{\mathbf{I}=0.1889} / \{NPV_{\mathbf{I}=0.1889} - NPV_{\mathbf{I}=0.1891}\}) * (\mathbf{I}_{0.1891} - \mathbf{I}_{0.1889})] + \mathbf{I}_{0.1889}$

$= [(0.01 / \{0.01-(-0.01)\}) * (0.1891-0.1889)] + 0.1889$

= 0.1890 = 18.90%

5.6 Result of cash flow calculation

From cash flow table explanation shows the total study worth of 24 years. The total worth is divided into gross sale income 566.96 MMUS$ and total cost 234.64 MMUS$. The total cost is divided into three parts.

a. Exploration cost 2.55 MMUS$.

b. Drilling & production facilities cost 133.50 MMUS$.

c. Operating cost 98.59 MMUS$.

Government take is divided into

a. Royalty cost 32.80 MMUS$.

b. Income tax @ 50% 149.76 MMUS$.

Cumulative annual cash flow = 142.67 MMUS$.

5.7 Economic Analysis

a. Since 1^{st} year till 5^{th} year of the project (2000-2004), cash flow is still in negative because total investment does not fully return in this time frame. Then, this period contains many expenses including investment, development and exploration.

b. The 5^{th} year (at 2004) is the first production year that produces 92 MMSCF/D of natural gas. The gross revenue sale income is 85.62 MMUS$ and cash flow becomes positive at 48.80 MMUS$. The cumulative taxable income is still minus value at –21.25 MMUS$.

c. The gas is continuously produced at a constant rate from 5^{th} year production (2004) to 6^{th} year (2005) which production rate is 92 MMSCF/D. At the 5^{th} year, this project earns 169.24 MMUS$ of total income. The cash flow becomes positive at 27.28 MMUS$ when reaches 6^{th} year.

d. The production rate continues decreasing in 7^{th}- 23^{th}year periods until 24^{th} year. At the last production year, cash flow and cumulative income belong to positive range which indicates the cumulative income are 299.53 MMUS$.

e. The natural gas production has completely paid back at 2^{nd} year of production that is observed from cumulative income recovering to positive range.

f. Total income after project has succeeded is 142.67 MMUS$. The total discount cash flow which calculated backward to 1^{st} year (2000) with i = 7.25% is 55.04 MMUS$.

g. Internal rate of return (IRR) is equal to 18.90%.

h. Profit to investment ratio (PIR) is calculated by using annual cash flow divided by CAPEX. Profit investment ratio is equal to 1.00.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The estimation of petroleum production efficiency in carbonate reservoir of the northeastern Thailand is not accurate and sufficient enough. The study of porosity and permeability distribution is necessary. In this thesis, the carbonate rock samples are collected from Saraburi, Lopburi and Phechabun provinces. These samples have moderated properties for gas reservoir. Porosity and permeability values were measured at the laboratory. The specimens had average porosity about 3.44% in limestone and 3.95% in dolomite. The permeability could not be successfully measured from the laboratory testing. The permeability is too low to be measured by the poro-perm cell instrument. The permeability values used in the simulation was based on data collected from papers, conference books and references. They give reasonable simulation results. The original rock permeability may not be good enough to produce gas but after acidizing treatment, the permeability becomes good effective value with an average more than 0.65 mD.

In the part of reservoir simulation, the model is created with the approximate size of 3.1x6.2x0.2 cubic-kilometers. The prospect reservoir area covers around 20 square-kilometers (4750 acres). The gross thickness is 65 feet and net thickness is 20 feet in each layer. The total gross thickness is 650 feet and total net thickness is 200 feet. The total grid block of reservoir area model is accounted to 1,097 grid blocks. The model has one exploration well, three appraisal wells and two development wells. Three of five development wells are changed from appraisal wells to development well. So that the model has six wells but exposes only five wells. The prospect reservoir has average permeability about 0.6 mD and average porosity about 0.03 (3%). The simulation gives reserve of 225 BCF and original gas in place of 250 BCF according to FASPU program. The petroleum production efficiency is 89%.

In the economic aspect, the gas production had started at 5^{th} year (1^{st} year production) with the rate of 92 MMSCF/D and declined 16% per year until 23^{th}year (20^{th} year production) that is the last year of gas production. The final production rate at 23^{th}year is 4.3 MMSCF/D. The pay back period is determined by using cash flow calculation. The natural gas production has completely paid back at 2nd year of the production. The internal rate of return is 18.90% and the profit to investment ratio is equal to 1. The project has the good potential for investment. The benefit of this study will improve ability to do reservoir modeling, simulation and software utilization. The study will also probably promote the petroleum exploration and production activities in the area.

6.2 The recommendations of porosity and permeability measurement.

1) The easy observation of the different characteristics between limestone and dolomite at field are

a. Crystal

The crystal of dolomite is formed in the rhomboidal shape like saddle shape. The crystal of limestone is the rhomboidal with general shape.

b. Acid reaction

Dolomite has lower reaction with acid than limestone.

c. Color

Color of dolomite is likely the transparence zone. Dolomite has magnesium and gypsum in it. Color of limestone is gray.

d. The lines on dolomite surface are as same as the elephant rind.

2) The poro-perm cell is the instrument for measuring the permeability. It has limitation that it cannot measure the too low permeability from carbonate rock as limestone and dolomite. But it can measure higher permeability in sandstone. The poro-perm cell can measure permeability in range of 0.5 mD and above. One of poro-perm cell limit is the low upstream flowing pressure. The maximum upstream pressure is about 100 psi. This instrument cannot pressure up more than 100 psi. The permeability measurement is not measured from the low pressure of poro-perm cell, if the researcher uses higher pressure of other poro-perm cell or changes the poro-perm instrument with higher capability so the researcher can measure permeability.

6.3 The recommendations of simulation

1)The black oil simulation manual is important. The researcher should study and learn to understand before working with simulation program.

2)The FORTRAN is used in the simulator. The researcher should know about basic FORTRAN.

3)The warning keywords that are shown on the blue pages on the simulation window are the error messages that occurred during array-verifications. The error messages will not occur, if the researcher inputs correct parameters with correct step. For example, "net thickness set equal to thickness for 17 cells, layer2" or "TH set= to difference between HTOPs in 1 cell, layer 2". The problem solving is to input new net thickness values in each grid block and build array again.

4)The contour intervals are difficult to draw by hand. Using coordinate x, y and import contour in the property map sets the contour. Contours are identified in each layer of the model.

5)The total gas production rate of five wells in this study started at 92 MMSCF/D and sustains for 2 years. The total rate declined at 2nd year of production. If the researcher decreases the total rate from 92 MMSCF/D to 90 or lower, the sustain rate can be prolonged more than 4 years and the gas production time can also be extended.

6)Simulation results are reference data that are used for decision making in the investment of petroleum exploration and production in the nearby petroleum reservoir area.

7)Simulation results are useful in the prediction of the future petroleum business in the northeastern Thailand.

8)Reliability of simulation result depends on the accuracy of the input data and the simulation model.

9)The repeating calculation manually often gives error. So the digitize calculation by computer will provide more accurate values and less time of calculation.

6.4 The recommendations of simulation of gas reservoir in the northeastern.

Most of the gas reservoirs in the northeastern Thailand are the carbonate reservoir. The prediction about petroleum production is very difficult and complex because the carbonate reservoir has fractures, caverns, massive and fine grains. Moreover, the carbonate reservoir in the northeastern Thailand composes of dolomite and limestone that have same characteristics. Dolomite is a form that similar to limestone but it composes of magnesium. It is difficult to distinguish dolomite from limestone. Permeability is often used to distinguish dolomite from limestone. Permeability value in dolomite reservoir is higher than limestone reservoir. The simulation suggestions for gas reservoir in the northeastern Thailand are as follows:

1) Study of the interest area used in the simulation process knows the problems, data details, history etc.

2) Porosity values in the northeastern Thailand rocks are uncertain because of the fraction in the reservoirs. Porosity determination is important. High porosity is in the fractured zone. If only high porosity is input in the simulation model, the results are not correct. The researcher should use the average porosity to input in the simulation process.

3) The completed data of gas reservoir in the northeastern Thailand should be collected and used in simulation so that the results are proximity of the actual performance.

6.5 The recommendations of simulation results used in the petroleum exploration and production

1) Simulation results are reference data used for decision-making in the investment of petroleum exploration and production in the other petroleum prospect in the northeastern Thailand.

2) Simulation results are useful in the prediction of the future petroleum business in the northeastern.

3) The simulation is the method of compiling program that creates the model that is similar to the actual by input the data in the simulation program. After history match, the modified input become more accurate and the production forecast is reliable. The simulation can reduce the time and money from real performance in other new fields. Then simulation is a considered method, which is useful for the estimation of petroleum production. The simulation accuracy depends on the quantity and quality of data.

REFERENCES

Assavapatchara, S., Charusiri, P. and Khantaprab, C. (1997). The Permian carbonate rocks in Thailand. In **The International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific** (p.139). Bangkok.

Assavarittiiprom, V., Chaisilboon, B. and Polachan, S. (1995). Review on petroleum exploration in Northeastern Thailand. In **Proceedings of the International Conference on Geology, Geotechnology and Mineral Resources of Indochina (Geo-Indo'95)** (pp.541-550). Khon Kaen.

Barnum, R.S. and Moore, K.S. (1985). **Results of Nam Phong 1A Production Tests, Korat Plateau, Thailand.** Exxon Production Research Company. (Unpublished menuscript).

Bhattacharya, S. (1999). **Improved Oil Recovery in Mississippian Carbonate Reservoirs of Kansas** [on-line]. Available: http://www.kgs.ukans.edu/PRS/publication/OFR99_22/discussion.html

Booth, J.E. (1998). The Khorat Plateau of NE Thailand-Exploration History and Hydrocarbon Potential. In **Proceedings of the SEAPEX Exploration Conference** (pp.169-203). Singapore.

Borns, D.j. (2001). **Development of a New-Generation Petroleum Reservoir Simulator** [on-line]. Available: http://www.energylan.sandia.gov/ngotp/news/mar/2001/march/mar_01.cfm.

Calvin, C. M. and Robert L. D. (1989). **Reservoir Simulation**. USA: Society of Petroleum Engineer.

Chierici, G. L. (1995). **Principles of Petroleum Reservoir Engineering**. Germany.

Chinoroje, O. and Cole, M.R. (1995). Permian carbonates in the Dao Ruang-1 exploration well Implications for petroleum potential, Northeast Thailand. In **Proceedings of the International Conference on Geology, Geotechnology and Mineral Resources of Indochina (Geo-Indo'95)** (pp.563-576). Khon Kaen.

Chonglakmani, C.,Charoentitira ,T. and Liengjarern, M. (1995). Permian carbonates of Loei area, Northeastern Thailand. In **Proceedings of the International Conference on Geology, Geotechnology and Mineral Resources of Indochina (Geo-Indo'95)** (pp. 577-587). Khonkean.

Doscher, T.M., (1993). Petroleum reservoir model. In S.P. Parker(ed). **McGraw-Hill Encyclopedia of Engineering** (pp.893-895). USA: McGraw-Hill.

Henry, B. C. (1997). **Modern Reservoir Engineering-A Simulation Approach**. New Jersey: Englewood Cliffs.

John, R. F. (1997). **Principles of Applied Reservoir Simulation**. Texas: Houston.

Kozar, M.G., Crandall, G.F., and Hall, S.E. (1992). Integrated Structural and Stratigraphic Study of the Korat Basin, Rat Buri Limestone (Permian),Thailand. In **Geologic Resource of Thailand : Potential for Future Development** (pp. 692-736). Bangkok.

Kriangkri, T. (1987). **The Reserve, Energy Production and Production Natural Gas Rate Determination.** Institute of Engineering, Suranaree University of Technology. (Unpublished menuscript).

Mineral Fuels Division. Department of Mineral Resources. Ministry of Industry. (1999). Petroleum Act and Petroleum Income Tax Act B.E. 1999_Thailand III. Bangkok.

Piyasin, S. (1995). The hydrocarbon potential of Khorat plateau. In **Proceedings of the International Conference on Geology, Geotechnology and Mineral Resources of Indochina (Geo-Indo'95)** (pp.551-562). Khon Kaen.

Pradidtan, S. (1995). Petroleum exploration in Northeastern Thailand: The revealed results and its potential. In **Proceedings of the International Conference on Geology, Geotechnology and Mineral Resources of Indochina (Geo-Indo'95)** (pp. 589-599). Khon Kaen.

Roger, B. (2001). **Oil Technology: Reservoir Efficiency Processes** [on-line]. Available: http:// fossil.energy.gov/techline/tl_baa2001_oil.shtml.

Sattayarak, N. (1992). Petroleum Exploration Opportunities in Thailand. In **the National Conference on Geologic Resources of Thailand: Potential for Future Development** (pp. 668-675). Bangkok.

Sattayarak, N., Pradidtan, S. and Chonglakmani, C. (1997). Stratigraphy and depositional environment of the upper Palaeozoic and Mesozoic sediments in the central and northeastern parts of Thailand. In **the International Conference on Stratigraphy and Tectonic Evolution of Southeast Asia and the South Pacific and the Associated Meeting of IGCP 359, IGCP 383 (Geo-Indo'97)** (pp. 7-14). Bangkok.

Shannon, P. (1988). **Fundamentals of Core Analysis and Special Core Analysis**. PTTEP Short Course: Bangkok. Thailand.

Wayne, A. (1999). **Carbonate Pore Facies as Predictors of Reservoir Recovery Efficiency** [on-line]. Available: http:// www.campublic.co.uk/science/publications/ JconfAs/ 4/ 895. htm.

APPENDIX A

GLOSSARY TERMS OF EVALUATION

Amortization - An accounting term referring to the process of writing off the cost or value of an asset over its expected service life. Intangible assets such as acquisition cost for non-producing properties, lease bonuses, title-clearing expenditures, geological and geophysical cost are "written off" or "amortized" in amortization accounts. Tangible assets such as physical equipment or in-place reserves are written off through depreciation or depletion accounts.

Capital Expenditure (CAPEX) - An accounting term is applied to expenditure on fixed assets, i.e. items that have a life beyond the current year. The value of such items is usually depreciated over its life. Other items with short life, and expenses such as operating costs, are treated as revenue items and are deducted in full immediately.

Depreciation - An accounting and tax term for allocating a portion of tangible asset cost to a time period. Property, plant and equipment are depreciated, as well as all the costs of developing producing wells and related facilities. Commonly used depreciation methods include straight-line and accelerated depreciation methods such as declining balance or sum-of-the-year's digits.

Development Well - A development well is one drilled on property that is considered proved. Consequently, the designation is arbitrary to the same degree as the property classification.

Discount Cash Flow (DCF) - Cash flows are estimates of future payments and receipts - usually on an annual basis. These are generally calculated in the money of the day terms. The DCF method then takes account of the fact that we would prefer to have a "real" sum of money in our hands now rather than later, because if we did, it could be re-invested to make more money. Thus it "costs" us something to receive it later (opportunity cost). The converse is true of capital costs (they cost less tomorrow than today because - inflation apart - the money can be kept in use in our financial system earning money). The purpose of DCF is to measure this time effect on value and cost, and it is a separate process from looking at inflation effects. Discounting is the exact mathematical inverse of compounding.

Discount Rate - The rate used to discount fund flows in the discount cash flow method and evaluation (e.g., for a discount rate of 5%, year n fund flow is divided by 1.05 to the (n-1) power). It should be chosen to represents the real rate of return the business can expect to make and as such represents the rate that can be expected by investing in other (or opportunity) projects. The following points need to be taken into account when choosing the discount rate:

a. Historic company earnings rates are a guide, but future opportunities may differ.

b. If most of a company's capital is borrowed, the rate should at least exceed the loan rate! Where a company's capital is from several sources sometimes an average cost of capital may be used to derive a minimum discount rate.

c. The relative risk of one business to another.

d. Future investment opportunities - limited, anticipated rate of return.

Expense or Expensed - A disbursement of outlay is subtracted from current revenue. In book or taxable income computations, this may be either OPEX (e.g., salaries and wages) or expensed investments. The entire amount receives tax relief in the year the cost is incurred.

Income Tax - A monetary assessment levied by a government, based upon taxable income.

Intangible Assets - Intangible assets are the class of assets that includes all types of minerals. No value may be established by direct inspection and the asset does not necessarily depreciate with time. It loses value only when produced and furthermore cannot be replaced. The exact differentiation between a tangible (capital) asset and an intangible asset is somewhat arbitrary. From a practical standpoint, such differentiation depends on the current applicable tax provisions governing a specific type of property. Evaluations should not rely solely on past evaluations since the laws regarding intangible assets change.

Internal Rate of Return (IRR) - The discount rate that sets the Present Value of a cash flow stream equal to zero.

Investment - An expenditure of funds to acquire physical of financial assets from which benefits are expected to occur for more than one year.

Net Present Value (NPV) - The value of a discrete or continuous cash flow stream discounted at some discount rate.

Operating Expense (OPEX) - Generally, a cost of conducting business activities or, specifically, cost directly involved with production or services.

Play - An area of localized exploration activity based on a geological hypothesis regarding existence of conditions favorable for mineral occurrence.

Profit - An imprecise term generally perceived to reflect the financial return from an investment. Profit is commonly defined as the excess of revenues over all costs and is also considered to be equivalent to income.

Revenue - The amount is received for the sale of production of manufactured products. Generally, the mathematical product of unit is price and volume. The chief source of cash inflow is most investment evaluations.

Royalty - Royalty is the interest of a party owning minerals in the ground where another party (the working interest) has gained the right to capture such minerals under a lease agreement. Such royalty interest is normally free of all costs of capture except for special treating costs that might be specified in the lease or assignment. This term is often used as an abbreviation for the term landowner's royalty. There are many specific forms of royalty.

Sliding Scale Royalty - A royalty varying in accordance with the amount of production, e.g., a 1/8 royalty if the production is 100 barrels per day or less, and 3/16 royalty if the production is greater than 100 barrels per day. Difficult problems of interpretation of the sliding scale royalty clause arise when government regulations on a unitization agreement limit production on the amount of oil allocated to a particular tract.

Tangible - Refers to an asset having material substance, as for example, equipment. A property value can be determined by objective appraisal.

Taxable Income - The computation of income in accordance with tax codes so as to serve as the basis for computing income taxes. Generally differs from book income (as reported in financial statement) because of different depreciation and depletion accounting procedures.

Write Off - An accounting term for a non-cash or book expense. It is the cost of a long-term asset allocated, period-by-period, over its deemed life. Also called an "Extinguishments". For example: depreciation, depletion and amortization expenses.

APPENDIX B

FIGURE OF PRESSURE DISTRIBUTION

At 1 year

5059	4623	3766
5009	4680	4480
4898	4345	4683
5002	4814	4915
5023	4818	4944
4904	4284	4822
5059	4777	4963
5123	4610	4972
5331	5094	5005
5387	5146	4720

At 2 year

4027	3569	2662
3970	3622	3410
3850	3262	3617
3965	3760	3861
3994	3774	3902
3885	3225	3789
4070	3771	3960
4165	3625	4001
4403	4154	4061
4475	4223	3777

Ay 5 year

2387	2103	1579
2308	2063	1960
2182	1715	2022
2269	2105	2185
2301	2142	2221
2233	1798	2144
2332	2095	2215
2354	1864	2151
2512	2248	2094
2548	2254	1687

At 10 year

1408	1249	944
1360	1220	1157
1283	1013	1185
1325	1231	1274
1334	1244	1286
1287	1039	1231
1330	1192	1256
1328	1049	1201
1402	1251	1157
1419	1253	936

At 20 year

768	686	527
741	672	640
700	563	653
718	673	694
720	678	698
697	573	670
715	651	682
713	577	654
751	677	631
759	676	512

Figure B.1 Pressure distribution of layer 1.

At 1 year

5434	5261	4971	4634
5359	5104	4668	3852
5290	5040	4697	4517
5239	4930	4358	4707
5256	5039	4824	4930
5259	5048	4827	4960
5249	4935	4295	4842
5324	5082	4787	4978
5423	5150	4621	4992
5541	5358	5110	5032
5585	5419	5170	4757

At 2 year

4430	4243	3936	3580
4345	4075	3616	2753
4268	4002	3640	3447
4214	3884	3274	3642
4234	4002	3770	3876
4247	4021	3783	3917
4252	3918	3237	3810
4353	4095	3781	3976
4482	4193	3635	4021
4629	4432	4171	4088
4687	4509	4248	3816

At 5 year

2681	2557	2363	2147
2606	2422	2136	1639
2527	2332	2075	1985
2467	2209	1724	2041
2477	2298	2113	2197
2490	2322	2149	2233
2497	2258	1807	2160
2560	2353	2103	2228
2642	2381	1875	2171
2743	2542	2266	2124
2778	2584	2281	1731

At 10 year

1583	1510	1398	1276
1535	1429	1268	979
1484	1374	1228	1171
1443	1299	1018	1196
1442	1341	1236	1281
1440	1346	1248	1292
1434	1301	1044	1240
1459	1342	1197	1263
1494	1344	1056	1214
1540	1421	1262	1175
1558	1441	1269	961

At 20 year

861	822	763	700
835	779	696	547
806	748	675	647
782	708	566	658
779	726	675	697
775	726	680	701
771	704	575	674
782	722	654	685
799	721	581	660
822	760	683	639
830	771	684	526

Figure B.2 Pressure distribution of layer 2.

At 1 year

5453	5280	4997	4688	4932
5375	5140	4714	3959	4700
5303	5065	4721	4582	4883
5249	4954	4376	4752	5006
5265	5060	4835	4953	5106
5271	5066	4837	4986	5163
5261	4956	4304	4879	5173
5339	5100	4796	5012	5241
5434	5168	4631	5029	5276
5554	5379	5131	5080	5270
5605	5453	5210	4837	5226
5748	5546	5304	5263	5248

At 2 year

4449	4264	3963	3635	3884
4363	4113	3664	2865	3640
4283	4029	3664	3515	3824
4224	3910	3293	3689	3951
4244	4026	3781	3900	4058
4260	4041	3793	3944	4127
4265	3940	3246	3849	4154
4369	4115	3792	4012	4247
4495	4213	3647	4058	4312
4642	4454	4193	4137	4330
4709	4547	4290	3898	4298
4794	4635	4387	4309	4315

At 5 year

2696	2572	2382	2183	2334
2620	2450	2169	1710	2165
2537	2353	2092	2030	2235
2475	2231	1740	2078	2282
2485	2317	2124	2219	2344
2500	2338	2158	2255	2387
2508	2277	1816	2189	2397
2574	2371	2113	2258	2436
2654	2401	1889	2210	2433
2756	2568	2294	2181	2388
2800	2624	2328	1829	2314
2849	2685	2394	2246	2351

At 10 year

1591	1519	1409	1297	1380
1543	1446	1287	1019	1281
1490	1386	1237	1197	1313
1449	1311	1027	1219	1332
1447	1353	1242	1293	1359
1446	1356	1253	1304	1373
1441	1312	1048	1255	1366
1468	1353	1203	1280	1373
1502	1358	1065	1237	1356
1550	1438	1279	1208	1320
1571	1465	1296	1015	1276
1575	1470	1300	1289	1295

At 20 year

867	827	769	711	752
839	788	706	569	700
809	754	680	660	714
785	714	571	668	720
782	732	678	702	732
779	732	682	706	736
775	709	578	681	731
786	727	657	692	733
803	728	585	670	724
827	769	691	655	707
838	783	698	556	686
845	795	706	694	699

Figure B.3 Pressure distribution of layer 3.

At 1 year

5700	5535	5294	4890	4759	4899
5695	5526	5283	4861	4725	4873
5581	5401	5172	4758	4038	4739
5472	5324	5085	4744	4642	4911
5364	5259	4968	4397	4783	5016
5381	5274	5070	4842	4962	5109
5399	5289	5080	4844	5003	5174
5392	5282	4971	4314	4903	5187
5467	5356	5112	4805	5033	5251
5578	5449	5177	4637	5052	5290
5642	5570	5391	5149	5119	5294
5769	5639	5494	5264	4919	5272
5824	5733	5623	5474	5348	5447

At 2 year

4592	4543	4371	4306	4218	4345
4504	4484	4297	4009	3706	3928
4419	4392	4147	3710	2946	3679
4338	4305	4051	3688	3577	3853
4263	4236	3926	3315	3721	3962
4285	4254	4036	3789	3910	4061
4210	4280	4056	3802	3962	4138
4218	4289	3958	3258	3874	4169
4429	4389	4129	3802	4034	4257
4654	4512	4224	3653	4082	4326
4739	4660	4469	4211	4177	4354
4865	4747	4591	4347	3984	4346
4976	4859	4739	4578	4441	4541

At 5 year

2989	2849	2672	2625	2452	2576
2815	2723	2597	2414	2232	2363
2723	2642	2475	2201	1761	2191
2674	2555	2369	2108	2069	2253
2569	2486	2246	1759	2103	2290
2576	2495	2327	2133	2230	2347
2609	2517	2351	2166	2270	2395
2620	2527	2292	1826	2209	2408
2694	2592	2384	2123	2278	2444
2775	2672	2416	1901	2240	2449
2819	2777	2589	2322	2230	2415
2906	2838	2671	2392	1929	2366
3017	2943	2813	2629	2457	2570

At 10 year

1863	1749	1675	1504	1399	1458
1752	1607	1534	1429	1324	1397
1648	1556	1461	1305	1048	1295
1601	1501	1395	1247	1221	1323
1576	1455	1319	1038	1233	1336
1568	1454	1359	1248	1299	1361
1572	1457	1364	1258	1312	1377
1569	1453	1321	1053	1266	1371
1591	1479	1362	1211	1291	1377
1642	1515	1368	1074	1255	1365
1689	1566	1453	1298	1238	1335
1726	1595	1494	1333	1070	1304
1805	1654	1574	1462	1358	1413

At 20 year

973	924	889	831	775	812
925	876	836	780	724	761
895	847	796	714	584	707
862	815	759	685	671	718
830	789	718	576	674	722
827	786	736	681	705	733
825	785	736	685	710	739
821	781	714	581	686	734
834	793	732	660	697	735
859	810	734	589	679	729
881	836	778	700	669	714
914	851	798	716	585	700
921	884	840	781	727	754

Figure B.4 Pressure distribution of layer 4.

At 1 year

5726	5639	5505	5351	5243	5296	5373
5669	5530	5352	5100	4846	5050	5256
5597	5438	5202	4801	4104	4805	5143
5530	5359	5107	4770	4684	4955	5164
5473	5290	4984	4413	4803	5043	5202
5460	5301	5082	4851	4974	5130	5254
5477	5316	5089	4848	5014	5193	5319
5494	5310	4980	4319	4916	5208	5360
5550	5382	5119	4807	5045	5269	5408
5613	5464	5179	4632	5061	5306	5445
5700	5582	5390	5151	5148	5332	5489
5786	5672	5520	5299	4971	5328	5533
5847	5756	5640	5494	5372	5481	5608
5893	5791	5685	5603	5512	5542	5641

At 2 year

4754	4657	4509	4340	4218	4267	4343
4688	4535	4342	4072	3800	4007	4218
4607	4432	4179	3755	3013	3746	4095
4532	4345	4075	3716	3620	3897	4113
4470	4270	3943	3332	3742	3989	4152
4460	4285	4050	3799	3922	4082	4210
4489	4311	4068	3807	3975	4158	4287
4524	4321	3970	3264	3890	4191	4349
4604	4419	4139	3806	4048	4277	4421
4692	4530	4227	3649	4091	4341	4484
4803	4674	4467	4213	4204	4390	4551
4911	4784	4620	4384	4038	4405	4615
4990	4885	4758	4599	4465	4575	4705
5046	4974	4836	4717	4682	4725	4781

At 5 year

2928	2859	2758	2646	2567	2593	2639
2873	2762	2632	2460	2296	2417	2548
2801	2674	2501	2233	1805	2236	2450
2730	2587	2389	2130	2100	2285	2430
2673	2515	2260	1774	2119	2311	2432
2661	2521	2339	2142	2240	2364	2460
2683	2544	2363	2174	2282	2411	2506
2712	2555	2304	1833	2223	2425	2539
2770	2618	2394	2127	2291	2460	2574
2834	2690	2422	1902	2256	2468	2597
2921	2795	2595	2336	2271	2459	2628
3010	2878	2704	2435	1989	2429	2665
3079	2969	2830	2650	2482	2605	2748
3105	3057	2946	2803	2638	2762	2819

At 10 year

1728	1689	1632	1567	1519	1532	1558
1695	1631	1555	1456	1361	1428	1501
1650	1576	1476	1324	1073	1321	1439
1604	1520	1406	1260	1239	1341	1419
1564	1472	1328	1045	1242	1348	1412
1550	1469	1366	1253	1305	1370	1420
1555	1473	1371	1262	1318	1385	1434
1562	1470	1328	1058	1273	1380	1438
1586	1495	1368	1214	1298	1385	1444
1614	1527	1374	1077	1266	1376	1444
1656	1579	1460	1309	1263	1361	1451
1701	1620	1514	1358	1104	1340	1467
1735	1669	1585	1474	1373	1434	1511
1789	1751	1685	1529	1484	1505	1548

At 20 year

947	925	892	854	828	834	847
928	891	848	794	744	777	815
901	858	804	724	597	720	780
872	826	766	691	679	727	767
847	798	722	580	679	728	761
837	794	740	684	708	737	763
837	794	740	687	713	743	767
839	790	717	583	689	739	768
850	802	736	661	700	740	769
865	818	738	590	683	734	768
889	844	782	705	681	727	771
913	866	809	728	601	716	779
932	894	846	787	734	764	802
961	927	892	836	784	796	827

Figure B.5 Pressure distribution of layer 5.

At 1 year

5842	5778	5698	5626	5417	5389	5483	5497
5795	5733	5647	5513	5361	5255	5307	5381
5731	5676	5556	5377	5136	4902	5094	5265
5670	5605	5460	5222	4832	4155	4846	5151
5613	5541	5382	5123	4792	4706	4976	5170
5573	5488	5316	5002	4434	4819	5062	5213
5547	5475	5324	5094	4860	4987	5150	5267
5509	5483	5330	5093	4847	5019	5204	5324
5521	5498	5322	4980	4313	4918	5215	5362
5635	5549	5388	5115	4801	5045	5273	5408
5719	5621	5471	5181	4639	5069	5316	5453
5871	5711	5593	5396	5159	5170	5359	5502
5944	5799	5697	5543	5327	5007	5369	5549
5978	5864	5782	5666	5524	5408	5519	5629
5992	5946	5871	5744	5675	5549	5683	5746

At 2 year

4862	4538	4753	4650	4543	4465	4364	4508
4817	4760	4664	4517	4350	4231	4278	4351
4784	4695	4564	4369	4110	3858	4053	4226
4723	4615	4457	4201	3788	3065	3789	4102
4656	4543	4369	4093	3739	3642	3919	4118
4618	4486	4299	3962	3353	3757	4008	4162
4602	4476	4310	4064	3809	3936	4103	4223
4630	4495	4328	4073	3807	3981	4169	4292
4659	4527	4336	3971	3257	3892	4199	4350
4728	4602	4427	4135	3800	4048	4281	4420
4905	4698	4538	4229	3655	4098	4351	4491
4917	4813	4685	4473	4221	4227	4417	4563
5002	4925	4812	4644	4413	4075	4446	4632
5089	5008	4915	4786	4632	4504	4615	4727
5154	5091	5022	4935	4830	4765	4803	4862

At 5 year

3042	2998	2931	2853	2780	2712	2727	2758
2987	2933	2865	2764	2654	2576	2601	2645
2931	2878	2784	2653	2488	2336	2448	2554
2889	2807	2694	2518	2258	1841	2265	2455
2829	2739	2608	2405	2151	2118	2303	2435
2790	2685	2538	2278	1793	2133	2327	2441
2675	2673	2542	2352	2153	2252	2379	2469
2790	2688	2559	2371	2178	2289	2420	2509
2813	2714	2569	2309	1834	2228	2432	2540
2870	2769	2627	2395	2129	2295	2466	2574
2943	2840	2699	2427	1912	2268	2479	2604
3031	2930	2808	2604	2348	2301	2490	2639
3114	3023	2906	2731	2468	2029	2474	2681
3173	3096	2998	2859	2683	2523	2647	2770
3241	3187	3108	3899	2881	2800	2839	2985

At 10 year

1785	1767	1726	1697	1659	1624	1625	1632
1762	1731	1693	1635	1571	1524	1536	1562
1732	1698	1644	1568	1473	1384	1446	1505
1696	1654	1588	1487	1338	1094	1337	1442
1660	1609	1533	1416	1272	1249	1351	1422
1633	1572	1486	1338	1056	1251	1357	1417
1617	1557	1481	1373	1258	1311	1378	1425
1616	1558	1482	1375	1264	1322	1389	1435
1622	1564	1479	1331	1058	1276	1384	1439
1644	1586	1502	1370	1217	1301	1388	1444
1678	1618	1533	1378	1084	1274	1384	1449
1719	1662	1588	1467	1317	1281	1379	1458
1763	1708	1638	1532	1378	1128	1365	1476
1798	1745	1687	1602	1493	1396	1458	1523
1825	1788	1733	1686	1608	1555	1568	1601

At 20 year

979	968	952	928	902	884	881	887
965	948	927	894	857	831	836	849
950	929	899	855	804	756	787	817
928	903	865	810	732	607	728	782
905	875	833	771	697	684	732	769
888	851	806	728	586	683	733	763
877	841	800	743	686	710	741	765
874	839	799	743	688	714	745	768
875	840	795	719	583	690	741	768
885	850	806	737	662	702	742	769
902	867	822	741	594	687	738	771
924	892	849	786	709	690	736	775
946	917	876	819	738	612	729	784
963	937	903	855	797	746	776	809
979	960	933	896	852	821	827	846

Figure B.6 Pressure distribution of layer 6.

At 1 year

5984	5858	5724	5641	5596	5554	5586	5609	5687
5869	5754	5667	5536	5390	5289	5338	5411	5574
5745	5695	5578	5400	5165	4939	5128	5289	5405
5703	5624	5480	5241	4856	4186	4876	5174	5281
5681	5561	5402	5141	4808	4730	4999	5190	5317
5624	5511	5338	5015	4439	4832	5080	5231	5423
5576	5497	5344	5108	4869	5000	5167	5285	5409
5591	5499	5343	5099	4851	5026	5214	5336	5518
5624	5511	5332	4984	4315	4923	5223	5371	5541
5682	5560	5396	5115	4803	5048	5280	5416	5617
5734	5634	5480	5185	4646	5077	5327	5466	5683
5853	5726	5605	5403	5170	5188	5380	5520	5739
5964	5817	5718	5563	5350	5034	5401	5573	5772
5993	5891	5813	5700	5566	5459	5566	5665	6794
6031	5968	5909	5827	5745	5697	5731	5780	5862
6063	6032	5971	5912	5829	5784	5846	5882	5903

At 2 year

4917	4852	4773	4686	4573	4497	4508	4537	4579
4861	4784	4686	4541	4380	4266	4310	4382	4476
4804	4716	4587	4394	4141	3896	4087	4250	4371
4748	4635	4479	4221	3812	3096	3819	4125	4278
4674	4565	4392	4111	3755	3666	3942	4138	4279
4642	4510	4322	3976	3358	3771	4026	4180	4295
4638	4500	4332	4078	3818	3950	4121	4241	4354
4645	4511	4342	4080	3812	3988	4180	4305	4403
4671	4540	4347	3976	3260	3897	4206	4358	4459
4735	4612	4435	4136	3801	4051	4287	4428	4523
4828	4712	4546	4233	3661	4106	4361	4503	4612
4936	4830	4698	4481	4232	4245	4438	4581	4697
5029	4946	4835	4666	4438	4104	4479	4655	4774
5127	5040	4950	4824	4678	4560	4666	4766	4878
5197	5138	5068	4974	4878	4821	4851	4900	4924
5249	5207	5149	5061	5002	4974	4986	5014	5056

At 5 year

3061	3013	2951	2874	2800	2746	2745	2770	2798
3009	2951	2881	2783	2676	2601	2624	2666	2713
2953	2893	2802	2672	2510	2362	2472	2570	2651
2900	2822	2710	2534	2276	1862	2286	2471	2563
2843	2756	2626	2420	2164	2135	2320	2450	2542
2806	2704	2558	2290	1797	2144	2341	2453	2536
2792	2691	2560	2365	2161	2264	2393	2482	2554
2800	2701	2571	2378	2184	2296	2429	2518	2585
2823	2725	2578	2314	1838	2233	2439	2547	2629
2871	2778	2634	2398	2133	2300	2472	2581	2647
2956	2852	2708	2433	1921	2279	2491	2616	2720
3041	2946	2820	2614	2362	2322	2513	2657	2771
3137	3042	2930	2754	2496	2059	2508	2704	2835
3204	3125	3032	2897	2731	2582	2699	2808	2917
3273	3218	3144	3042	2934	2862	2892	2944	3021
3321	3281	3225	3099	3008	2944	2968	3037	3082

At 10 year

1795	1777	1735	1708	1672	1640	1639	1645	1665
1772	1741	1702	1646	1584	1539	1550	1575	1605
1742	1707	1655	1580	1486	1399	1460	1515	1557
1706	1663	1598	1496	1349	1106	1349	1451	1508
1670	1619	1543	1425	1279	1259	1361	1431	1482
1644	1583	1498	1345	1059	1257	1364	1424	1471
1628	1568	1492	1380	1263	1317	1385	1431	1474
1624	1566	1489	1379	1267	1325	1393	1440	1483
1629	1571	1485	1334	1061	1279	1387	1443	1485
1650	1592	1507	1372	1220	1305	1392	1449	1496
1685	1625	1539	1382	1090	1281	1390	1456	1512
1728	1671	1596	1473	1326	1295	1392	1468	1522
1774	1719	1652	1546	1394	1146	1384	1490	1563
1816	1763	1707	1624	1521	1429	1488	1546	1607
1852	1815	1769	1705	1636	1588	1598	1624	1668
1885	1858	1815	1862	1710	1675	1672	1685	1704

At 20 year

985	974	957	934	909	892	889	894	903
971	954	932	900	864	839	844	856	873
955	934	905	862	811	764	795	823	845
933	908	871	816	737	613	734	787	816
911	881	839	776	701	689	737	773	799
895	858	812	732	587	686	737	767	791
883	847	806	747	688	713	745	768	790
878	843	803	745	689	715	748	771	791
879	844	799	721	584	692	743	770	791
889	854	809	739	663	703	744	772	795
907	872	825	743	596	690	742	774	802
929	897	854	789	713	696	742	780	812
952	923	884	826	747	621	739	791	828
972	946	915	867	812	764	792	821	854
992	973	948	913	872	845	849	863	890
1006	992	971	944	915	896	894	901	912

Figure B.7 Pressure distribution of layer 7.

At 1 year

5915	5883	5826	5758	5692	5650	5643	5658	5678
5886	5844	5774	5684	5595	5538	5544	5576	5619
5844	5779	5689	5562	5424	5329	5374	5446	5524
5792	5715	5595	5418	5188	4967	5154	5313	5425
5737	5645	5496	5256	4874	4203	4897	5198	5352
5692	5586	5418	5155	4823	4739	5012	5211	5340
5663	5542	5358	5029	4450	4842	5094	5253	5365
5646	5527	5361	5120	4877	5011	5183	5310	5411
5640	5524	5356	5108	4859	5035	5226	5355	5448
5651	5533	5342	4990	4320	4929	5231	5386	5486
5692	5581	5404	5115	4806	5053	5288	5432	5534
5759	5655	5489	5190	4650	5084	5338	5484	5593
5838	5748	5617	5408	5181	5203	5398	5542	5655
5916	5839	5735	5579	5369	5055	5425	5600	5717
5983	5916	5835	5724	5595	5492	5597	5696	5793
6032	5983	5920	5839	5759	5712	5745	5797	5866
6072	6040	5989	5927	5871	5841	5854	5886	5920

At 2 year

4973	4935	4867	4785	4706	4653	4639	4650	4668
4937	4889	4807	4703	4600	4533	4531	4560	4604
4887	4812	4710	4569	4416	4308	4348	4419	4500
4825	4738	4605	4412	4164	3925	4114	4275	4391
4761	4658	4495	4237	3830	3113	3840	4150	4308
4709	4592	4409	4126	3770	3675	3955	4159	4292
4677	4543	4344	3991	3369	3780	4040	4202	4317
4663	4532	4351	4091	3827	3961	4137	4266	4370
4666	4538	4356	4089	3819	3997	4192	4324	4421
4692	4564	4357	3982	3265	3903	4214	4374	4477
4755	4634	4443	4136	3804	4056	4295	4443	4548
4848	4735	4556	4238	3665	4112	4371	4521	4632
4955	4854	4711	4486	4243	4259	4457	4604	4719
5059	4971	4854	4684	4458	4125	4505	4684	4805
5148	5069	4976	4850	4709	4595	4699	4799	4902
5212	5154	5081	4986	4893	4836	4866	4918	4995
5266	5227	5165	5091	5023	4985	4993	5024	5060

At 5 year

3100	3072	3023	2963	2906	2867	2853	2858	2869
3070	3035	2976	2902	2831	2783	2778	2794	2822
3028	2972	2900	2804	2701	2630	2650	2693	2745
2974	2910	2816	2686	2527	2382	2490	2587	2660
2916	2840	2723	2547	2290	1875	2301	2488	2588
2867	2777	2641	2434	2178	2145	2331	2466	2556
2834	2730	2575	2303	1807	2153	2352	2470	2555
2819	2717	2576	2376	2169	2273	2405	2500	2579
2822	2722	2583	2386	2191	2303	2438	2533	2605
2844	2744	2587	2320	1842	2238	2445	2559	2638
2896	2796	2642	2399	2137	2305	2479	2594	2680
2973	2872	2717	2439	1926	2287	2501	2633	2733
3063	2968	2833	2621	2374	2338	2532	2679	2793
3153	3066	2948	2772	2516	2080	2534	2733	2861
3232	3153	3056	2922	2761	2618	2733	2841	2949
3292	3233	3155	3053	2947	2877	2906	2961	3040
3344	3302	3237	3156	3079	3032	3037	3069	3105

At 10 year

1828	1811	1784	1750	1719	1696	1688	1689	1695
1809	1789	1756	1716	1675	1647	1643	1652	1667
1784	1753	1713	1658	1599	1556	1567	1590	1620
1751	1716	1663	1588	1496	1410	1471	1525	1567
1716	1673	1606	1504	1357	1114	1358	1461	1518
1683	1632	1553	1433	1288	1265	1367	1440	1491
1659	1598	1508	1352	1065	1262	1371	1434	1481
1643	1583	1501	1386	1267	1322	1391	1441	1484
1636	1578	1496	1384	1271	1329	1398	1448	1487
1641	1582	1490	1338	1064	1282	1390	1450	1492
1662	1603	1512	1374	1223	1308	1396	1456	1503
1697	1638	1545	1386	1094	1286	1396	1465	1521
1740	1684	1605	1479	1334	1305	1403	1481	1545
1786	1733	1664	1558	1406	1159	1399	1506	1579
1828	1779	1721	1639	1539	1450	1507	1566	1627
1861	1824	1775	1711	1643	1596	1606	1633	1677
1891	1864	1821	1768	1717	1683	1679	1694	1713

At 20 year

1002	993	979	961	943	930	926	927	930
992	981	963	941	918	902	899	904	913
978	961	938	907	873	849	854	866	883
960	939	909	867	817	771	801	828	850
939	914	875	820	742	616	739	792	821
919	889	844	781	705	692	741	778	804
904	867	818	736	590	688	740	772	796
892	856	811	751	691	715	748	773	795
886	851	807	747	691	716	750	774	794
886	851	802	723	585	693	745	774	795
896	861	812	740	664	705	746	776	799
914	879	829	745	598	693	745	779	807
937	905	859	792	716	701	748	787	819
960	931	891	832	753	627	746	800	837
981	955	922	875	821	774	802	831	864
997	978	952	916	876	849	853	868	895
1011	997	975	947	919	900	898	906	917

Figure B.8 Pressure distribution of layer 8.

At 1 year

5908	5889	5803	5757	5620	5608	5647	5673	5655	5666
5890	5848	5777	5685	5594	5537	5543	5574	5627	5675
5851	5793	5702	5577	5441	5349	5393	5460	5555	5597
5799	5728	5607	5430	5203	4985	5170	5324	5466	5544
5745	5659	5507	5267	4888	4221	4913	5207	5394	5512
5700	5601	5430	5165	4833	4751	5024	5220	5380	5485
5671	5561	5372	5038	4452	4850	5108	5268	5401	5452
5654	5546	5375	5130	4886	5022	5198	5325	5438	5476
5648	5542	5368	5117	4868	5045	5238	5367	5472	5512
5658	5549	5351	4997	4326	4936	5239	5394	5499	5527
5699	5596	5413	5125	4812	5059	5295	5439	5542	5558
5765	5669	5497	5195	4653	5089	5345	5491	5594	5635
5844	5764	5628	5422	5191	5213	5411	5552	5656	5678
5922	5854	5747	5591	5383	5070	5443	5613	5720	5781
5989	5932	5850	5739	5613	5513	5617	5711	5789	5830
6034	5990	5924	5842	5760	5713	5748	5798	5844	5883
6089	6043	5997	5938	5885	5842	5794	5889	5905	5898
6123	6086	6005	5989	5913	5884	5869	5893	5956	5909

At 2 year

4980	4940	4902	4851	4715	4620	4662	4682	4708	4746
4941	4892	4808	4703	4599	4530	4529	4557	4609	4732
4894	4827	4723	4585	4434	4328	4367	4434	4528	4718
4832	4751	4618	4425	4180	3943	4130	4285	4439	4551
4768	4672	4507	4248	3844	3129	3855	4158	4361	4498
4716	4607	4421	4137	3779	3687	3967	4168	4347	4482
4684	4564	4359	4001	3370	3788	4054	4217	4366	4485
4670	4552	4366	4102	3836	3973	4151	4281	4403	4585
4673	4558	4369	4099	3828	4007	4204	4336	4457	4610
4698	4580	4367	3989	3270	3910	4222	4381	4494	4658
4761	4649	4452	4145	3810	4061	4302	4449	4552	4719
4853	4749	4563	4242	3667	4117	4378	4527	4628	4751
4962	4871	4723	4501	4253	4269	4469	4613	4715	4803
5065	4986	4867	4697	4472	4140	4523	4697	4814	4809
5154	5087	4992	4867	4728	4618	4720	4815	4907	4933
5213	5160	5084	4988	4893	4836	4867	4917	4950	4978
5287	5239	5169	5126	5054	4997	5034	5038	5064	5072
5371	5284	5253	5158	5060	5007	5042	5053	5071	5084

At 5 year

3109	3075	3047	2996	2923	2868	2872	2869	2871	2904
3072	3036	2976	2902	2829	2781	2776	2792	2825	2853
3033	2983	2910	2815	2714	2644	2664	2703	2761	2700
2979	2920	2826	2696	2538	2394	2501	2594	2684	2780
2921	2850	2732	2555	2300	1886	2311	2493	2601	2716
2871	2789	2650	2442	2185	2154	2340	2472	2573	2667
2839	2746	2587	2311	1808	2159	2363	2481	2571	2662
2824	2732	2588	2384	2176	2281	2415	2511	2593	2684
2827	2737	2593	2394	2198	2310	2446	2541	2619	2708
2849	2756	2595	2326	1847	2244	2451	2564	2647	2731
2900	2808	2650	2407	2142	2310	2485	2599	2688	2775
2976	2884	2724	2443	1929	2293	2508	2638	2739	2820
3068	2983	2844	2634	2384	2349	2544	2687	2798	2891
3157	3080	2961	2784	2530	2094	2552	2745	2870	2900
3237	3169	3071	2938	2780	2640	2753	2856	2952	3042
3292	3237	3157	3053	2945	2874	2905	2957	3053	3093
3346	3310	3240	3160	3082	3047	3040	3077	3124	3168
3363	3238	3269	3186	3114	3108	3083	3146	3192	3230

At 10 year

1838	1826	1790	1779	1752	1702	1692	1695	1703	1716
1810	1790	1757	1717	1675	1647	1643	1652	1668	1682
1787	1759	1719	1665	1607	1565	1575	1596	1629	1644
1754	1722	1669	1594	1502	1417	1477	1529	1573	1578
1719	1679	1611	1509	1363	1121	1363	1464	1529	1565
1686	1639	1559	1438	1292	1270	1372	1444	1502	1531
1661	1608	1515	1357	1066	1265	1377	1440	1490	1513
1646	1592	1507	1390	1271	1326	1396	1446	1492	1507
1640	1587	1502	1388	1275	1333	1402	1452	1495	1515
1643	1589	1495	1342	1067	1285	1393	1453	1498	1520
1664	1610	1517	1379	1226	1311	1400	1459	1508	1525
1699	1645	1550	1389	1096	1290	1401	1469	1525	1536
1743	1693	1611	1486	1340	1311	1410	1487	1550	1563
1788	1742	1671	1566	1415	1168	1409	1513	1584	1599
1831	1789	1729	1648	1550	1463	1519	1574	1629	1648
1861	1827	1776	1711	1642	1594	1605	1632	1679	1691
1892	1868	1826	1770	1721	1690	1678	1679	1718	1722
1897	1870	1837	1812	1732	1692	1680	1710	1724	1726

At 20 year

1013	1004	990	972	954	941	937	938	941	952
993	982	964	940	917	901	899	903	913	923
980	964	941	911	877	854	858	870	892	911
961	943	912	870	820	775	804	831	860	889
940	917	878	823	745	620	742	794	830	853
921	893	847	783	707	695	743	780	811	848
905	872	822	738	591	690	743	775	803	832
894	861	815	753	692	717	751	776	800	829
888	856	810	750	693	718	752	777	799	828
888	855	805	725	587	695	746	775	798	827
898	865	815	742	666	706	748	777	801	832
915	883	831	747	599	695	748	781	808	840
938	910	863	796	719	704	752	789	819	850
961	936	896	837	758	631	751	803	837	867
982	960	927	880	827	781	808	836	862	892
997	979	952	916	876	848	853	867	885	903
1014	1010	979	968	913	906	897	882	906	919
1026	1023	1014	991	950	942	935	909	928	935

Figure B.9 Pressure distribution of layer 9.

At 1 year

5943	5931	5857	5815	5781	5748	5735	5763	5789	5797
5915	5896	5809	5763	5726	5614	5653	5672	5694	5705
5897	5855	5783	5691	5600	5543	5549	5583	5636	5684
5859	5804	5713	5589	5454	5363	5406	5478	5573	5615
5808	5739	5618	5441	5216	5003	5184	5343	5485	5563
5753	5669	5517	5277	4902	4249	4930	5229	5416	5534
5708	5613	5440	5173	4839	4772	5039	5244	5404	5509
5677	5573	5382	5044	4452	4859	5121	5289	5422	5473
5661	5559	5385	5138	4894	5031	5208	5343	5456	5494
5656	5554	5378	5125	4877	5053	5247	5384	5489	5529
5664	5559	5359	5005	4335	4944	5247	5409	5514	5538
5706	5605	5420	5132	4819	5065	5302	5453	5556	5572
5771	5679	5504	5201	4659	5095	5353	5505	5608	5649
5851	5773	5637	5431	5199	5221	5420	5567	5671	5683
5928	5863	5756	5600	5392	5080	5454	5630	5737	5798
5996	5943	5860	5750	5625	5526	5630	5727	5805	5846
6039	5996	5930	5846	5764	5717	5752	5806	5852	5891
6094	6049	5983	5942	5849	5748	5798	5847	5893	5906
6128	6092	6011	5993	5917	5819	5826	5881	5904	5917

At 2 year

5027	4983	4968	4989	4894	4796	4809	4856	4875	4903
4986	4929	4914	4857	4726	4624	4675	4708	4726	4768
4947	4898	4814	4709	4603	4535	4534	4565	4617	4742
4902	4838	4734	4596	4447	4342	4380	4451	4547	4629
4840	4762	4629	4436	4192	3960	4143	4304	4450	4572
4775	4682	4517	4258	3858	3158	3872	4179	4371	4516
4723	4618	4431	4144	3785	3708	3982	4190	4355	4503
4690	4576	4368	4006	3369	3797	4066	4238	4376	4509
4676	4564	4376	4109	3843	3981	4161	4299	4417	4614
4680	4569	4378	4107	3837	4014	4213	4352	4461	4675
4704	4590	4375	3997	3279	3917	4229	4395	4505	4719
4767	4658	4459	4152	3817	4067	4308	4463	4569	4772
4859	4758	4571	4248	3673	4123	4385	4541	4646	4816
4968	4881	4731	4509	4261	4277	4478	4628	4734	4871
5070	4996	4876	4705	4481	4150	4535	4714	4823	4929
5160	5098	5003	4878	4740	4630	4733	4831	4911	4958
5217	5166	5088	4992	4896	4839	4870	4923	4970	4999
5301	5256	5174	5049	4918	4902	4914	4956	4992	5049
5397	5308	5261	5165	5067	5013	5054	5063	5073	5087

At 5 year

3168	3121	3098	3076	3021	2997	2974	2925	2941	3054
3116	3102	3059	3025	2945	2869	2883	2876	2883	2957
3077	3041	2981	2906	2832	2784	2779	2797	2828	2856
3038	2991	2918	2823	2723	2654	2672	2715	2776	2715
2985	2927	2833	2703	2546	2406	2510	2607	2700	2796
2926	2857	2739	2561	2308	1903	2322	2507	2629	2745
2877	2797	2657	2446	2187	2165	2349	2486	2598	2692
2843	2755	2594	2314	1806	2164	2371	2495	2594	2687
2829	2742	2595	2390	2181	2287	2422	2524	2611	2704
2832	2746	2600	2399	2203	2315	2452	2553	2635	2726
2853	2764	2601	2331	1854	2249	2456	2575	2659	2749
2905	2815	2655	2413	2147	2314	2490	2610	2697	2793
2980	2892	2729	2448	1933	2297	2514	2650	2745	2836
3072	2991	2851	2641	2391	2355	2552	2701	2806	2897
3161	3088	2969	2792	2538	2103	2562	2761	2876	2906
3241	3178	3080	2947	2790	2651	2765	2870	2955	3048
3294	3241	3160	3055	2946	2875	2907	2962	3011	3099
3342	3319	3235	3146	3087	3042	3019	3080	3135	3176
3389	3245	3278	3192	3125	3116	3103	3176	3204	3251

At 10 year

1895	1879	1826	1803	1785	1762	1745	1714	1791	1798
1848	1835	1797	1751	1726	1689	1675	1668	1687	1696
1813	1793	1759	1718	1676	1648	1644	1653	1670	1684
1790	1764	1723	1669	1612	1571	1580	1603	1638	1653
1757	1726	1673	1598	1507	1424	1482	1536	1589	1594
1722	1683	1615	1512	1367	1131	1369	1472	1540	1576
1689	1643	1562	1440	1293	1277	1377	1452	1513	1542
1664	1612	1519	1359	1065	1268	1381	1448	1502	1524
1648	1598	1511	1393	1274	1329	1399	1454	1501	1517
1642	1592	1506	1390	1278	1335	1405	1458	1503	1523
1646	1594	1498	1345	1070	1288	1396	1459	1504	1526
1667	1614	1520	1382	1229	1314	1403	1465	1513	1530
1701	1649	1553	1391	1099	1293	1404	1476	1529	1542
1745	1698	1615	1491	1345	1315	1415	1495	1555	1568
1790	1747	1676	1570	1420	1174	1416	1523	1589	1600
1833	1794	1734	1654	1556	1469	1525	1583	1630	1649
1862	1829	1777	1713	1643	1595	1606	1634	1661	1673
1883	1872	1793	1759	1685	1649	1627	1668	1679	1684
1898	1864	1842	1817	1736	1701	1681	1673	1683	1698

At 20 year

1024	1021	1001	996	993	991	987	990	997	1008
1006	1002	987	979	972	953	951	956	964	975
994	983	965	942	918	902	900	905	915	925
981	967	944	914	880	857	861	873	895	914
963	945	915	872	823	778	807	835	864	893
942	920	880	824	747	625	745	798	834	857
922	896	849	784	708	698	746	784	815	852
906	875	824	739	590	691	745	779	807	836
895	864	817	755	694	718	752	780	804	833
889	858	812	751	694	719	754	780	802	831
889	857	806	726	589	696	748	778	801	830
899	867	817	744	667	708	750	780	804	835
916	886	833	749	600	696	749	784	811	843
940	912	865	799	721	706	754	794	824	855
963	939	898	839	760	634	755	808	842	872
984	963	930	883	830	784	811	840	866	896
998	981	953	916	876	848	853	868	886	904
1015	1012	980	968	913	906	897	883	907	920
1027	1025	1015	991	950	942	935	910	929	936

Figure B.10 Pressure distribution of layer 10.

APPENDIX C

GRAPH OF PRESSURE DISTRIBUTION

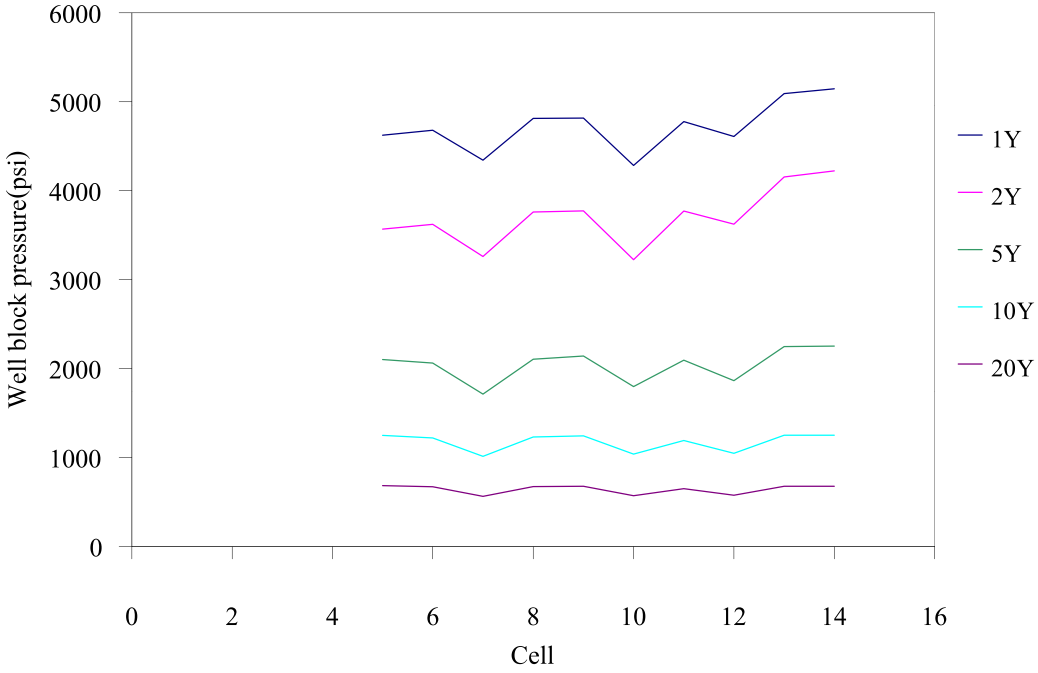


Figure C.1a Pressure distribution of layer 1 (3 wells) at various times.

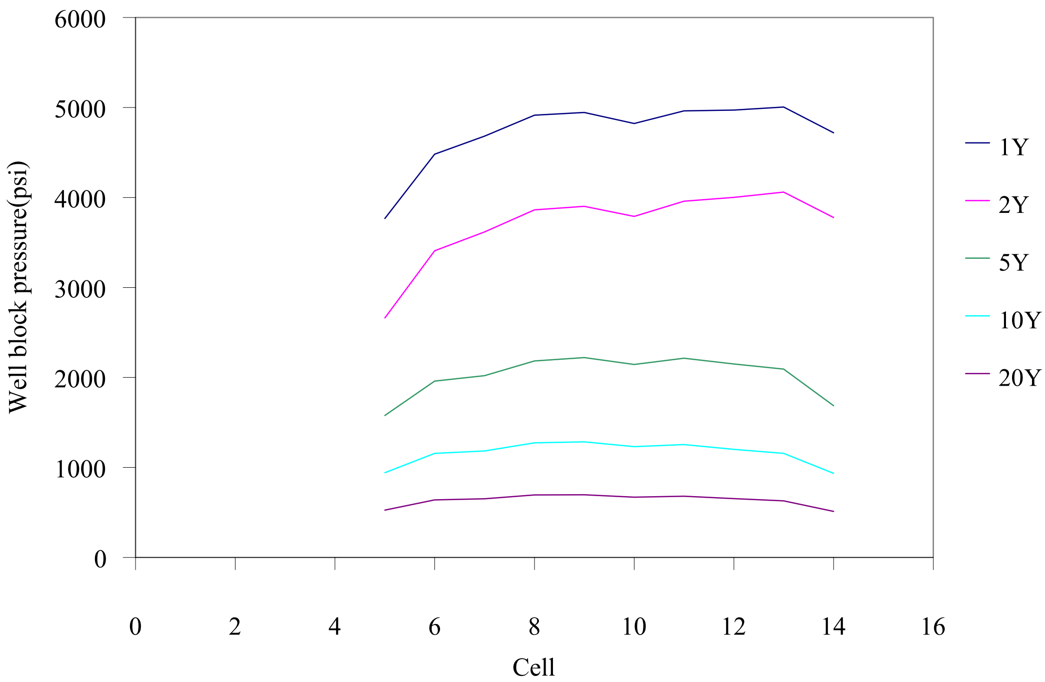


Figure C.1b Pressure distribution of layer 1 (2 wells) at various times.

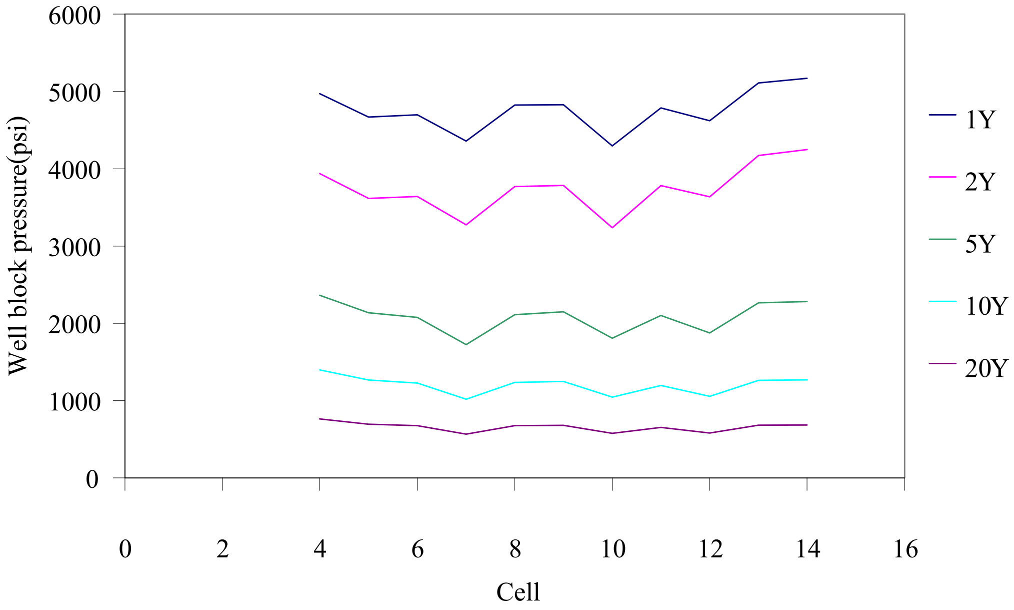


Figure C.2a Pressure distribution of layer 2 (3 wells) at various times.

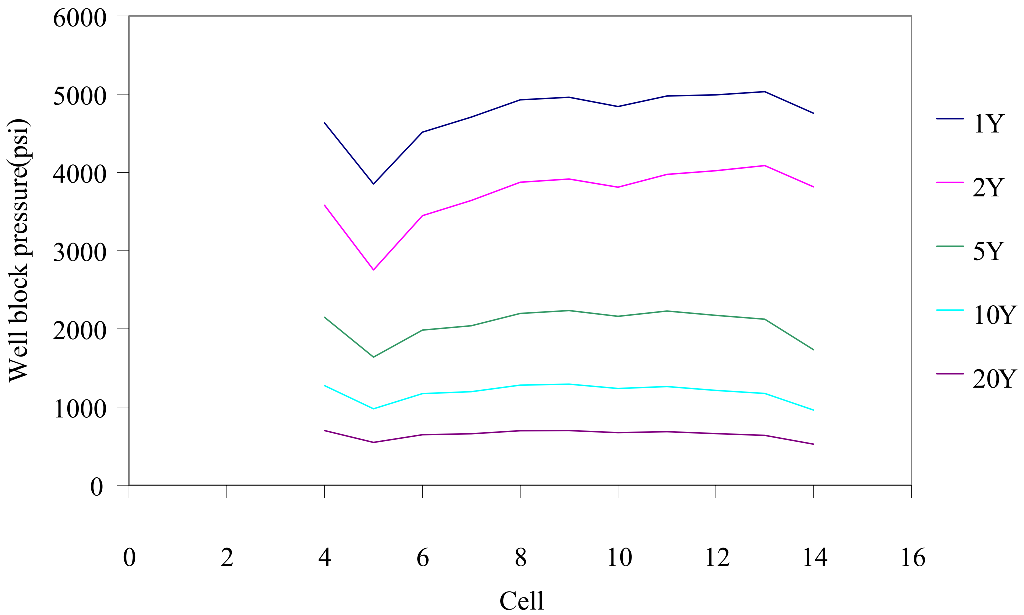


Figure C.2b Pressure distribution of layer 2 (2 wells) at various times.

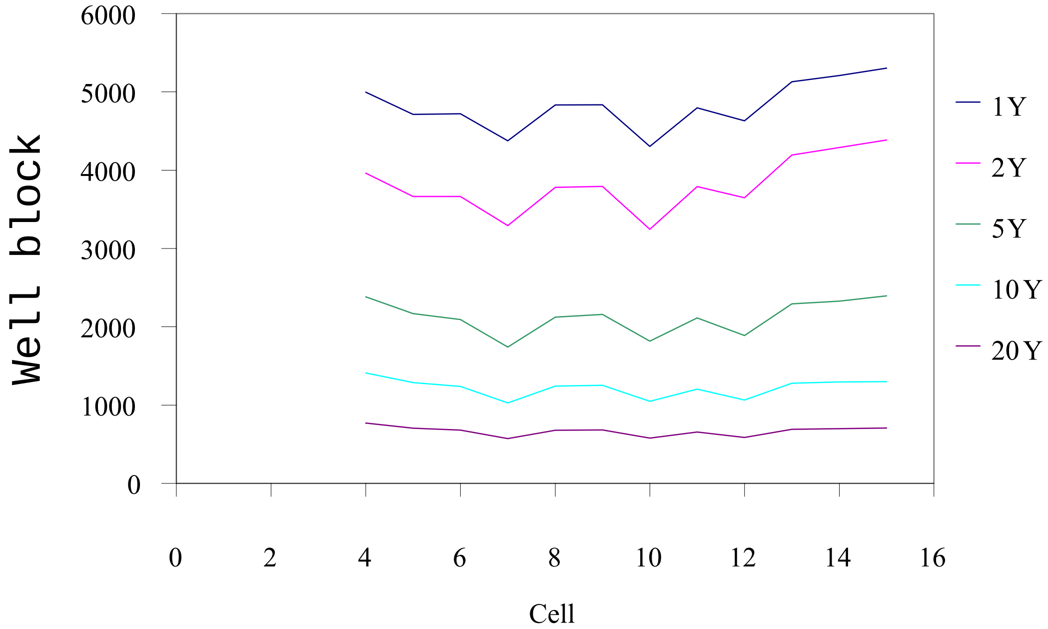


Figure C.3a Pressure distribution of layer 3 (3 wells) at various times.

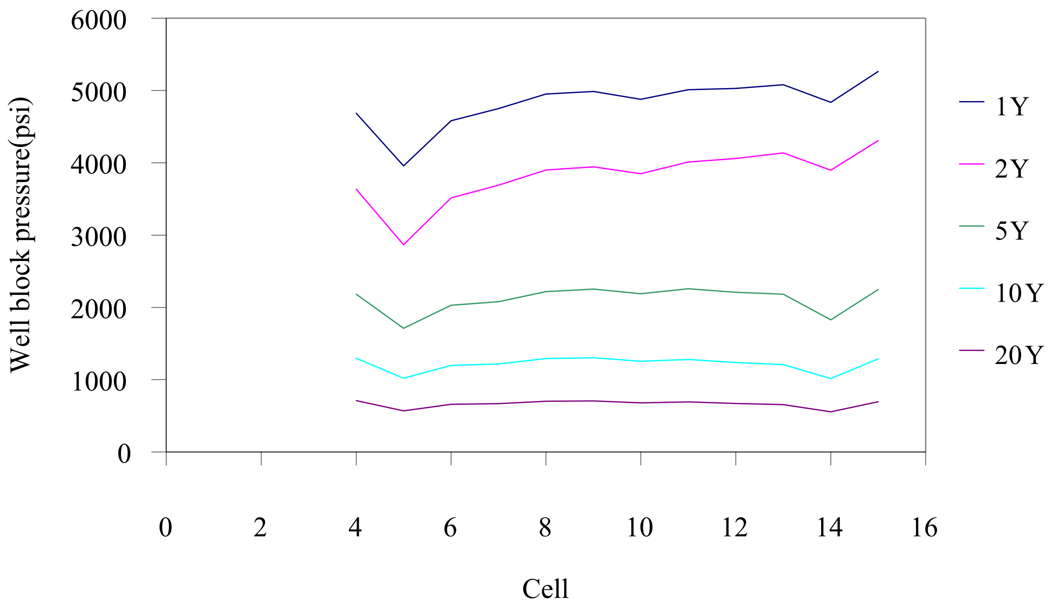


Figure C.3b Pressure distribution of layer 3 (2 wells) at various times.

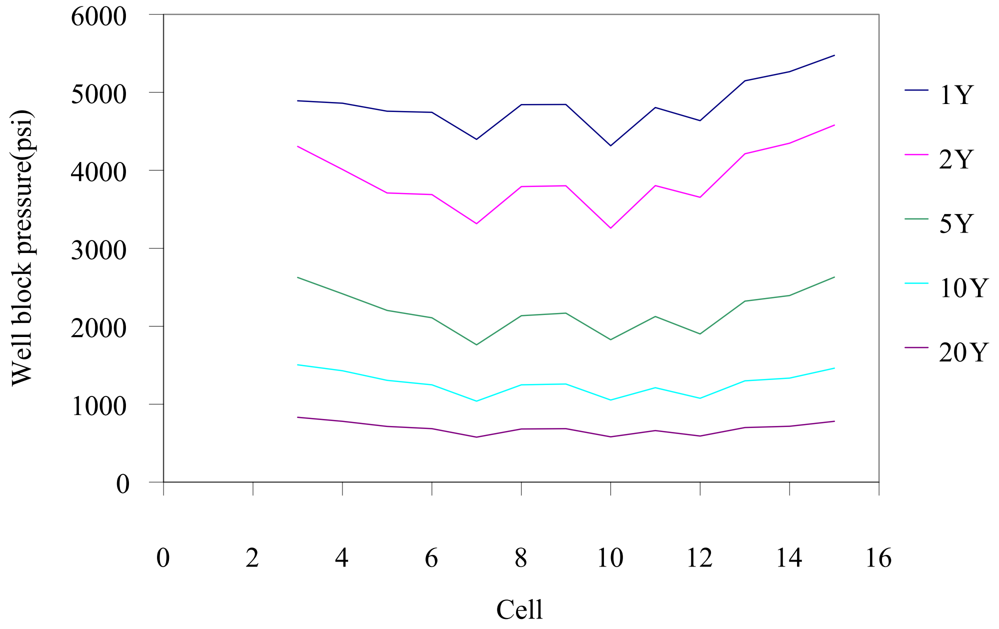


Figure C.4a Pressure distribution of 4 (3 wells) at various times.

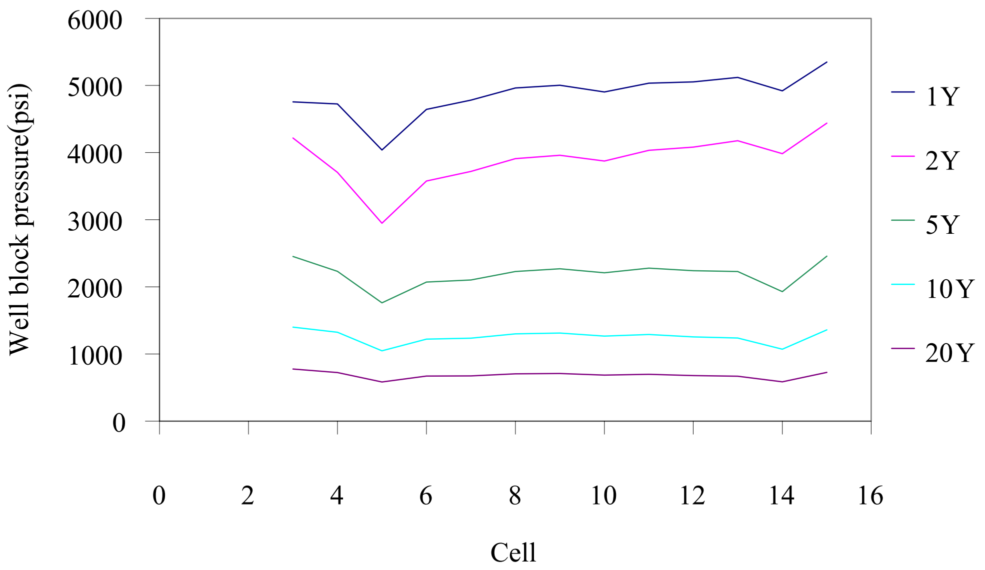


Figure C.4b Pressure distribution of 4 (2 wells) at various times.

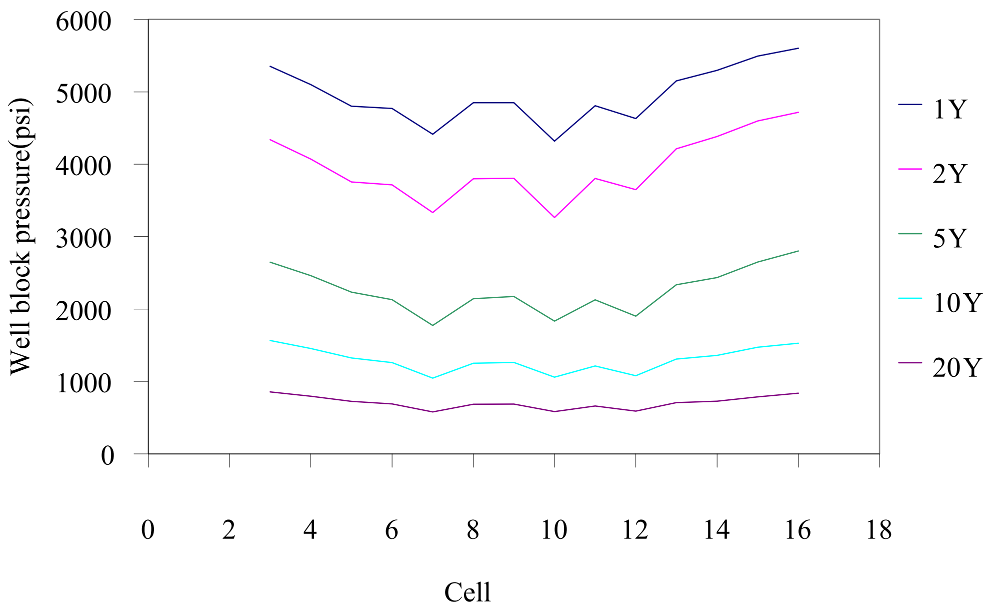


Figure C.5a Pressure distribution of layer 5 (3 wells) at various times.

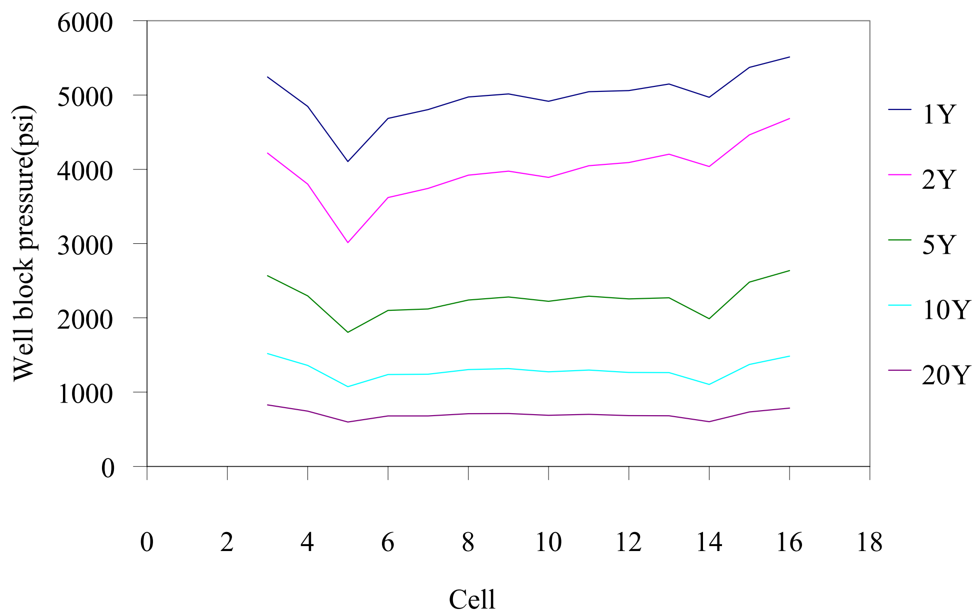


Figure C.5b Pressure distribution of layer 5 (2 wells) at various times.

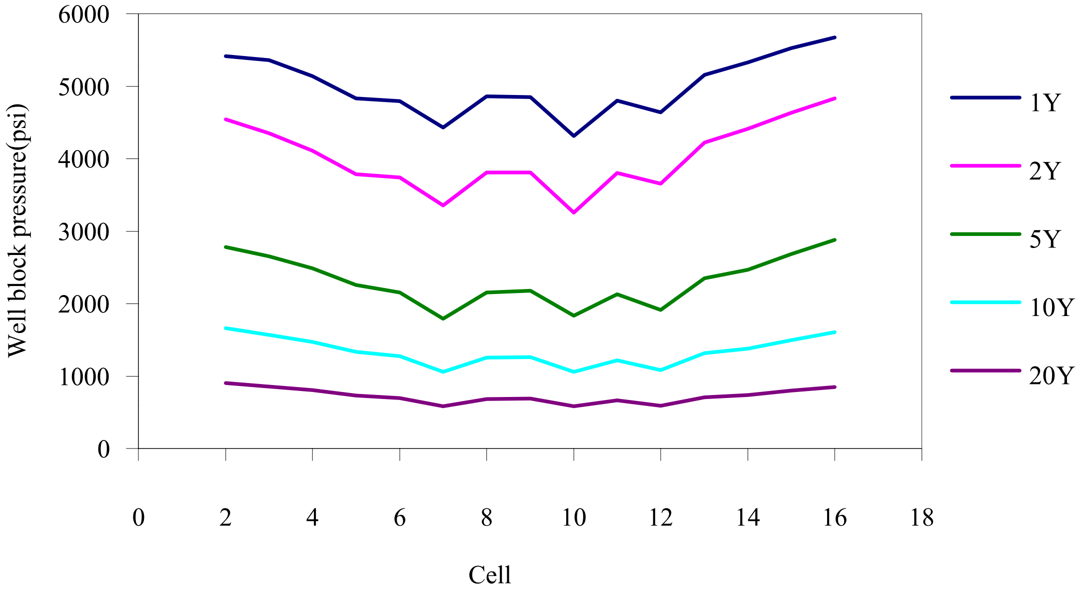


Figure C.6a Pressure distribution of layer 6 (3 wells) at various times.

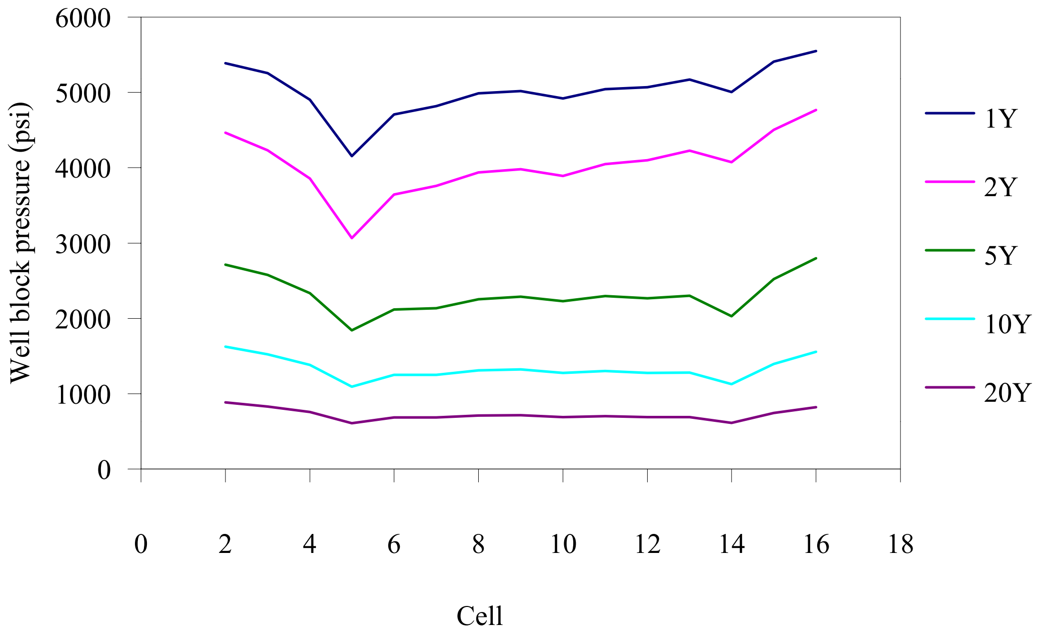


Figure C.6b Pressure distribution of layer 6 (2 wells) at various times.

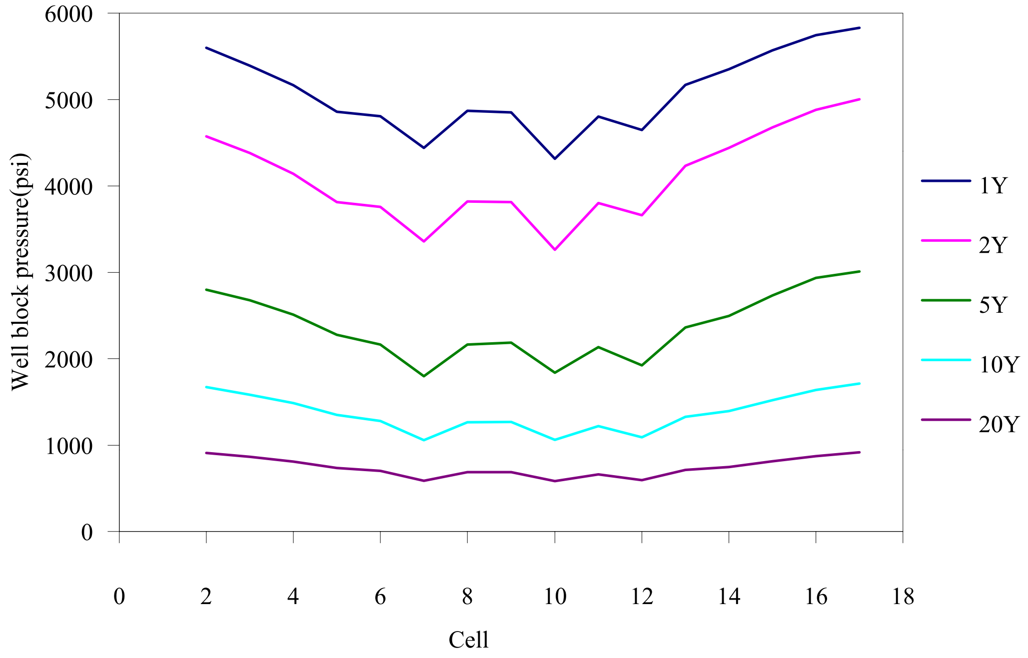


Figure C.7a Pressure distribution of layer 7 (3 wells) at various times.

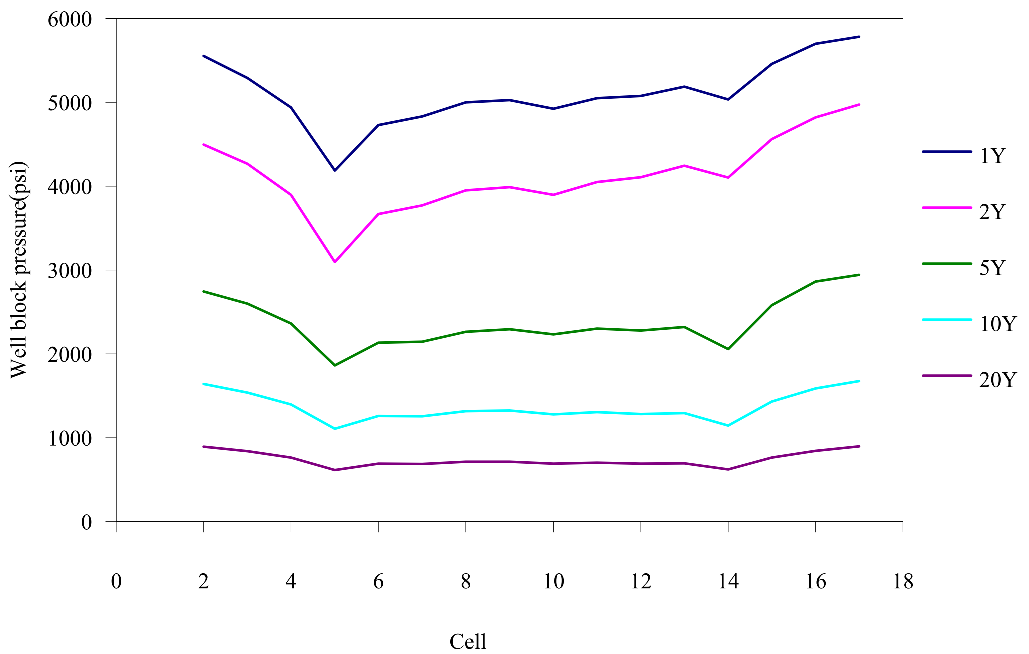


Figure C.7b Pressure distribution of layer 7 (2 wells) at various times.

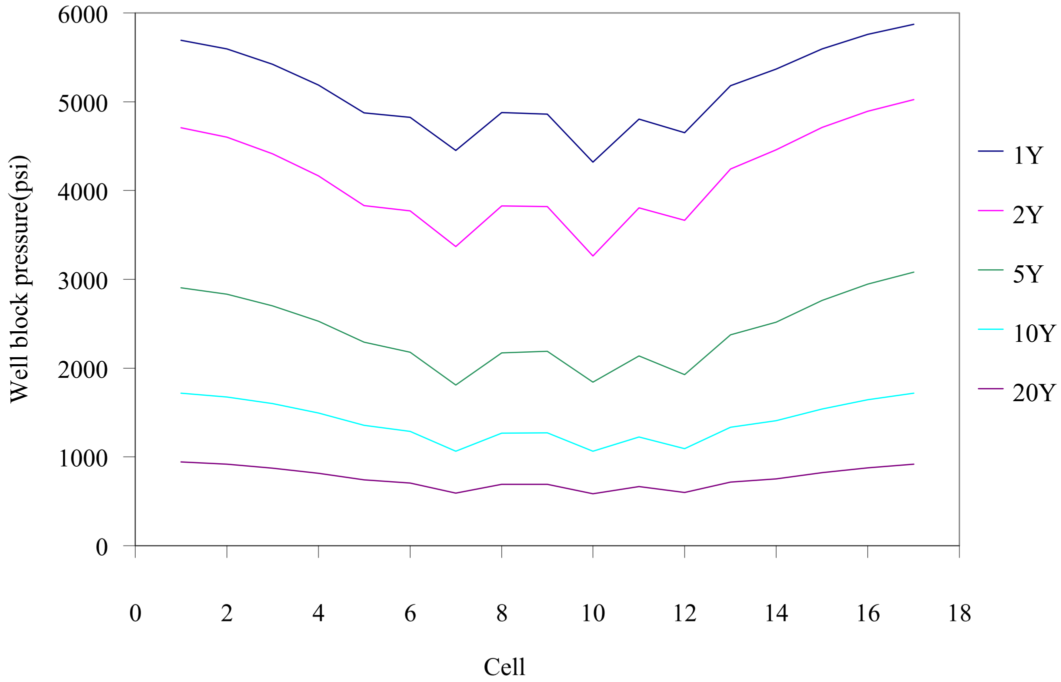


Figure C.8a Pressure distribution of layer 8 (3 wells) at various times.

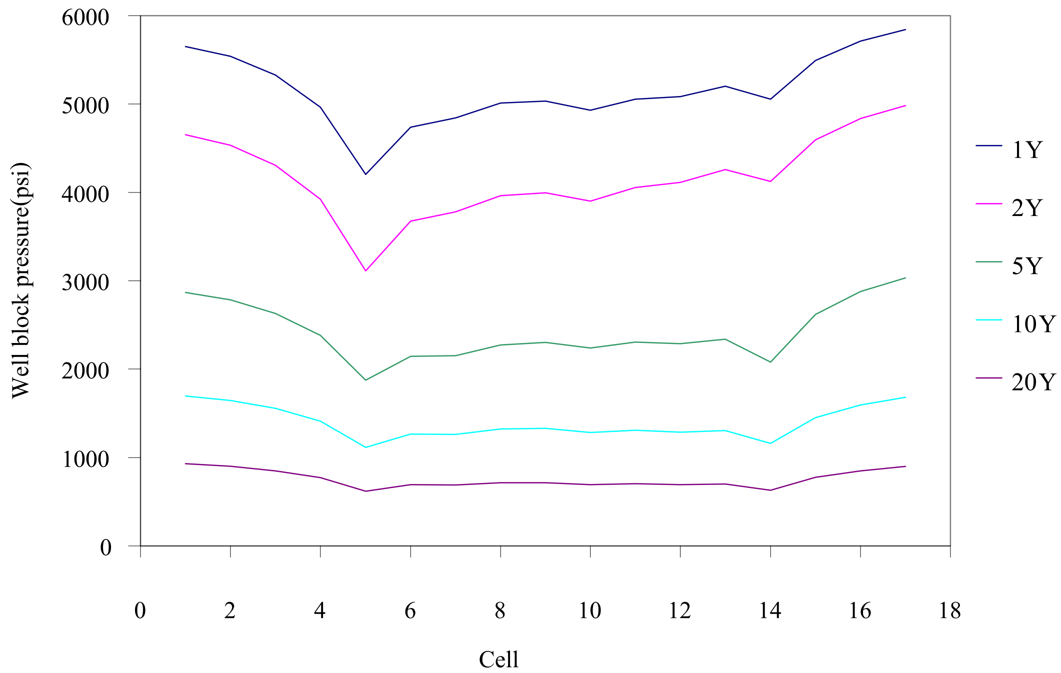


Figure C.8b Pressure distribution of layer 8 (2 wells) at various times.

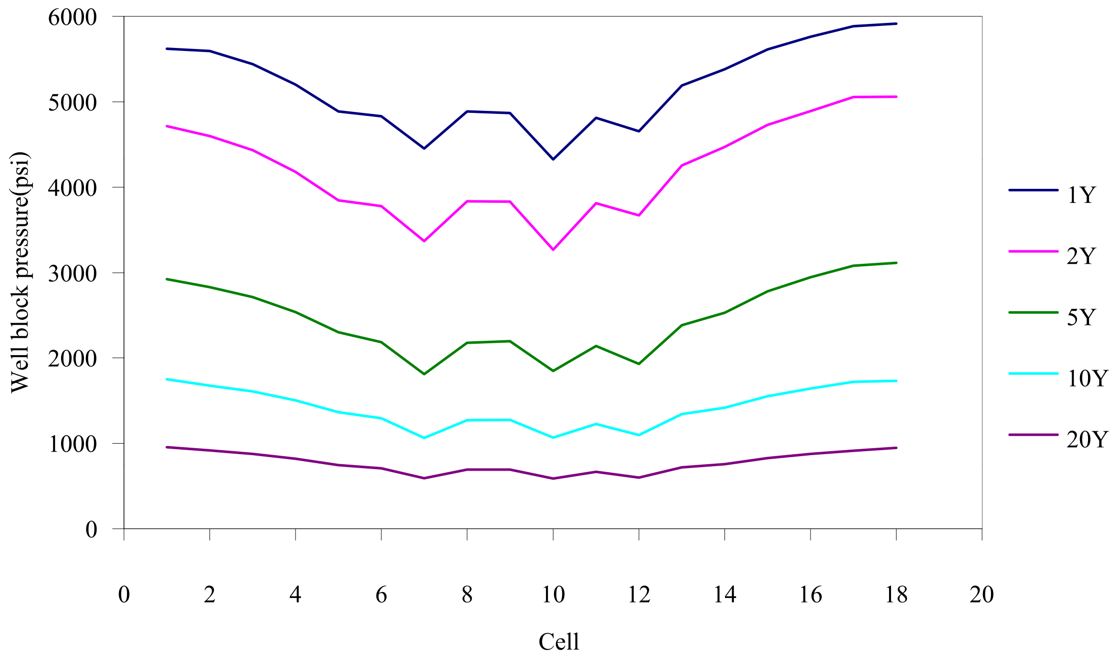


Figure C.9a Pressure distribution of layer 9 (3 wells) at various times.

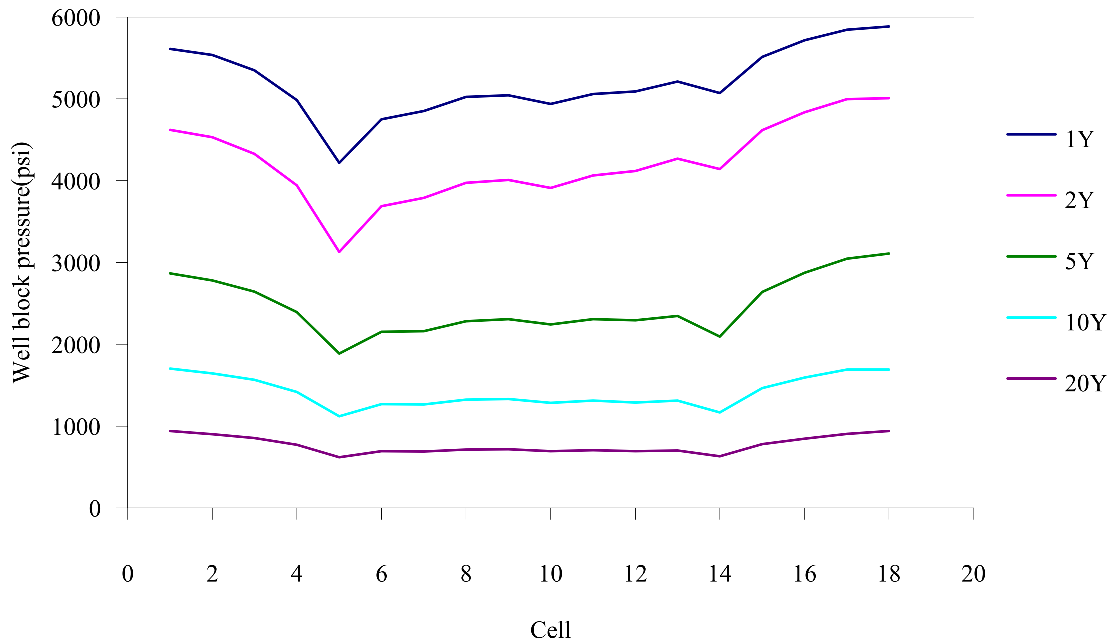


Figure C.9b Pressure distribution of layer 9 (2 wells) at various times.

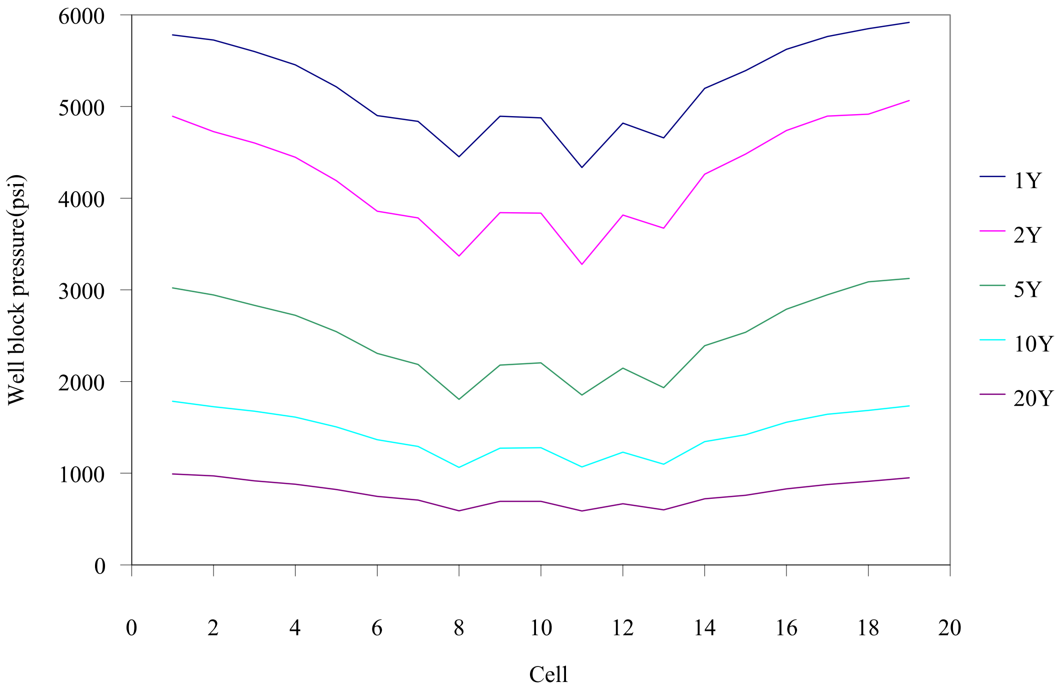


Figure C.10a Pressure distribution of layer 10 (3 wells) at various times.

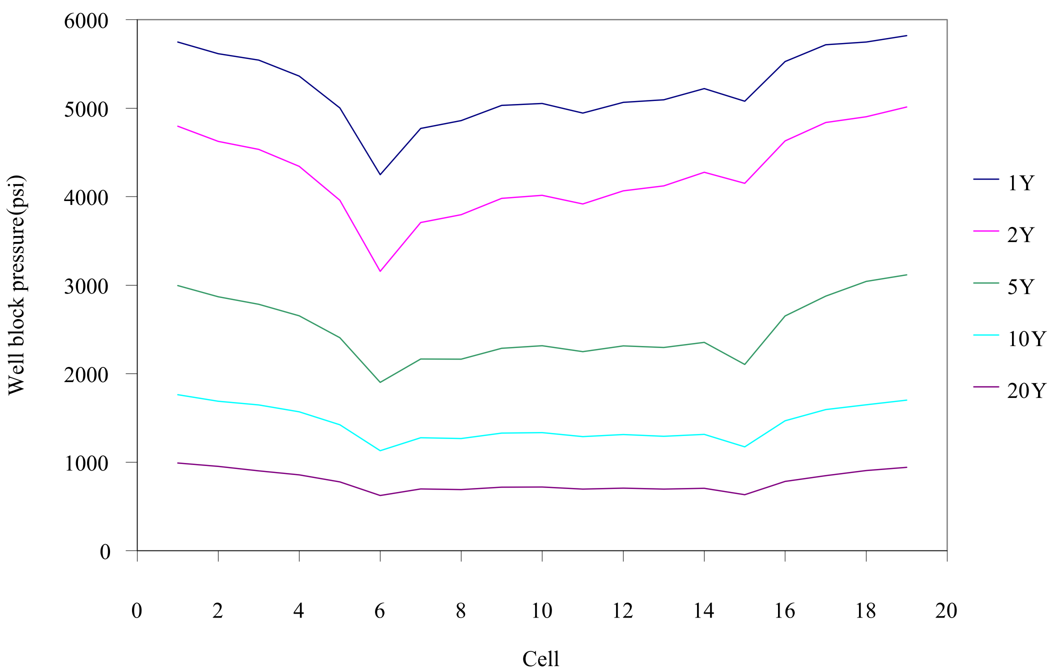


Figure C.10b Pressure distribution of layer 10 (2 wells) at various times.

BIBLIOGRAPHY

Miss Manward Kangkun was born on 25th November 1973 in Surin province. She had graduated with a Bachelor's Degree in Geotechnology from Suranaree University of Technology in 1998. After graduation, she had studied the Master's Degree in Geotechnology at Suranaree University of Technology. During graduate study, 1999 – 2001, she was part times work in position of research assistant in the School of Geotechnology, Institute of Engineering, Suranaree University of Technology.