Feasibility assessment of utilizing thermal wells in shale oil production

by

Eziz Sopyyev

12992

Dissertation in partial fulfillment of
the requirement of the
Bachelors of Engineering (Hons)
(Petroleum Engineering)

MAY 2014

University Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

Mohammad Amin Shoushtari

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Eziz Sopyyev

ABSTRACT

We are living in We were living in an *oleocene* – the age, of oil, where oil and money are linked as cheap energy which is driving power of our modern oil based economy and we have reached its peak. Now its best time to introduce unconventional hydrocarbon reserves to satisfy demand on energy, which is mainly originated from hydrocarbons.

Best alternative for conventional hydrocarbons is shale with its oil and gas reserves. Being present almost at any point of earth's crust makes it more favorable compared to other alternatives. With all its advantages, shale brings up batch of challenges as well. Extracting oil from shale is no simple task; plenty still needs to be understood to make the process more cost-effective to increase economic flow rates.

In current work in-situ methods of shale oil production will be observed. Many of this methods are still under pilot stage and need more improvements. Meanwhile, impact of thermal effect on shale formation and shale oil production will be discussed. In parallel to all above mentioned main target of this work is to determine amount of introduced heat to formation and its efficiency.

ACKNOWLEDGEMENTS

I would like to begin my work with thanking and praising to Allah, for His guidance and blessing. To get to this point it took a lot of effort and diligence. Many challenges were accepted and had overcome.

My gratitude goes to my supervisor Mr. Mohammad Amin Shoushtari who have guided and supervised me throughout my final year project.

Also, I would like to thank all of my fellow students from Petroleum Engineering department who were with me all the time.

Reaching up this point would be impossible without participation of UTP, which provided me with the chance of studying Petroleum Engineering program, that would lead to better life expectations and have a great engineering job in future.

My salutation would be incomplete without giving a credit to my parents and family. Without their support and believe in me nothing of these would happen.

This dissertation is dedicated to people whom I love and appreciate very much, my family: dad, mom, brother, wife and my little Princess Medine.

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ABBREVIATIONS AND NOMENCLATURES

ARI	Advanced Resources International
EIA	Energy Information Agency
ICP	In-situ Conversion Process
WTI	West Texas Intermediate

CHAPTER 1

INTRODUCTION

1.1. Background

Our planet has limited amount of natural resources, whether it is hydrocarbons or water or any other natural source necessary for human beings. As human developed he improved his technology and standards of his living. Our modern life requires a lot of cheap and easy extractable energy. Thus main target of human in pursuance of energy laid on hydrocarbons. Our modern world runs on two sources which are money and oil. Money has no direct value but it is a key to obtain so desired oil resources and products made out of it, on the other hand too many consumable goods which are made of it as well. We were living in an *oleocene* – the age, of oil, where oil and money are linked as cheap energy which is driving power of our modern oil based economy (Hall, Ramirez-Pascualli, 2013).

As it was mentioned before hydrocarbons are in a limited amount and not distributed evenly among the world. Moreover this finite amount of hydrocarbons are depleting day by day. So, to be able to meet their energy needs scientists, engineers and economists of almost every nation were developing and discovering new forms of energy source that could replace hydrocarbons.

Unconventional hydrocarbon (e.g. shale oil or gas) reserves seem to be best alternative to conventional hydrocarbon, as renewable energy source as solar or wind power is not sufficient to meet energy requirements of world. According to report by Advanced Resource International (ARI) under sponsorship of Energy Information Agency (EIA), total reserves of world from shale formations are consisting of 7.795 trillion cubic feet of recoverable shale gas and 335 billion barrels of recoverable shale oil (Daly, 2013). This significant numbers and allocation of the recoverable reservoirs (refer to Appendix I for map of distribution) force engineers from different nations to discover undiscovered and develop new technologies.

As it is named “unconventional” we can easily understand that methods to produce them are also different than conventional ones. Even if extraction of unconventional hydrocarbons especially from shale formation started in last decade, there were several successful methods developed. They vary from company to company and from field to field as well. Reasons of that are not all of formations have similar properties (except that shale has ultralow permeability) and methods are still in process of development and improvement. Methods and techniques as in-situ production of shale oil are successfully and widely used in recent days. This method does affect the shale reservoirs thermally and change properties of oil present in shale formations to desired conditions, thus it could be produced. Heating the reservoir itself by steam circulation can lead to positive production and higher EOR from shale formations.

Due to all aforementioned and its environmental impacts during its production shale oil was not produced in large amounts up today. But with availability of newer technology and growth of economical feasibility of shale oil production will push shale oil production to higher levels and change the age of conventional hydrocarbons to age of unconventional ones.

1.2. Problem Statement

It is well knows fact that shale oil production had its boom after significant production of shale gases and being developed in last decades only. Even though many methods and techniques of extracting shale oil were discovered they are not fully developed and didn’t get their full performance abilities yet. Thus there is a place to develop and improve technologies.

Need to note that techniques available to produce shale oil by in-situ heating methods are at pilots stages and require testing; none of these techniques has shown large-scale economically feasible production. Companies are still developing and optimizing their in-situ methods. Controlling the heat injected into reservoir enables to fine-tune properties of fluid to be produced as an outcome (Allix et. al 2011).

Introduced heat will have significant effect to formation rock, as it will induce pore pressure in low permeable formations as shale. Heated formation’s pore pressure may be higher by 30% compared to its isothermal state (Farrokhrouz, Asef 2013). There is a necessity of assessing effect of heat introduced into shale formation and its effect on shale oil production. Inquiring amount of heat introduced to formation, as it affect produced shale oil which is converted from kerogen, is the main problem that will be dealt with in current work.

1.3. Objectives and Scope of Study

Among objectives of current project I would like to mention that they conclude of:

- Learning and analyzing the available methods and techniques of shale oil production
- Assess feasibility of using steam circulation as an in-situ method in shale reservoirs
- Determine the heat transfer rate of circulated steam and its efficiency
- Determine amount of heat that can be introduced to formation

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1. What is Shale and Shale Oil?

Shale is rock from clastic sedimentary group composed of mud and containing other minerals like calcite and quartz. It is very fine grained and has ultra low permeability. Shale deposits have formed around 450 million years ago under the sea bed and contain large amount of fossils and organic compounds. (Novikov, 2011) Thus shale is a very good source to produce hydrocarbons. Oil shale is type of shale containing organic reach material *kerogen* from which shale oil can be produced. Due to its similar properties with crude oil shale oils is considered as a substitute of it (Gruveshenko, Gruveshenko, 2012).

Shale is the most abundant rock and it has properties of fine grains and laminations. It is a sedimentary rock with nearly same grain size, range and composition. If lamination is absent than rock is referred as mudstone. (Farrokhrouz, Asef 2013).

Kerogen is organic compound and defined as immature crude oil. It didn't get enough amount of heat to transform into oil or gas. When kerogen contained in shale is buried deep enough it may start to transform into oil. (Aleklett, Lardelli, 2012). The produced oil will be called shale oil.

2.2. Difference between Shale Oil and Oil Shale

Need to define that there is a giant difference between oil produced from shale formation also known as "shale oil" and oil shale; it's similar to apple and orange juice (Chaudhary, Ehlig, Wattenbarger 2011).

As it's described by author "Oil shales correspond to immature source rocks that can be retorted to recover the oil resulting from industrial cracking of contained kerogen" (Huc, 2013). Oil shale is an inaccurate designation, reasons of that are kerogen is not a crude and rock carrying it is not shale (Gue, 2011).

On the other hand, shale oil is totally different than oil shale, and it doesn't require heating the reservoir to produce oil. Oil trapped in micro fractures and pores of shale rock usually has better properties compared to West Texas Intermediate (WTI) standard crude oil which is marketed (Chaudhary, Ehlig, Wattenbarger 2011). Sometimes crudes from tight reservoirs are called shale oil as well. These are crudes migrated from source rock into tight rock formations as cap rocks. Oil or gas produced from these formations should be called tight oil or tight gas (Prishepa, Averyanova 2013). Detailed illustration of above mentioned types of crudes are shown in Figure 1.

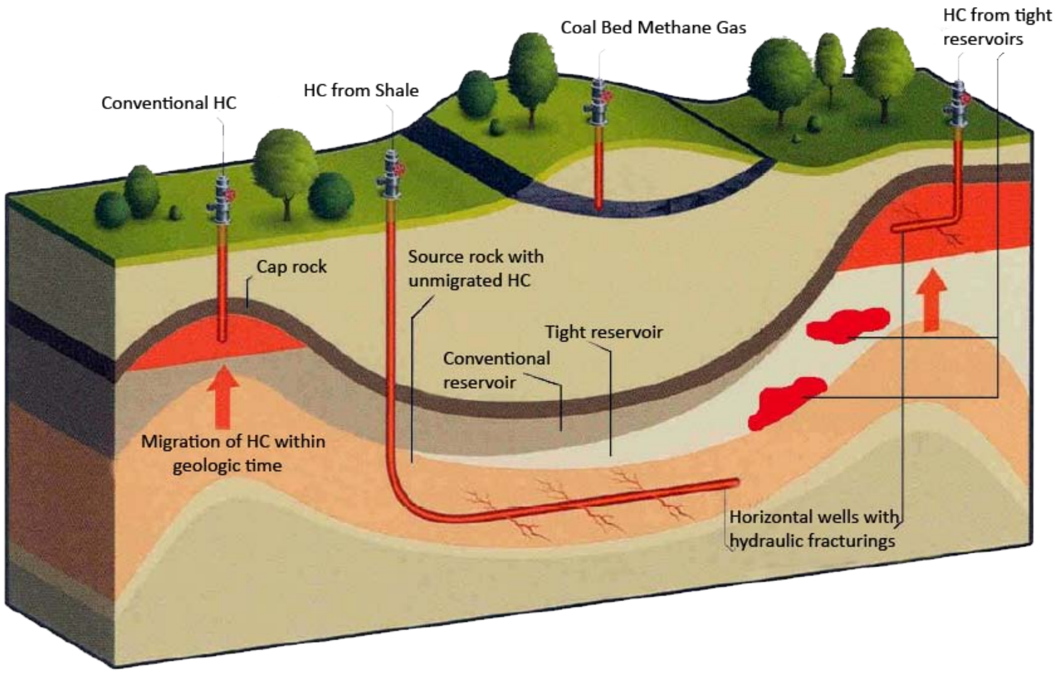

Figure 1. Types of crudes according to reservoirs (Source: Prishepa, Averyanova 2013)

2.3. Methods of Shale Oil Production

Production of shale oil need big amounts of investment and energy, as it's necessary to drill several wells with horizontal borehole structure and apply newest technologies available in market. Thus cost of shale oil extraction increases by times compared to conventional crude oil (Aleklett, Lardelli 2012). Modern technologies, involving various approaches forming in situ "retorting" are being developed nowadays. In general they will work in conjunction with horizontal drilling and engineered fracturing, including use of heaters (electric, gas and etc.), hot gas or steam injection, to induce fracturing and retorting, fracturing and heating using electrofracking, even radio frequency and microwaves (Huc 2013).

There are two major methods of extracting oil from oil shale formations which are ex-situ and in-situ methods. In ex-situ method of oil extraction, shale rocks are mined and heated at surface. Crude extracted with this method will be called oil from oil shale. This method will not be considered in this paper as it is not relevant to current paper. On the other hand in-situ methods of extraction will deliver crude from oil shale formation and it will be called as shale oil. This method considers production of oil from kerogen without mining of oil shale formations, and production of oil from kerogen directly from shale formations also known as true in-situ (Vygon et.al 2013). In-situ technologies heat oil shale beneath the crust by hot fluids injection into rock or by using linear and planar heating sources thus distributing heat evenly through targeted area. Shale oil is then produced through drilled wells into the formation (Wayne 2012).

Nowadays decades of companies are competing in development of in-situ methods and concepts of carrying underground retorting techniques. During World War II modified in-situ extraction of shale oil was performed in Germany, but without success. One of the first successful in-situ extractions took place in Kvarntorp, Sweden during shale oil extraction with underground gasification by electrical energy also known as Ljungström method in period of 1940-1966 (Wayne 2012).

Shell as one of pioneers in this area of expertise developed ICP (in-situ conversion process) method of extracting oil from shale formations. This method uses electrical heating elements for oil shale heating for duration of approximately 4 years under 700 ^{0}F (370 ^{0}C). Target area is isolated from groundwater by freeze wall consisting of wells filled with coolant circulations (Allix et.al 2011). Illustration of Shell ICP process can be found in Appendix IV.

Exxon Mobil has come up with Electrofrac method, where kerogen is heated by means of hydraulic fracture where instead of normal fracturing fluid electrically conductive proppant. Heating is done electrically through this proppant (Grushevenko, Grushevenko 2012). General illustration of this method is also in Appendix IV.

Chevron also developed their method called CRUSH process, where heated CO_2 is injected into reservoir under huge pressure via drilled wells and hydraulic fractures in which gas circulates. During this process heated air is re-circulated back thus providing a space for kerogen to breakdown into oil under injected heat (Vygon et.al.2013). For illustration of Chevron CRUSH in-situ method refer to Appendix IV.

2.4. Heat Transfer

In nature most of the time heat transfer occurs in 3 modes which are conduction, convection and radiation. When a temperature difference exists in a body (material), energy will be transferred from high-temperature region to low-temperature region. Conduction is process of energy transfer between adjoining regions with different temperatures without movement of body (material) (Holman 2010).

Transfer of heat from high-temperature part of body to low-temperature part of body by circulation or movement of fluid is known as convection heat transfer. (Incropera, DeWitt 2004) Heat transfer is influenced by many properties of body and the fluid.

Heat conduction and heat convection depend on the type of material they pass through. Conduction is more important at undamaged formation rock, while convection is more significant for wellbore cases and cases of continuous fluid circulation (Farrokhrouz, Asef 2013).

Radiation is the transfer of heat by means of electromagnetic waves. Heat transfer by radiation mode doesn't involve movement or interaction of material, and has negligible effect in wellbore thus it can be assumed that it doesn't affect the process (Farrokhrouz, Asef 2013).

2.5. Convection in Horizontal Concentric Cylinders

According to our model biggest portion of heat will be introduced to reservoir formations at horizontal section, where heated steam will be circulated through tubing located inside casing. Heat transfer between casings and tubing having different diameters and allocated by same central axis is best defined by free convection heat transfer between long, horizontal concentric cylinders, for illustration refer to Figure 2. In this case governing equation will be as stated below:

$$q_c = \frac{2\pi k_{eff}\, L}{\ln(D_i - D_o)}(T_i - T_o) \qquad (1)$$

where

q_c : heat transfer rate
L : length of pipe
k_{eff} : effective thermal conductivity
T_i : inner temperature
T_o: outer temperature
D_i : inner diameter
D_o: outer diameter

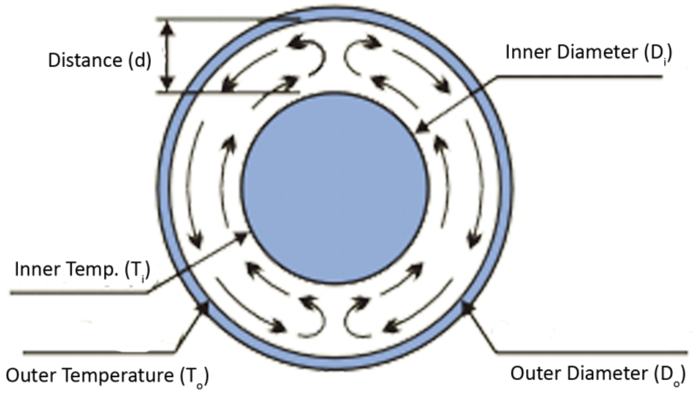

Figure 2. Free convection in annular space between horizontal concentric cylinders cross-sectional view (Source: Incropera, DeWitt, 2004)

Effective thermal conductivity is calculated as

$$\frac{k_{eff}}{k} = 0.386(Ra_C^*)^2\left(\frac{Pr}{0.861 + Pr}\right)^2 \qquad (2)$$

Where

$$Ra_C^* = \frac{Ra_L\left(ln\frac{D_o}{D_i}\right)^4}{d^3\left(D_i^{-\frac{3}{5}} + D_o^{-\frac{3}{5}}\right)^5} \qquad (3)$$

And

$$Ra_L = \frac{g\beta\,(T_i - T_o)d^3}{\upsilon\alpha} \qquad (4)$$

k: thermal conductivity
Ra^*_C : Rayleigh number for cross-section
Ra_L: Rayleigh number for length
g: gravitational acceleration
d: distance between two cylinders
β: volumetric thermal expansion
ν: dynamic viscosity
α: thermal diffusivity

Equation 1 can be used for range $10^2 \le Ra^*_C \le 10^7$, for $Ra^*_C < 10^2$ $k_{eff} \approx k$. Solving Equation 1 will let us determine heat transfer by free convection per unit length of cylinder, in our case casing.

2.6. Geothermal Gradients and Average Temperatures

Jalyon Ralph in his Glossary named Mindat.org defines geothermal gradient as rate of increase of temperature in the Earth with increase of depth. Gradient varies from place to place as it depends on parameters as heat flow and thermal conductivity of rocks. Average geothermal gradient of Earth's crust is approximated as 25 ^{0}C per kilometer of vertical displacement.

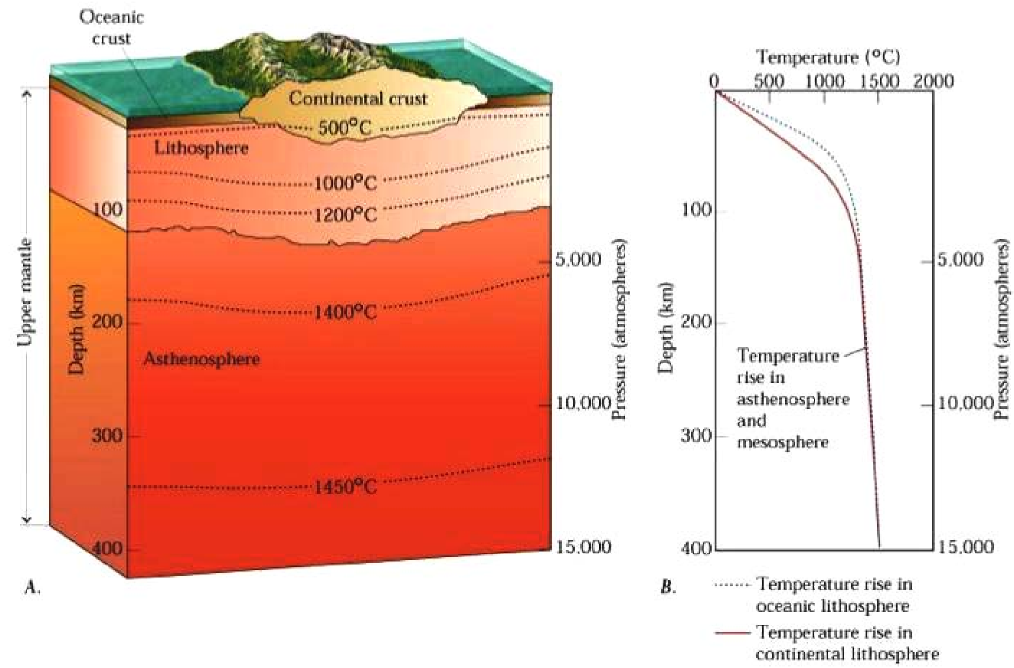

Figure 3. Earth's temperature change with change of depth (Source: Forrest, Marcucci, Scott 2007)

Geothermal gradient can be calculated with formula (Forrest, Marcucci, Scott 2007)

$$Geothermal\ gradient = \frac{Formation\ Temperature - Mean\ \ Surface\ Temperature}{Formation\ Depth}$$

To use above formula we need to know surface temperature. Average surface of Earth is 14 ^{0}C (Cain 2009). Need to notice that this is overall average temperature, as it may differ from location, e.g. in desert areas it can reach up to 55 ^{0}C and in Antarctica it can drop down up to -89 ^{0}C. Thus for more accurate results local surface temperatures should be used.

CHAPTER 3

METHODOLOGY

Methodology chart of my research is illustrated in Appendix II. Overall methodology will be as described below:

- Continue studying on relevant and valid sources
- Learn and analyze methods and techniques for shale oil production
- Calculate heat transfer rate with various parameters
- Compare, analyze and discuss results
- Choose optimum parameters for most efficient heat transfer rate

To assess feasibility of steam circulation as an in-situ method in shale oil production, two horizontal wells are going to be drilled and connected in U form as shown in figure below.

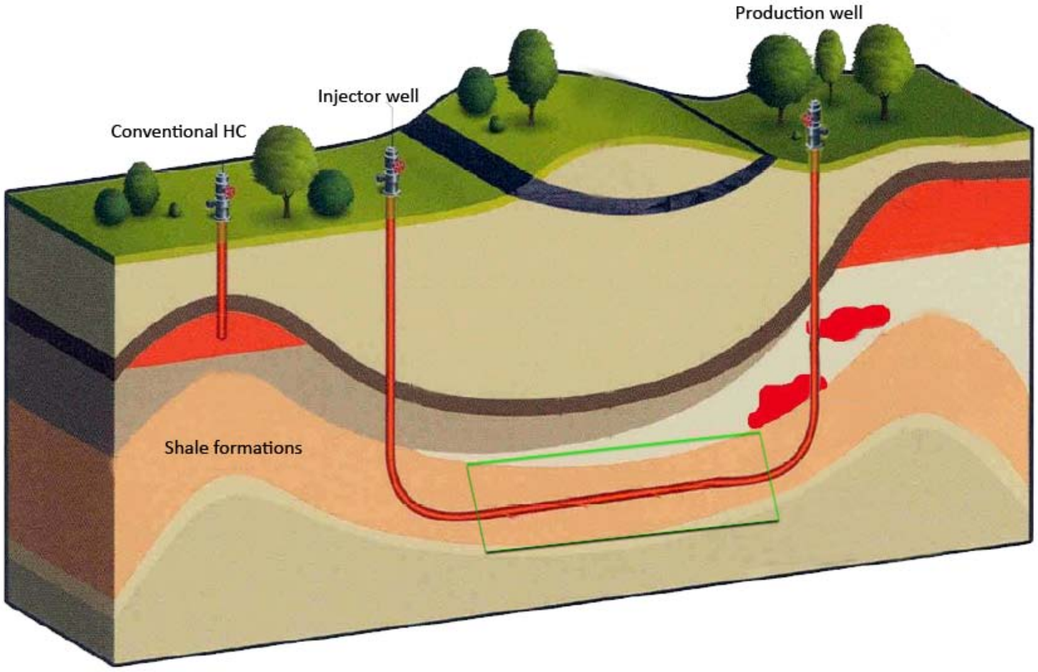

Figure 4. Proposed well design for steam circulation (Source: adopted from Prishepa, Averyanova 2013)

Main focus point of this project will be horizontal part of proposed design which is shown in green rectangle in Figure 4. My interest lies in it as most of heat exchange with shale formation will happen in horizontal section of well, while vertical sections will be passing through other types of rock formations as well. Zooming into green rectangle we can see configuration of casing and tubing as concentric cylinders similar to shown in Figure 5.

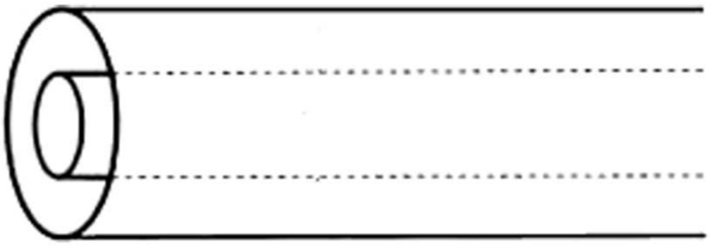

Figure 5. Casing (outer cylinder) and tubing (inner cylinder) in horizontal layout

To determine heat transfer rate q_c mainly Equation 1 will be implemented, where *Ti* will be temperature of steam circulated and *To* will be the formation temperature. *To* (temperature of formation) will be approximated from thermal gradients and surface temperature. *Di* and *Do* will represent diameter of tubing and casing accordingly.

Several sensitivity analyses will be done with varying parameters of *Di*, *Do*, *Ti* and *L*, in calculating q_c with aid of Equation 1. After several calculation trials with varying parameters, attained best results will be analyzed.

Based on selected good results efficiency of introduced heat to formation will be discussed. Optimum parameters will be selected and offered for further improvements and analysis.

3.1. Study Plan

Gantt chart for current project including FYP 1 and FYP 2 is illustrated in Appendix III. This chart clearly illustrates all milestones.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Results

As it was mentioned before several calculations were done. Results are presented in table form below, for all set of values *To* equals to 101.5 ^{o}C (Calculated from geothermal gradient formula, assuming average reservoir depth of 3500 m).

Table 1. Results with constant and varying parameters set 1.

Constant variables: *Di* = 2.875 inch (0.073 m) *Do* = 4.5 inch (0.1143 m)			
L (m)	q_c (KiloWatts)		
	Ti=200 ^{o}C	*Ti*=250 ^{o}C	*Ti*=300 ^{o}C
50	4.6265	7.520	10.5200
60	5.5591	9.0245	12.6240
70	6.4857	10.5287	14.7280
80	7.4122	12.0328	16.8320
90	8.3387	13.5369	18.9360
100	9.2653	15.0140	21.0400

Table 2. Results with constant and varying parameters set 2.

Constant variables: *Di* = 3.5 inch (0.0886 m) *Do* = 4.5 inch (0.1143 m)			
L (m)	q_c (KiloWatts)		
	Ti=200 ^{o}C	*Ti*=250 ^{o}C	*Ti*=300 ^{o}C
50	5.0197	8.1488	11.3991
60	6.0237	9.7787	13.6789
70	7.0276	11.4085	15.9587
80	8.0316	13.0383	18.2385
90	9.0356	14.6681	20.5101
100	10.0396	16.2978	22.7982

Table 3. Results with constant and varying parameters set 3

Constant variables: *Di* = 2.875 inch (0.073 m) *Do* = 5.5 inch (0.1397 m)			
L (m)	q_c (KiloWatts)		
	Ti=200 ^oC	*Ti*=250 ^oC	*Ti*=300 ^oC
50	4.9330	8.0093	11.2038
60	5.9205	9.6112	13.4446
70	6.9073	11.2131	15.6854
80	7.8940	12.8149	17.9261
90	8.8808	14.4168	20.1669
100	9.8675	16.0187	22.4077

Table 4. Results with constant and varying parameters set 4

Constant variables: *Di* = 3.5 inch (0.0886 m) *Do* = 5.5 inch (0.1397 m)			
L (m)	q_c (KiloWatts)		
	Ti=200 ^oC	*Ti*=250 ^oC	*Ti*=300 ^oC
50	5.3690	8.7159	12.1920
60	6.4428	10.4591	14.6307
70	7.5167	12.2023	17.0692
80	8.5905	13.9455	19.5076
90	9.6643	15.6887	21.9461
100	10.7381	17.4319	24.3846

Table 5. Results with constant and varying parameters set 5

Constant variables: *Di* = 4.5 inch (0.1143 m) *Do* = 5.5 inch (0.1397 m)			
L (m)	q_c (KiloWatts)		
	Ti=200 ^oC	*Ti*=250 ^oC	*Ti*=300 ^oC
50	5.9627	9.6796	13.5404
60	7.1552	11.6156	16.2485
70	8.3478	13.5516	18.9566
80	9.5403	15.4875	21.6646
90	10.7329	17.4234	24.3727
100	11.9255	19.3594	27.0808

Table 6. Results with constant and varying parameters set 6

Constant variables: *Di* = 3.5 inch (0.0886 m) *Do* = 7 inch (0.1778 m)			
L (m)	q_c (KiloWatts)		
	Ti=200 ^{o}C	*Ti*=250 ^{o}C	*Ti*=300 ^{o}C
50	5.7870	9.3945	13.1415
60	6.9444	11.2734	15.7698
70	8.1018	13.1523	18.3981
80	9.2593	15.0312	21.0264
90	10.4167	16.9101	23.6546
100	11.5741	18.7890	26.2829

Table 7. Results with constant and varying parameters set 7

Constant variables: *Di* = 4.5 inch (0.1143 m) *Do* = 7 inch (0.1778 m)			
L (m)	q_c (KiloWatts)		
	Ti=200 ^{o}C	*Ti*=250 ^{o}C	*Ti*=300 ^{o}C
50	6.4706	10.5042	14.6938
60	7.7648	12.6051	17.6326
70	9.0589	14.7059	20.5714
80	10.3531	16.8068	23.5101
90	11.6472	18.9076	26.4489
100	12.9413	21.0085	29.3877

Table 8. Results with constant and varying parameters set 8

Constant variables: *Di* = 5.5 inch (0.1397 m) *Do* = 7 inch (0.1778 m)			
L (m)	q_c (KiloWatts)		
	Ti=200 ^{o}C	*Ti*=250 ^{o}C	*Ti*=300 ^{o}C
50	7.0308	11.4125	15.9644
60	8.4362	13.6950	19.1573
70	9.8422	15.9775	22.3501
80	11.2483	18.2660	25.5430
90	12.6543	20.5425	28.7359
100	14.0604	22.8251	31.9288

4.2. Discussions

From above given results, next charts were generated for analyses purposes.

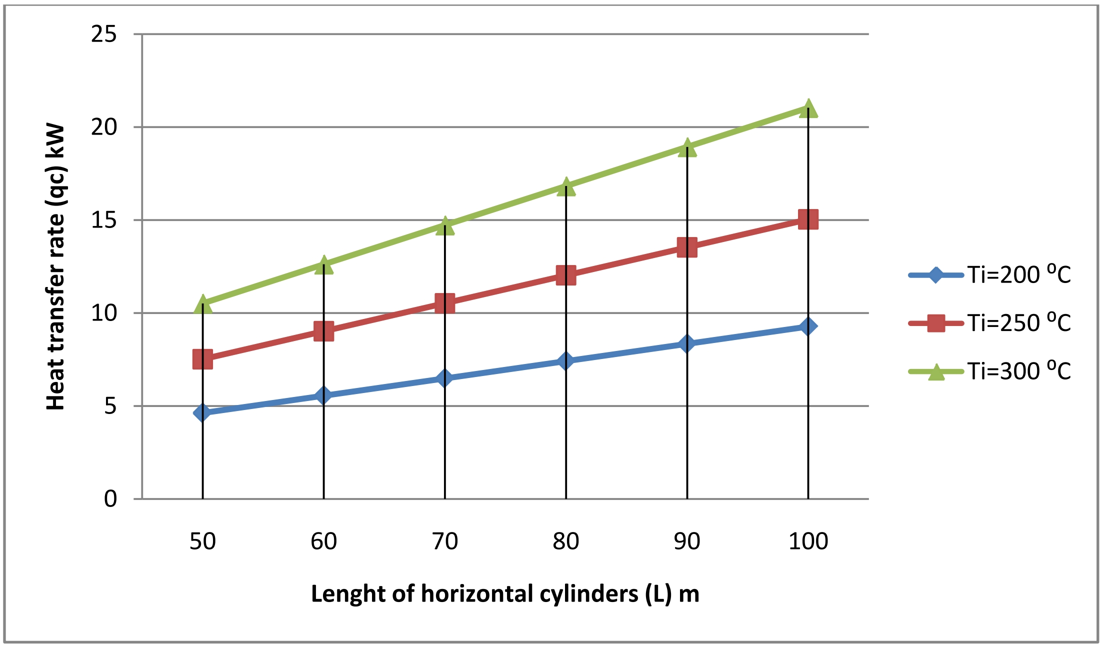

Figure 5. Representation of results set 1.

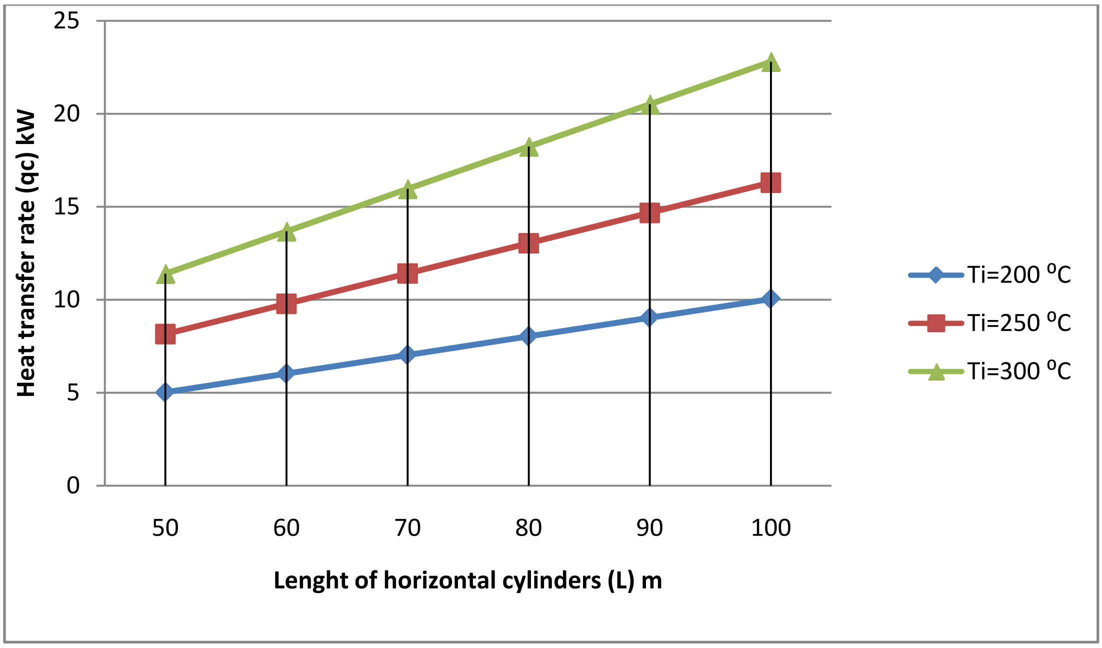

Figure 6. Representation of results set 2.

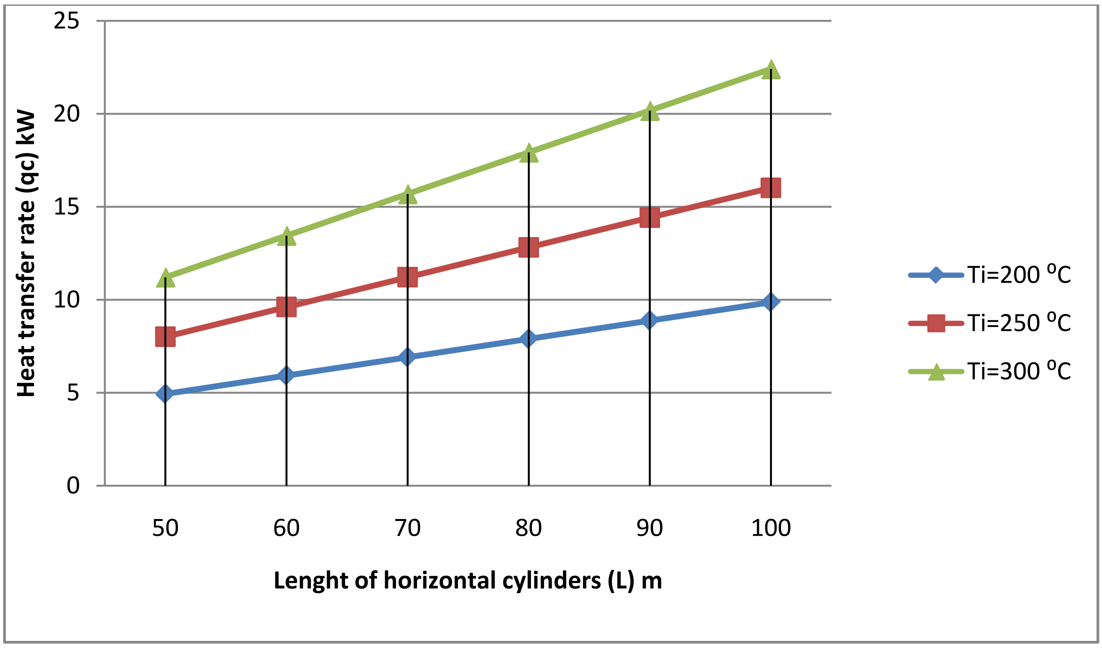

Figure 7. Representation of results set 3.

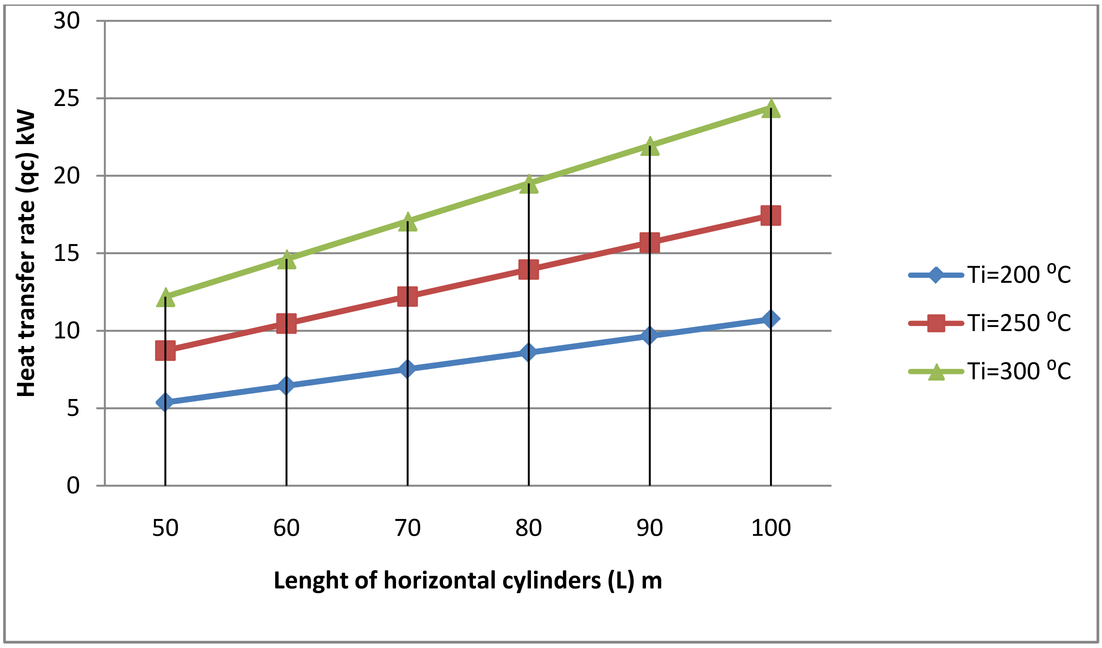

Figure 8. Representation of results set 4.

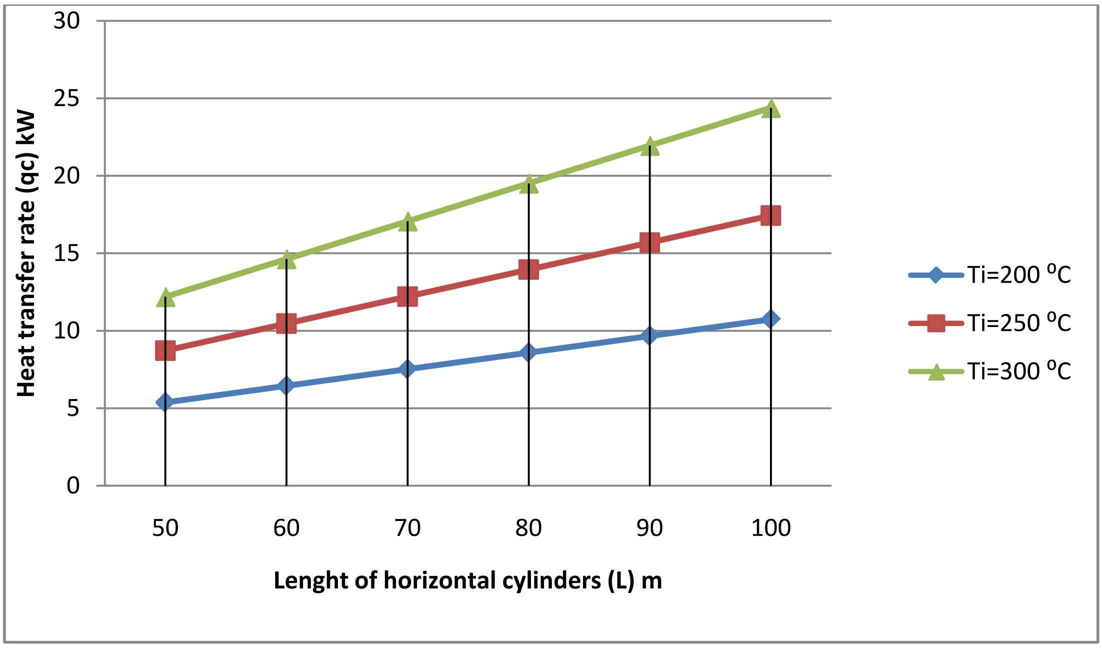

Figure 9. Representation of results set 5.

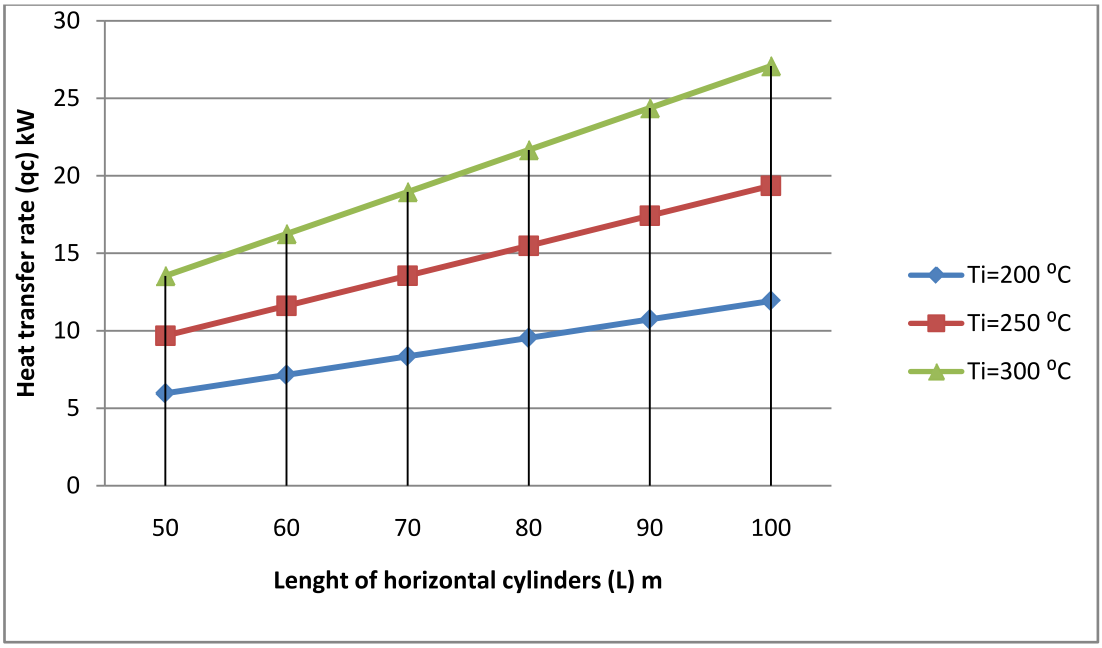

Figure 10. Representation of results set 6.

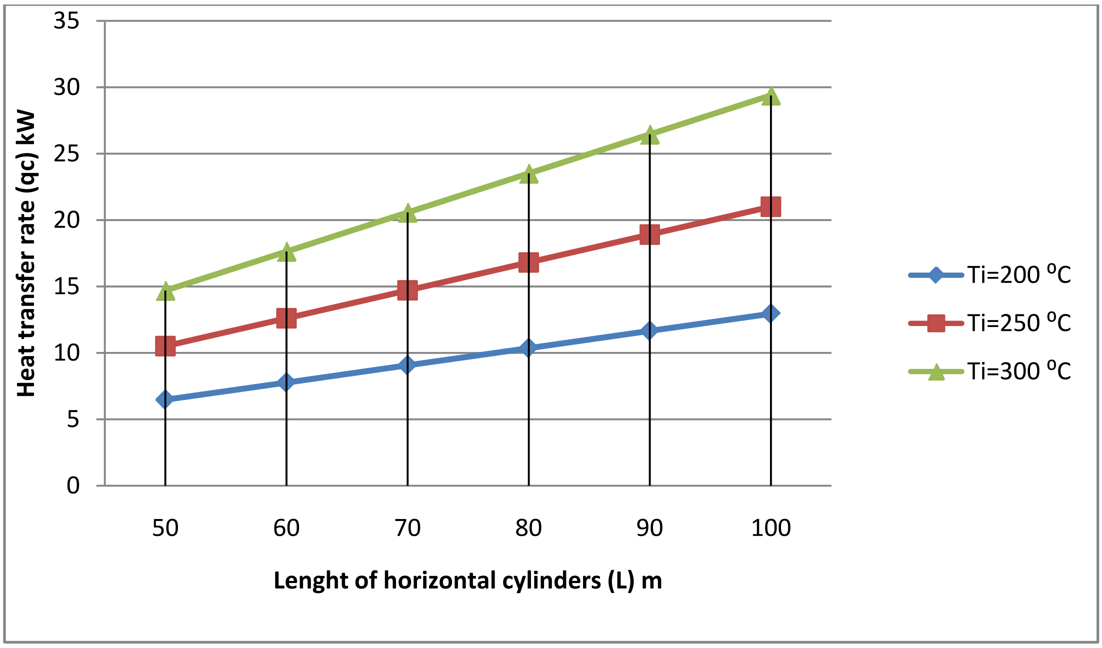

Figure 11. Representation of results set 7.

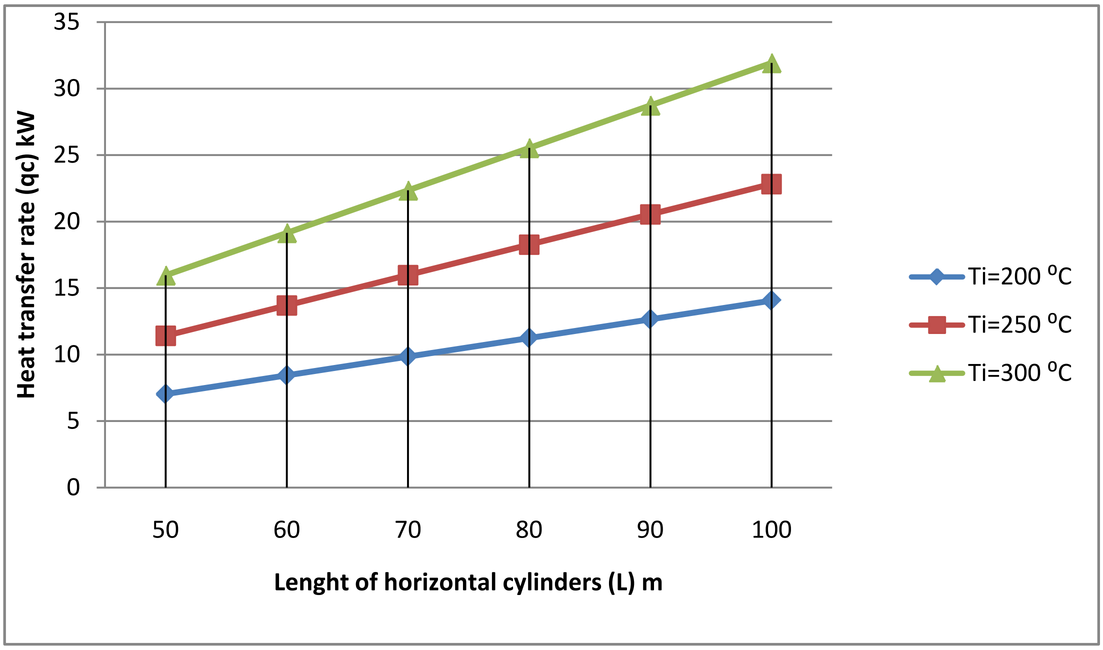

Figure 12. Representation of results set 8.

As we can see from the graphs, higher value of steam temperature (*Ti*) more heat is transferred. Along with it, lengthier the horizontal part of well trajectory, more heat will be transferred to formation. Moreover diameters play significant role in heat transfer rate, bigger the sizes and less gap between them results higher heat transfer rate. This will be illustrated on graph shown below, on the basis of *Do*=7 inch with varying *Di* from 3.5 to 5.5 inches at *Ti*=200 ^{o}C:

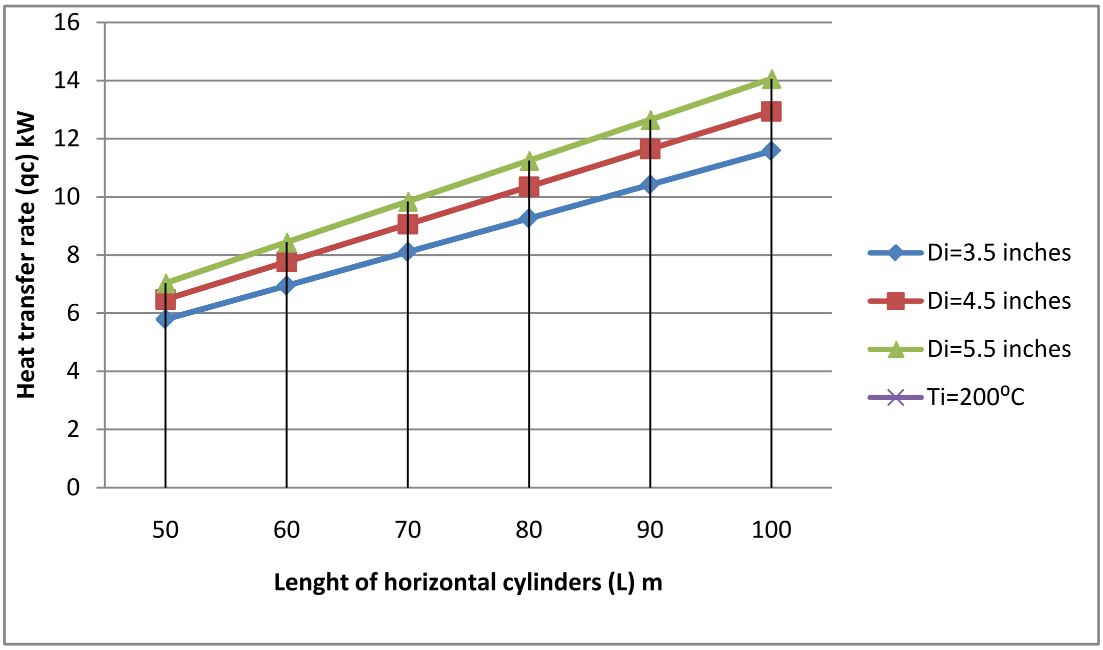

Figure 13. Heat transfer rate at different tubing diameters.

After determining that larger diameter for tubing and casing sizes with smaller gaps are most efficient in transferring heat, I have recalculated Equation 1 with new parameters.

For this instance I chose to work with steam having next properties.

a) Steam having temperature of 204.5 ^{o}C, at 240 psi pressure with 200 bbl/d flow rate
b) Steam having temperature of 149 ^{o}C at 250 psi pressure with 300 bbl/d flow rate

These conditions are very used in various fields with steam circulation. Above shown parameters will be used for altering L and depth of formation, leading to change *To*. For depth range I will calculate ranging from 500 m to 4 km, with step size of 500m. As it was mentioned before for every kilometer of depth temperature of formation will increase by 25 ^{o}C.

For tubing and casing sizes I chose 5.5 inches and 7 inches accordingly, as they show most efficient transfer rates.

Results with new parameters are shown below.

Table 9. Results with constant and varying parameters for depth of 500 m

Constant variables: Di = 5.5 inch (0.1397 m) Do = 7 inch (0.1778 m) To = 26.5 ^{o}C		
L (m)	q_c (KiloWatts)	
	Ti=149 ^{o}C	Ti=204.5 ^{o}C
100	30.88	20.0875
200	61.7616	40.175
300	92.6426	60.2625
400	123.523	80.3501
500	154.404	100.438
600	185.285	120.525
700	216.166	140.613
800	247.647	160.7
900	277.927	180.788
1000	308.808	200.875

Table 10. Results with constant and varying parameters for depth of 1000 m

Constant variables: Di = 5.5 inch (0.1397 m) Do = 7 inch (0.1778 m) To = 39 ^{o}C		
L (m)	q_c (KiloWatts)	
	Ti=149 ^{o}C	Ti=204.5 ^{o}C
100	17.4087	27.9702
200	34.8175	55.9404
300	52.2262	83.9106
400	69.6348	111.8808
500	87.0435	139.851
600	104.4522	167.8212
700	121.8610	195.7915
800	139.2697	223.7616
900	156.6783	251.7318
1000	174.087	279.702

Table 11. Results with constant and varying parameters for depth of 1500 m

Constant variables: *Di* = 5.5 inch (0.1397 m) *Do* = 7 inch (0.1778 m) *To* = 51.5 ^oC		
L (m)	q_c (KiloWatts)	
	Ti=149 ^oC	*Ti*=204.5 ^oC
100	14.8462	25.1566
200	29.6924	50.3132
300	44.5386	75.4698
400	59.3848	100.6264
500	74.2310	125.783
600	89.0772	150.9396
700	103.9234	176.0962
800	118.7699	201.2528
900	133.6158	226.4094
1000	148.462	251.566

Table 12. Results with constant and varying parameters for depth of 2000 m

Constant variables: *Di* = 5.5 inch (0.1397 m) *Do* = 7 inch (0.1778 m) *To* = 64 ^oC		
L (m)	q_c (KiloWatts)	
	Ti=149 ^oC	*Ti*=204.5 ^oC
100	12.403	22.4401
200	24.806	44.8802
300	37.209	67.3203
400	49.612	89.7604
500	62.015	112.2005
600	74.418	134.6406
700	86.821	157.0807
800	99.224	179.5208
900	111.627	201.9609
1000	124.03	224.401

Table 13. Results with constant and varying parameters for depth of 2500 m

Constant variables: *Di* = 5.5 inch (0.1397 m) *Do* = 7 inch (0.1778 m) *To* = 76.5 ^{o}C		
L (m)	q_c (KiloWatts)	
	Ti=149 ^{o}C	*Ti*=204.5 ^{o}C
100	10.0839	19.8214
200	20.167	39.6428
300	30.2517	59.4642
400	40.3356	79.2856
500	50.4195	99.1070
600	60.5034	118.9284
700	70.5873	138.7498
800	80.6712	158.5712
900	90.7551	178.3926
1000	100.839	198.214

Table 14. Results with constant and varying parameters for depth of 3000 m

Constant variables: *Di* = 5.5 inch (0.1397 m) *Do* = 7 inch (0.1778 m) *To* = 89 ^{o}C		
L (m)	q_c (KiloWatts)	
	Ti=149 ^{o}C	*Ti*=204.5 ^{o}C
100	7.8959	17.3018
200	15.7918	34.6038
300	23.6877	51.9054
400	31.5836	69.2072
500	39.4795	86.509
600	47.3754	103.8108
700	55.2713	121.1126
800	63.1672	138.4144
900	71.0631	155.7162
1000	78.959	173.018

Table 15. Results with constant and varying parameters for depth of 3500 m

Constant variables: *Di* = 5.5 inch (0.1397 m) *Do* = 7 inch (0.1778 m) *To* = 101.5 ^{o}C		
L (m)	q_c (KiloWatts)	
	Ti=149 ^{o}C	*Ti*=204.5 ^{o}C
100	5.8499	14.8834
200	11.6998	29.7668
300	17.5497	44.6502
400	23.3969	59.5336
500	29.2495	74.4170
600	35.0994	89.3004
700	40.9493	104.1838
800	46.7992	119.0672
900	52.6491	133.9506
1000	58.4990	148.8341

Table 16. Results with constant and varying parameters for depth of 4000 m

Constant variables: *Di* = 5.5 inch (0.1397 m) *Do* = 7 inch (0.1778 m) *To* = 114 ^{o}C		
L (m)	q_c (KiloWatts)	
	Ti=149 ^{o}C	*Ti*=204.5 ^{o}C
100	3.9626	12.5691
200	7.9252	25.1380
300	11.8878	37.7073
400	15.8504	50.2764
500	19.813	62.8455
600	23.7756	75.4146
700	27.7382	87.9837
800	31.7008	100.5528
900	35.6634	113.1219
1000	39.6263	125.691

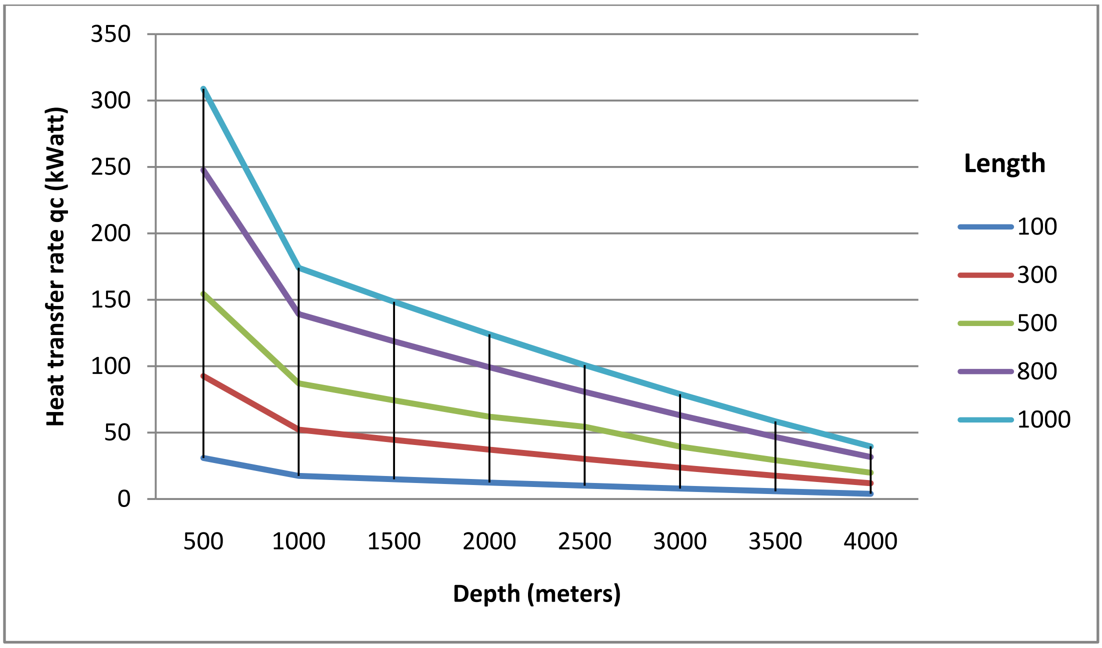

Figure 14. Heat transfer rate at varying depth of formation rock and length of horizontal section.

From above shown chart we can see that amount of transferred heat is reversely proportional to depth. As depth increases heat transfer decreases. Need to note that above chart represents results with various lengths of horizontal section and not changing tubing, casing sizes (5.5 inches and 7 inches respectively) with Ti=149 ^{o}C. Similar chart can be produced for Ti=204.5 ^{o}C, as well which will have similar pattern.

CHAPTER 5

CONCLUSION

In conclusion it could be said that the highest heat transfer rate will occur at next conditions:

- Larger diameters of both casing and tubing with less gap between them
- Longer horizontal tubing configuration
- Bigger difference between steam temperature and formation temperature
- Shallow depth

From results driven through calculations it is possible to conclude that sufficient amount of heat can be transferred into formation. As an in-situ method steam circulation will have high impacts and be more efficient in shallow formations, lengthier and large in diameters horizontal section of pipeline. Other advantage of this method is that it eliminates direct injections and hydraulic fracturing operations, which results less disturbance to environment and minimum potential of underground water contamination.

In future contribution of unconventional hydrocarbon reserves to fulfill our energy demand will be significant. For now as technologies and methods haven't been developed to advance levels it's not economically feasible to produce unconventional reserves in commercially big volumes. Analysts and engineers look forward with great expectations. By 2030 shale oil extraction in US may reach up to 2 million barrels per day.

Thermal effects have substantial impact on shale formation and shale oil production. It can improve and destroy oil recovery from shale formations. Thus it needs to be dealt with care. Despite to challenges standing before utilizing thermal wells in shale oil production they can be achieved successfully and lead to good production.

Need to note that all companies are in stage of development of in-situ technologies or at the stage of their pilot testing and application in experimental scales. Developing of all above mentioned methods will lead to safer energy extraction with minimal impact on nature.

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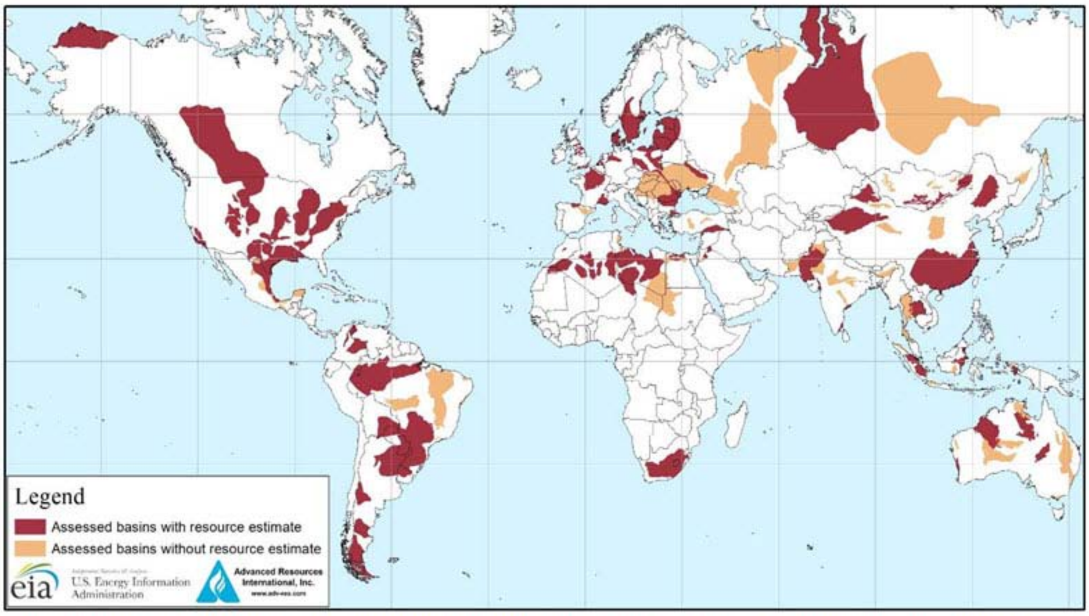
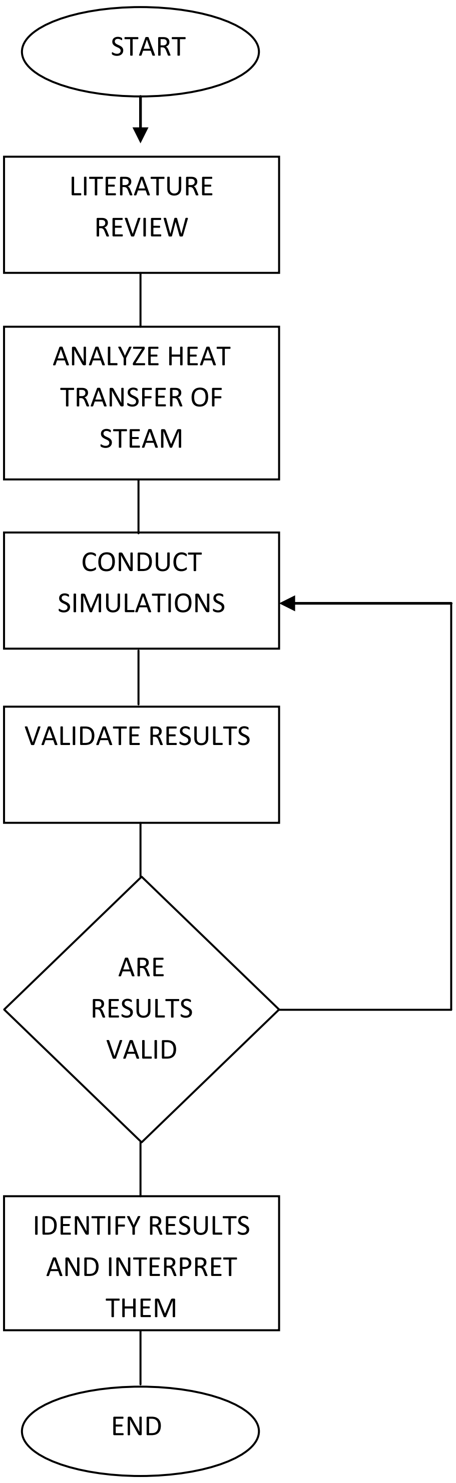
APPENDIX I



Source: United States basins from U.S. Energy Information Administration and United States Geological Survey; other basins from ARI based on data from various published studies.

Map of basins with shale oil and gas formations. Updated on May 2013

APPENDIX II



Methodology chart of project.

APPENDIX III

#	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project title														
2	Preliminary Research Work														
3	Submission of Extended Proposal														
4	Proposal Defense														
5	Project work (con't)														
6	Submission of Interim Report (draft)														
7	Submission of Interim Report														

- Suggested milestone - Process

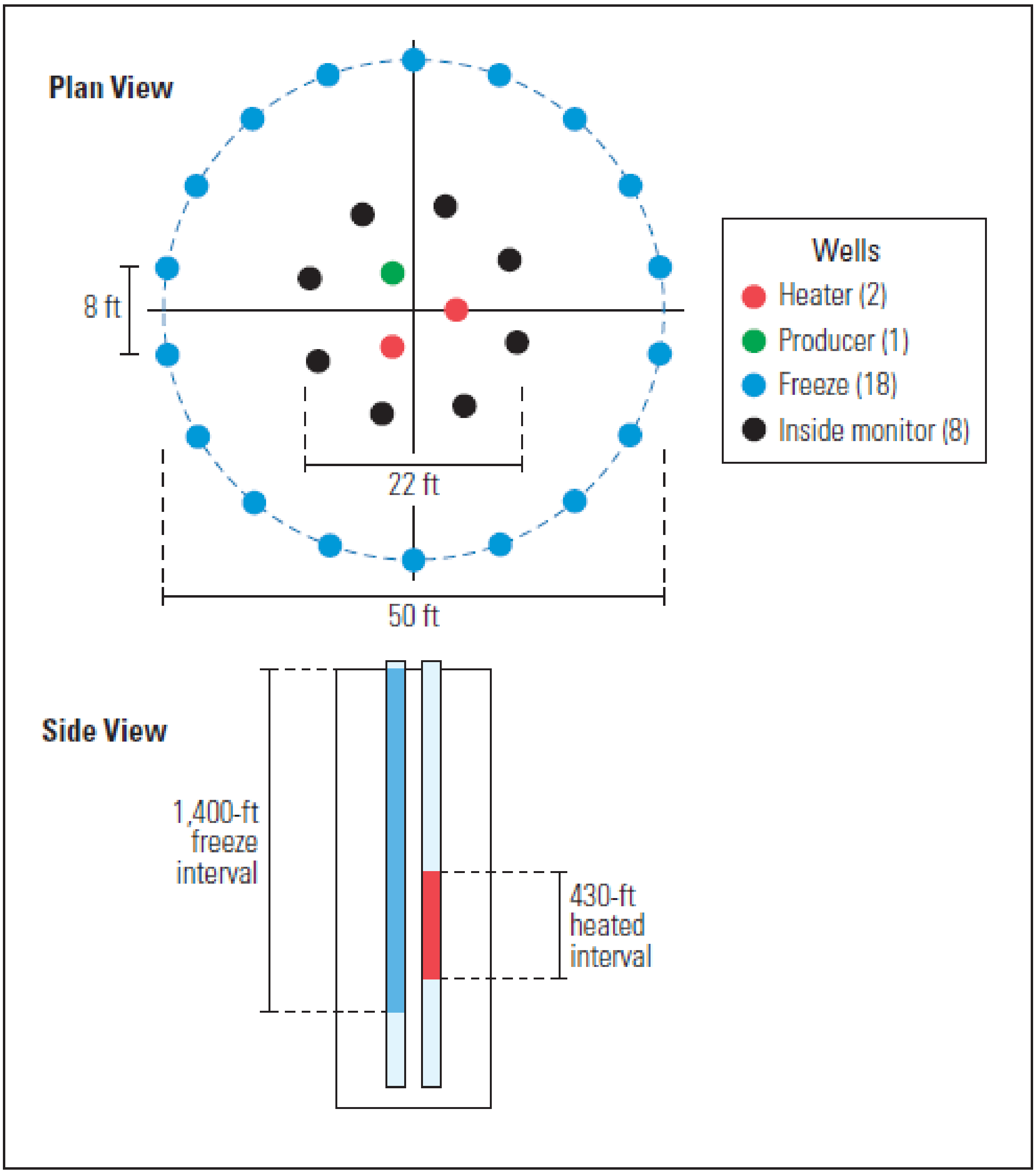
Gannt Chart for FYP 1 with milestones.

#	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	13	15	16
1	Continuation of Project work														
2	Submission of Progress Report														
3	Pre-SEDEX														
4	Submission of Draft Final Report														
5	Submission of Dissertation (soft bound)														
6	Submission of Technical Paper														
7	Viva														
8	Submission of Dissertation (hard bound)														

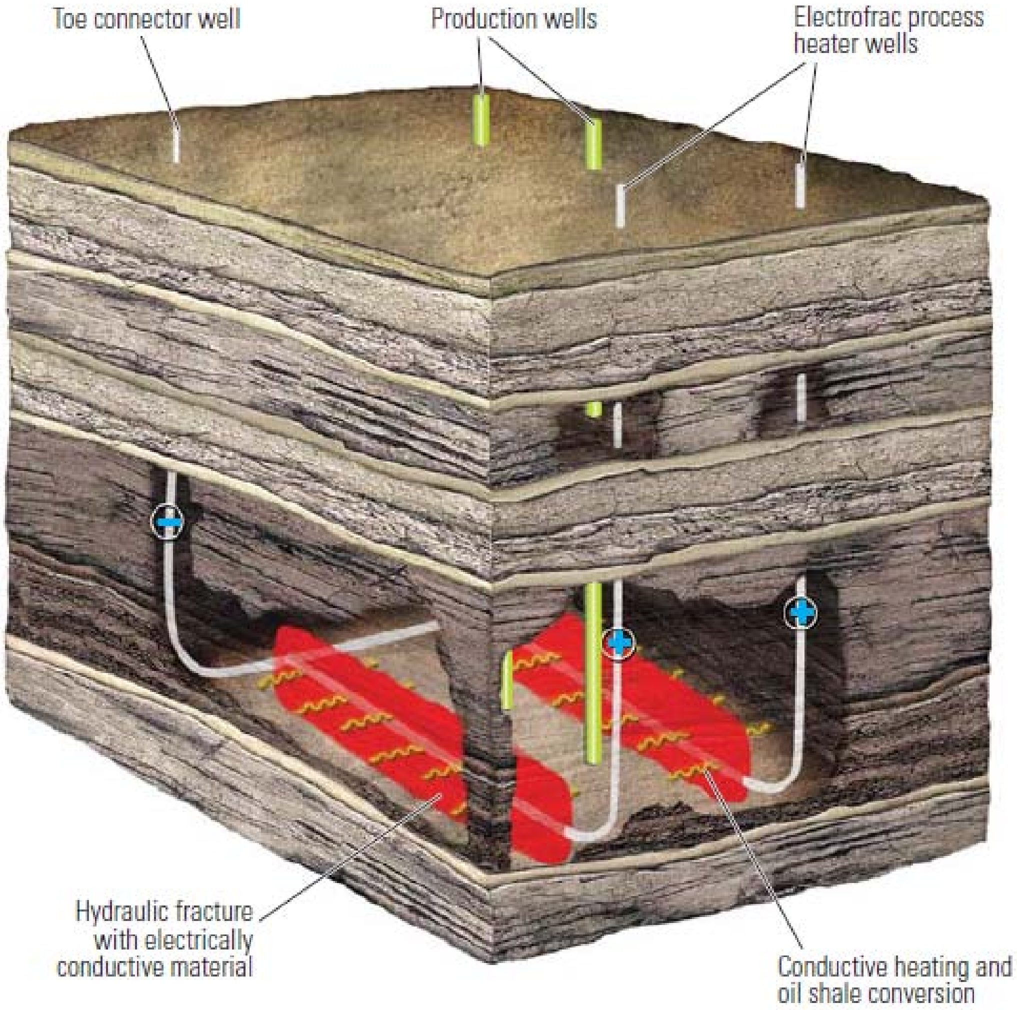
- Suggested milestone - Process

Gannt Chart for FYP 2 with milestones.

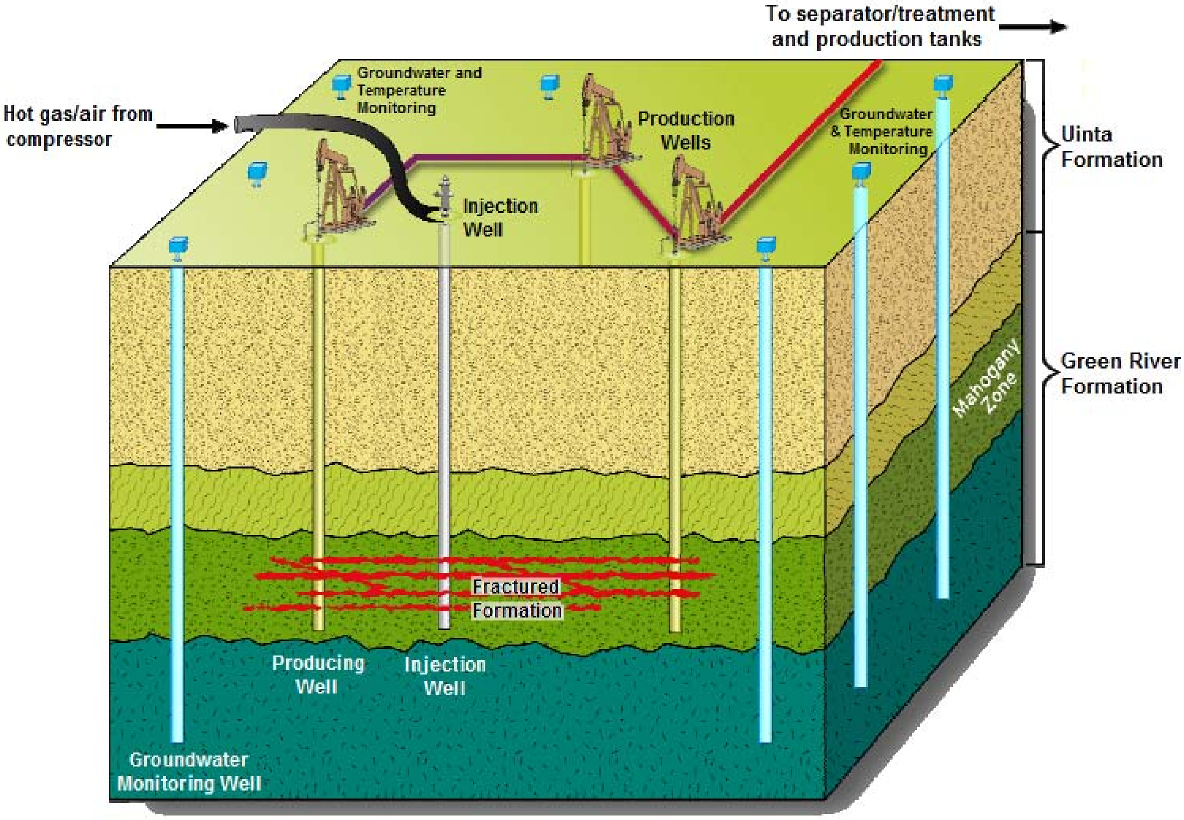
APPENDIX IV



Shell ICP technology with Freezing Wall



ExxonMobil Electrofrac method



Chevron CRUSH in-situ process