CHAPTER 8

RESULTS

The study needed a very systematic approach in order to incorporate all the important factors with minimum error possible. Before reaching a base case from which the results would be extracted, certain scenarios were adopted and their viability tested. One of the scenarios was to have to different layers, one being gas sand and the other an oil sand. Interpreting those results, it was clear that there was a lot of cross-flow from the oil sand to the gas sand and the scenario was abandoned. After trying a couple of other scenarios, the base case having a single oil sand was adopted.

The well deviation, geothermal gradient and the initial parameters (Appendix B) were picked up from one of the existing wells. The radial aquifer model is made to be four times the size of the reservoir. Some of the reservoir parameters can be seen in Appendix A. The important parameters that are studied in detail are shown as follows:

• Solution GOR	(200,500,800) SCF/STB
• Gas Injection Rate	(0.5, 0.75, 1) MMSCF/D
• k_{rw} End Point Saturation	(0.3, 0.5, 0.7)
• k_{rw} Corey Exponent	(1, 2, 3)
• Productivity Index	(2, 6, 10)
• Artificial Lift Depth	(4000, 6000, 8000) feet MD or
	(3400, 5000, 6600) feet TVD

It can be observed that each factor has 3 levels, being low, mid and high. The combinations are varied and simulation runs are made feeding these different combinations. First, the well is made to flow naturally till it loads up or produces less than 20 bbl/d of oil, then it is followed by either gas lift or ESP. The production of the artificial lift is stopped if it produces less than 20 bbl/d of oil or the production response starts oscillating.

Gas lift design criteria are not subjected to compressor pressure limitation and no unloading valves have been designed. Desired gas rate is injected continuously and the assumption made is that the compressor is able to deliver the required pressure for that injection rate at the desired injection depth. The ESP is designed at 3000 STB/D of liquid and the same pump is used for different productivity index. But it is slightly altered for different solution GOR. A gas separator efficiency of 95 percent is used throughout the study.

The simulation runs and the results recorded from them showed the impact of various sensitivities that were varied. The main idea is to grab hold of the concept and only the results of importance will be discussed.

Although there are a total of 9 combinations for the k_{rw} end point saturation (3-levels) and Corey's exponent (3-levels) but only the results for two extreme combinations that would produce the highest and the lowest water cuts are shown here. An example of the highest and lowest water producing profile is shown in Figure 8.1.

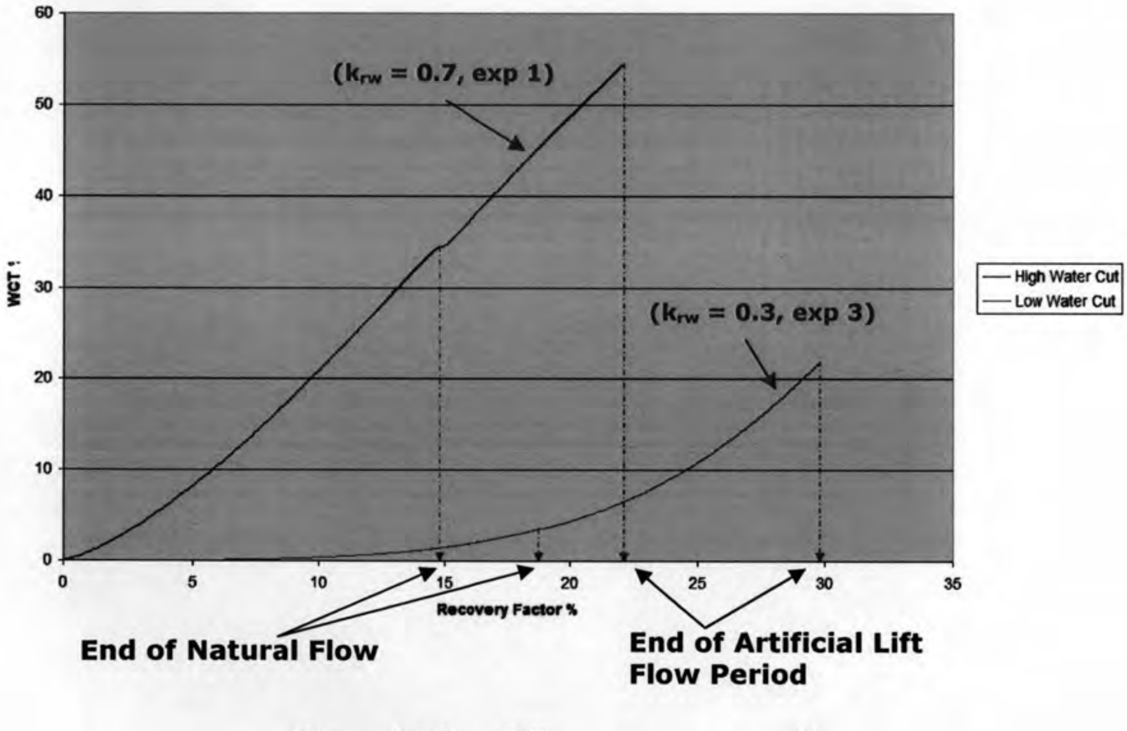

Figure 8.1 Two different water cut profiles

Although the values of recovery factors might be slightly exaggerated but the comparison results of one lift method to the other are still true. These recovery factors may not be achievable in real field production due to one reason or the other and changing the correlation of the Vertical Lift Performance (VLP) will deliver different recovery factors, but the focus is on the criteria which will favor Electrical

Submersible Pump (ESP) over continuous gas lift. In designing the ESP, one thing to keep in mind for varying other sensitivities is that the design criteria of the ESP should be kept constant in order to see the effect of other variables not associated with the ESP itself. For example:

$$P.I. = \frac{q}{P_R - P_{wf}} \qquad \text{STB/D/psi} \qquad (8.1)$$

For a P.I. = 10

Design Rate q = 3000 STB/D

P_R = any value during ESP installation

All these values will result in a fixed flowing bottom-hole and this pressure is not be changed even if the ESP is landed at different depths in order to see the effect of gas expansion on the performance of the ESP. But the number of stages will change as we install the ESP deeper in the well in order to deliver the specified design rate. Keeping these design limitations in mind and also the fact that the ESP is designed for the specific productivity index but at times the well tends to deliver less (i.e. the well has lower P.I.). So the ESP design will be for a known GOR (i.e. different design for a different GOR) but same design for all productivity indexes.

The well's measured depth is displayed in all the graphs because different wells can have different measured depth (MD) for the same true vertical depth (TVD) and friction has an important role in the production but the various equivalent landing depth of the ESP or the gas injection depths are given as follows:

- 4000' MD = 3400' TVD
- 6000' MD = 5000' TVD
- 8000' MD = 6600' TVD

In designing the gas lift, it is not necessary to design the unloading valves as we are not concerned about the compressor capabilities but are interested in injecting the specified gas injection rate, and the software makes the assumption that the compressor is big enough to deliver the required pressure to inject the gas to the specified depth.

8.1 Solution GOR of 200 SCF/STB and P.I. of 10 STB/psi/D

(a) Landing Depth of 4000' MD

The ESP design detail is computed for a landing depth of 4000' MD is shown below:

Well Head Pressure	500	(psig)
Flowing BH Pressure	2200	(psig)
Pump Intake Pressure	512.743	(psig)
Pump Intake Rate	3328.84	(RB/day)
Free GOR Entering Pump	4.72949	(scf/STB)
Pump Discharge Pressure	1841.02	(psig)
Pump Dischage Rate	3238.04	(RB/day)
Total GOR Above Pump	110.14	(scf/STB)
Mass Flow Rate	968456	(lbm/day)
Total Fluid Gravity	0.84873	
Average Downhole rate	3255.13	(RB/day)
Head Required	3613.63	(feet)
Fluid Power required	73.4077	(hp)
GLR At Pump Intake(V/V)	0.2969	
Bo At Pump Intake (V/V)	1.11486	
Inlet Temperature	276.043	
Bg At Pump Intake (V/V)	0.038546	

Figure 8.2 ESP design calculations for 4000'MD

The model of pump is chosen on the basis of covering the operating range from reasonably low pumping rate to a rate slightly above the design rate. The pump which has the efficiency close to the designed rate is chosen and this model of the pump is selected for all the remaining design criteria. The pump plot is shown in Figure 8.3.

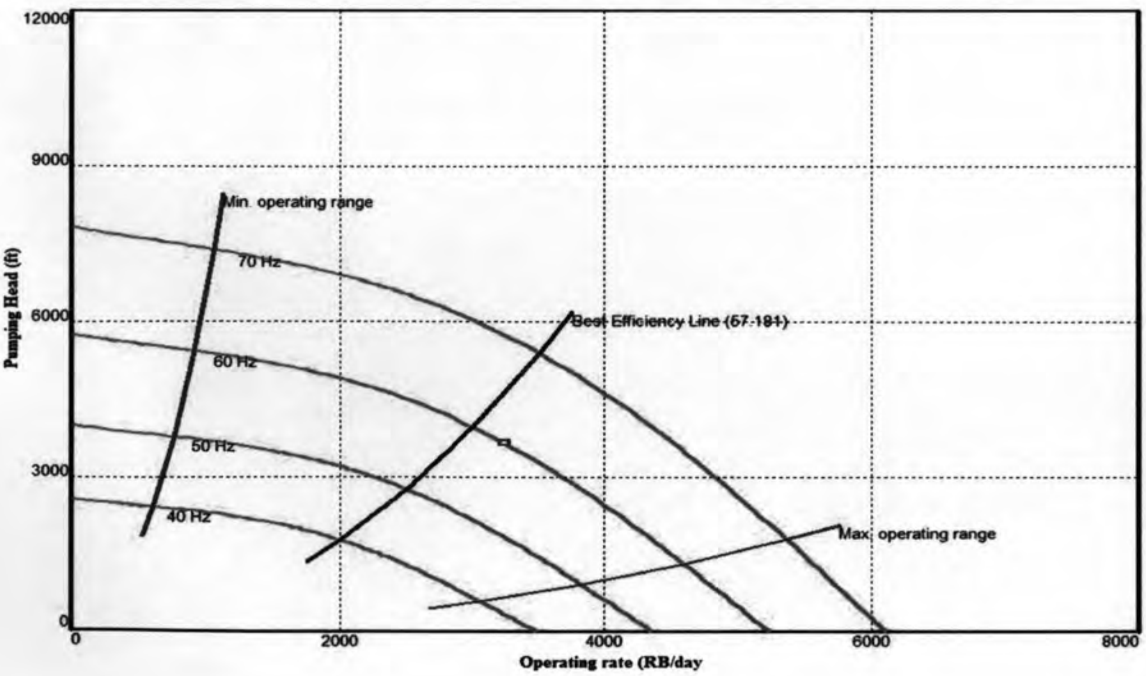

Figure 8.3 Electrical submersible pump plot for 4000'MD

Figure 8.4 shows the production results for varying gas injection rates and the ESP production at 60 Hz. The thing in keep in mind is that the production profiles as well as the injection rates for different scenarios are different. It might not be a good idea to select the better performing artificial lift method if time is of concern. For this study, the focus is on cumulative production only.

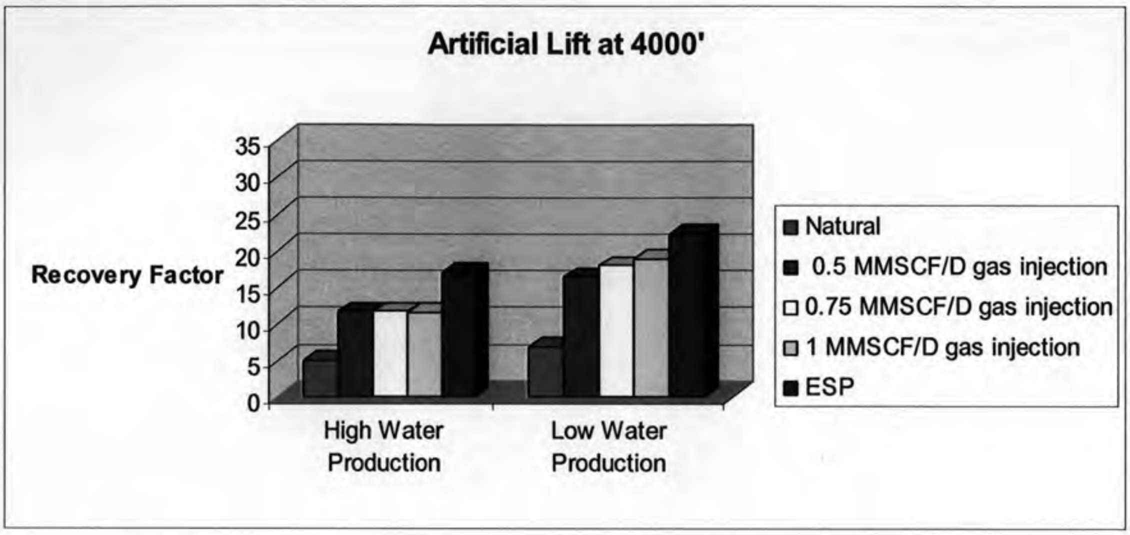

Figure 8.4 Performance comparison at 4000' MD (GOR= 200 SCF/STB and P.I. = 10 STB/psi/D)

The high water production and the low water production can be translated as the high water cut and the low water cut for the scenarios in this study. The natural flow period for low solution GOR delivers very low cumulative production. At high water cuts, increasing the gas injection rate does not help much to decrease the gradient. As a result, the recovery factor does not vary much as more gas is injected. Among the five scenarios, the ESP delivers the highest production. For low water cuts, it is observed that the performance of the gas lift starts to catch up with the ESP and the difference between the productions reduces as more gas is injected.

The recorded results are at times subjected to the software error and hence the bigger picture is of the primary concern rather than being exact on the delivered values.

(b) Landing Depth of 6000' MD

The ESP design detail is computed for a landing depth of 6000'MD is shown in Figure 8.5.

Well Head Pressure	500	(psig)
Flowing BH Pressure	2200	(psig)
Pump Intake Pressure	1066.87	(psig)
Pump Intake Rate	3383.59	(RB/day)
Free GOR Entering Pump	0	(scf/STB)
Pump Discharge Pressure	2404.75	(psig)
Pump Dischage Rate	3335.25	(RB/day)
Total GOR Above Pump	200	(scf/STB)
Mass Flow Rate	975664	(lbm/day)
Total Fluid Gravity	0.82969	
Average Downhole rate	3354.59	(RB/day)
Head Required	3723.26	(feet)
Fluid Power required	76.1977	(hp)
GLR At Pump Intake(V/V)	0	
Bo At Pump Intake (V/V)	1.17023	
Inlet Temperature	302.684	

Figure 8.5 ESP design calculations for 6000'MD

At this depth, it is observed that there is no gas going in the pump intake. For a solution GOR of 200 SCF/STB, the bubble point is slightly above 1000 psig and the gas does not break free at this depth and hence will increase the efficiency of the ESP. The pump plot for the ESP is shown in Figure 8.6.

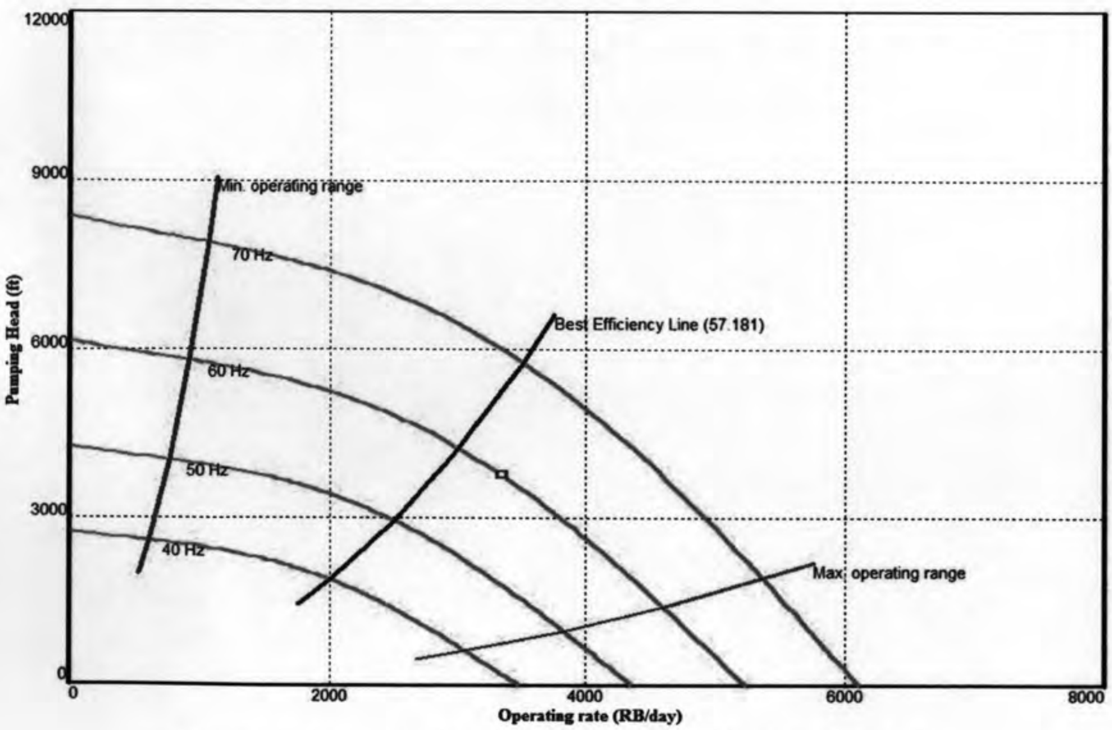

Figure 8.6 Electrical submersible pump plot for 6000'MD

Figure 8.7 compares the performance of the artificial lift when set deeper into the well:

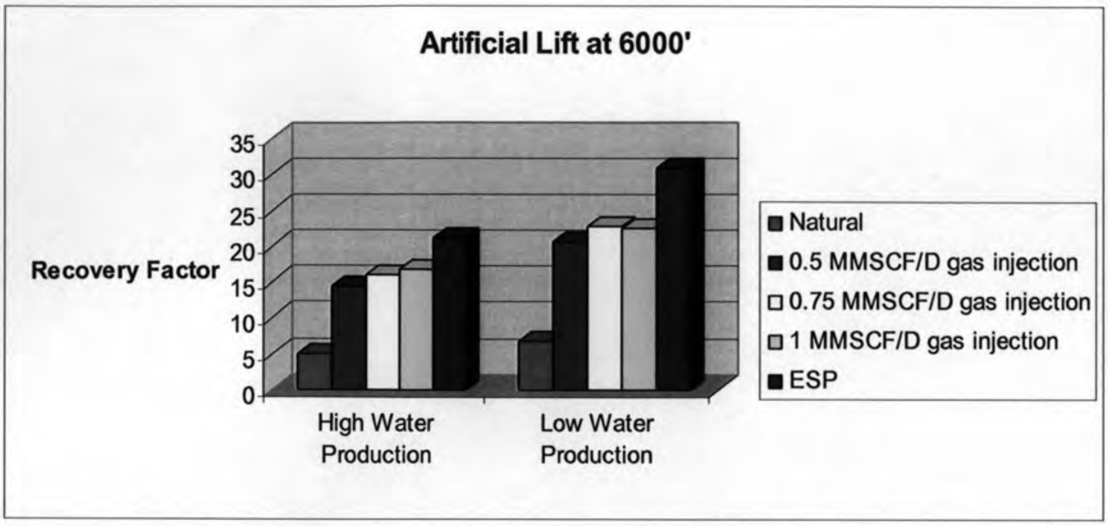

Figure 8.7 Performance comparison at 6000' MD (GOR = 200 SCF/STB and P.I. = 10 STB/psi/D)

The gas lift starts to show substantial improvement when injected at lower depths. The higher the injection rate, the more the GOR of the well. For high water cuts, the varying injection rate of the gas lift starts to impact the gradient of the well and hence we see small step incremental as the injection rate is increased. For low water cuts, the well delivers more of oil and less of water and hence the oil production of both the gas lift and the ESP is better as compared to high water cut profile.

For low solution GOR wells, gas lift having been constraint to the highest injection rate of 1MMSCF/D is unable to achieve productions like ESP's. Since the gas lift available for the field in consideration seldom goes above 1MMSCF/D, for these reasons the constraints were set.

(c) Landing Depth of 8000' MD

The ESP design detail is computed for a landing depth of 8000'MD is Figure 8.8.

Well Head Pressure	500	(psig)
Flowing BH Pressure	2200	(psig)
Pump Intake Pressure	1642.78	(psig)
Pump Intake Rate	3376.52	(RB/day)
Free GOR Entering Pump	0	(scf/STB)
Pump Discharge Pressure	2958.71	(psig)
Pump Dischage Rate	3348.06	(RB/day)
Total GOR Above Pump	200	(scf/STB)
Mass Flow Rate	975664	(lbm/day)
Total Fluid Gravity	0.82797	
Average Downhole rate	3361.56	(RB/day)
Head Required	3669.79	(feet)
Fluid Power required	75.1035	(hp)
GLR At Pump Intake(V/V)	0	
Bo At Pump Intake (V/V)	1.15943	
Inlet Temperature	318.733	

Figure 8.8 ESP design calculations for 8000'MD

The pump plot (Figure 8.9) as compared to the ones at different setting depths shows that there is very little increase in the pump head for the deeper depth indicating the requirement for only a few additional stages in order to deliver fluid to the surface.

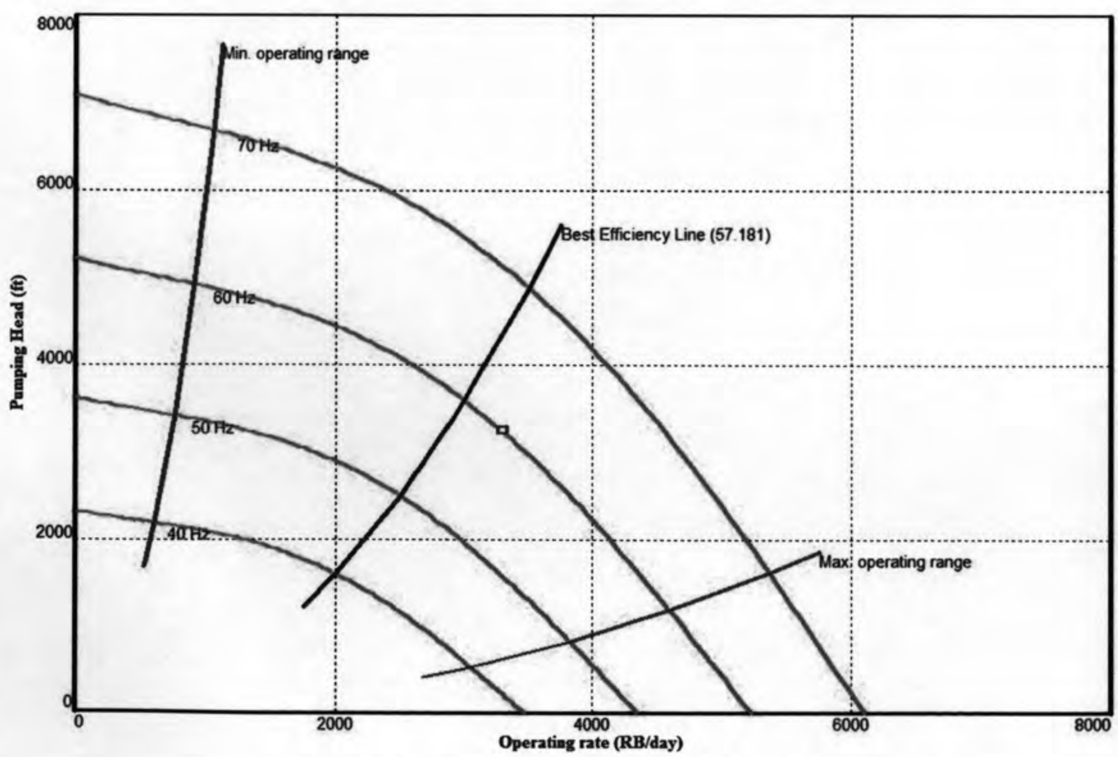

Figure 8.9 Electrical submersible pump plot for 8000'MD

Figure 8.10 shows the artificial lift performances when the setting depth is at 8000' MD:

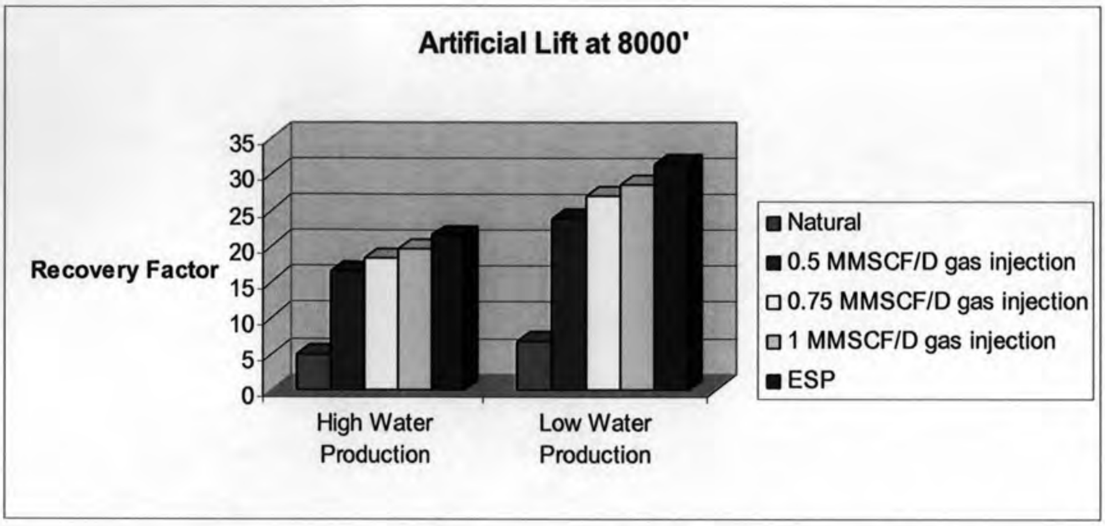

Figure 8.10 Performance comparison at 8000' MD (GOR = 200 SCF/STB and P.I. = 10 STB/psi/D)

It is observed that the cumulative production of gas lift comes very close to the ESP's cumulative production. This is limit of our range for which we vary the depth. It can be possible that for this design of the ESP the gas lift may outperform at depths deeper than the ones considered for this study. If there is gas sand at deep depths, it can also be seen as an injection point for the gas lift, meaning that having a single oil tank but varying the setting depth and injection rate can be translated into equivalent scenarios having gas sand delivering gas into the well at different rates.

The normal understanding of ESP going to the high water cut wells is true for high GOR wells. But for low GOR well, if the relative permeability combination yields a low water cut profile then the ESP will definitely produce more.

As for the gas lift, the deeper the gas injection point, the better cumulative production for low GOR wells. But this is not always true for high GOR wells because after a certain Gas Liquid Ratio (GLR), there tends to be a reversal in gradient.

8.1.1 Impact of Artificial Lift Setting Depth for GOR of 200 SCF/STB

In order to see clear impact of setting depth for both Gas lift and ESP, the performance of the gas lift and ESP are plotted for different depths. Figure 8.11 shows the graph of different injection depth for gas lift.

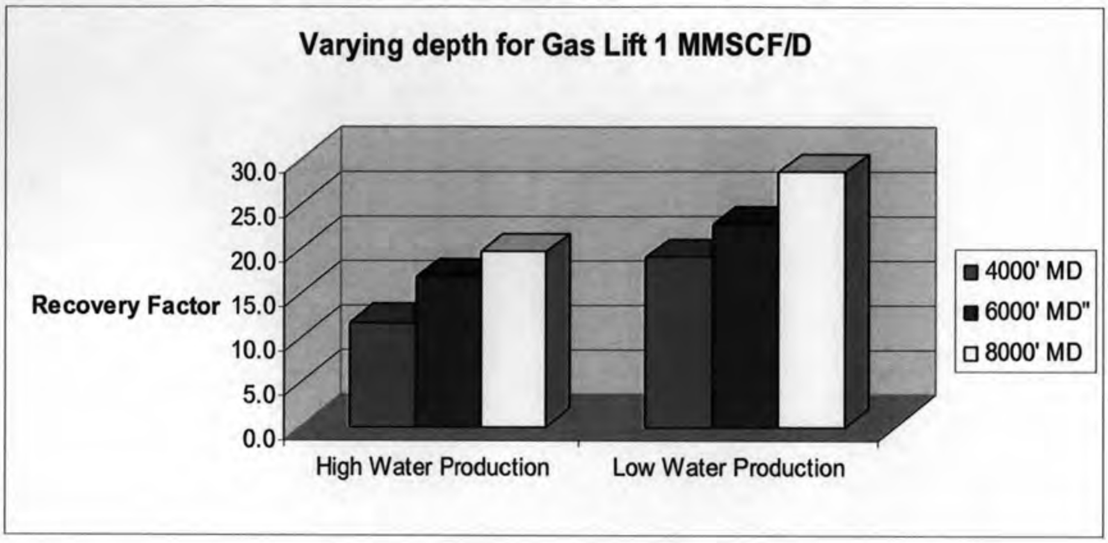

Figure 8.11 Varying injection depth for GOR = 200 SCF/STB and P.I. = 10 STB/psi/D

The gradual increase as the depth of injection increases the cumulative oil production for both high water cut and low water cut profiles assures that the deeper we inject the gas, the lighter the gradient in the well and hence we can drain more oil from the reservoir. For this study, the abandonment pressure is not fixed and the reservoir is allowed to deplete as much as the artificial lift's capability, although in real field there is a problem of sand and the formation starts to collapse if it is depleted beyond a certain pressure.

There is a difference between optimum and maximum. Since cost is not considered in this study, the preference is to obtain maximum oil regardless of the cost and the time it takes to do so. However, there is a constraint set that the well has to be abandoned if the oil flow rate drops below 20 STB/D.

In the real field, there is not a single well where the injection valves are set as deep as the ones in the research model but recently a new technology has evolved in which the injection would be possible below the packer and these results will be able to show the impact of gas injection rates and injection depths.

Complying with the design limitations of the ESP, Figure 8.12 shows the results for varying the landing depth.

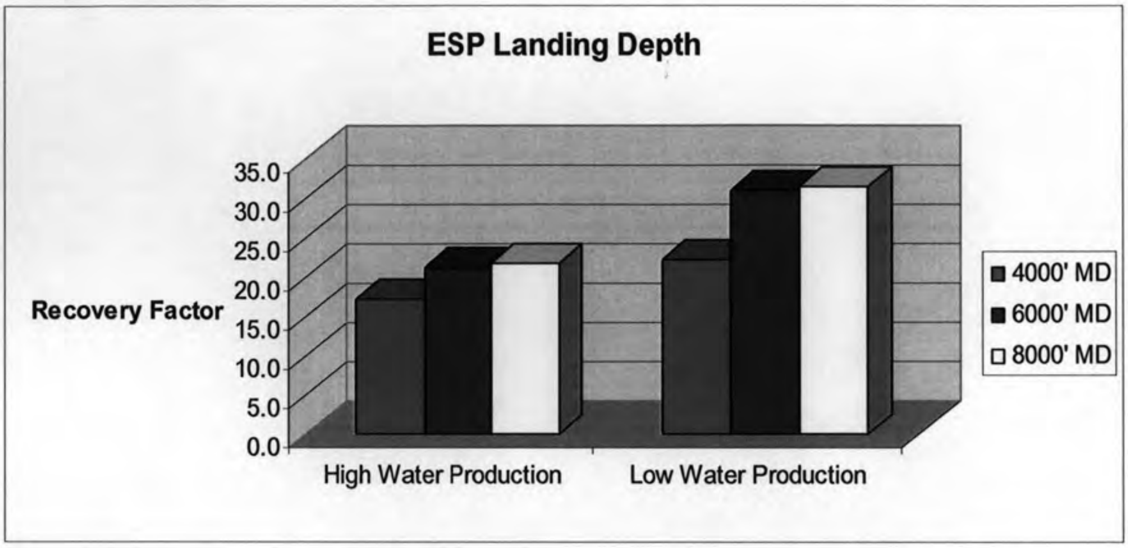

Figure 8.12 Varying pump landing depth for GOR = 200 SCF/STB and P.I. = 10 STB/psi/D

In Figure 8.12, we can see that there is a substantial difference in the cumulative oil production between 4000'MD and 6000'MD. This is due to the fact that the bubble point for a solution GOR of 200 SCF/STB is around 1000 psig. When the oil travels upwards towards the surface, there is a decrease in pressure. At a point which the pressure drops below the bubble point, the gas starts to break free from the solution, and hence there is more gas going into the pump.

We see a very less change in the cumulative production from 6000'MD and 8000'MD because at this depth the pressure is still above the bubble point and there is no gas breaking out of the solution. Though it is true that if we land ESP deeper into the well we can lower the abandonment pressure, but here as the designed liquid rate is fixed so the flowing bottom-hole pressure is the same for 6000' MD and 8000' MD.

8.2 Solution GOR of 500 SCF/STB and P.I of 10 STB/psi/D

(a) Landing Depth of 4000'MD

As the solution GOR increases, the performance of the artificial lift against one another starts to deviate from the trend observed earlier. The graph below shows results when artificial lift is set at the shallowest depth:

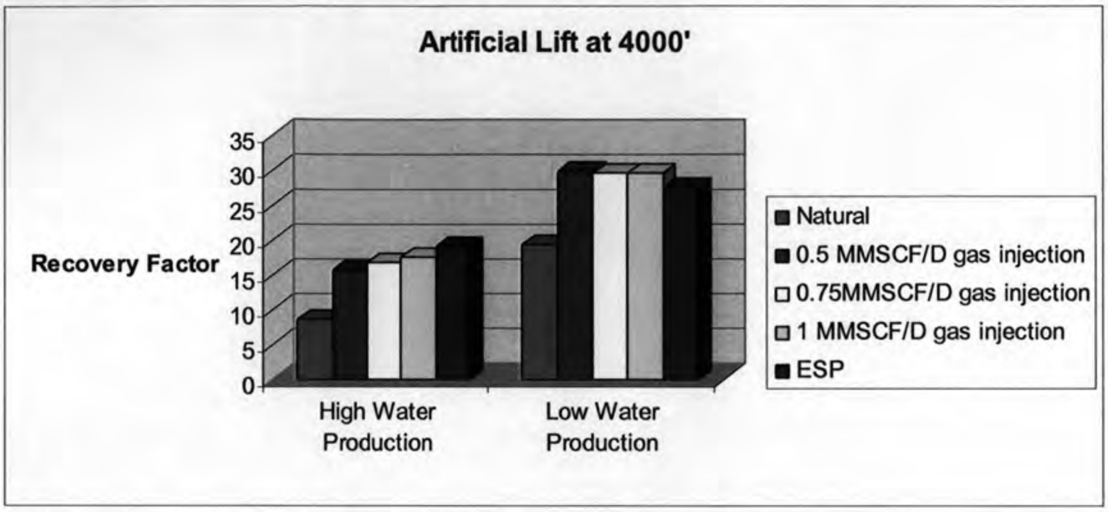

Figure 8.13 Performance comparison at 4000' MD (GOR = 500 SCF/STB and P.I. = 10 STB/psi/D)

At shallow depth, as the pressure decreases, the gas expands itself and hence there is more gas intake by the ESP for the low water cut profile and hence the gas lift performs better. When the water cut is high, the ESP is subjected to lesser gas intake. At the same time, since water increases the gradient of the well, the gas injected is not sufficient to reduce the gradient to outperform ESP.

(b) Landing Depth of 6000'MD

When the artificial lift is set deeper, we observe that the gas lift outperforms ESP for both high and low water cut profiles. The reason that even at high water cut the gas lift performs better is that when gas is injected little deeper in the well it then can reduce the gradient and hence reducing the bottom-hole flowing pressure and recovers more whereas ESP still has gas going into the pump. Figure 8.14 shows these results.

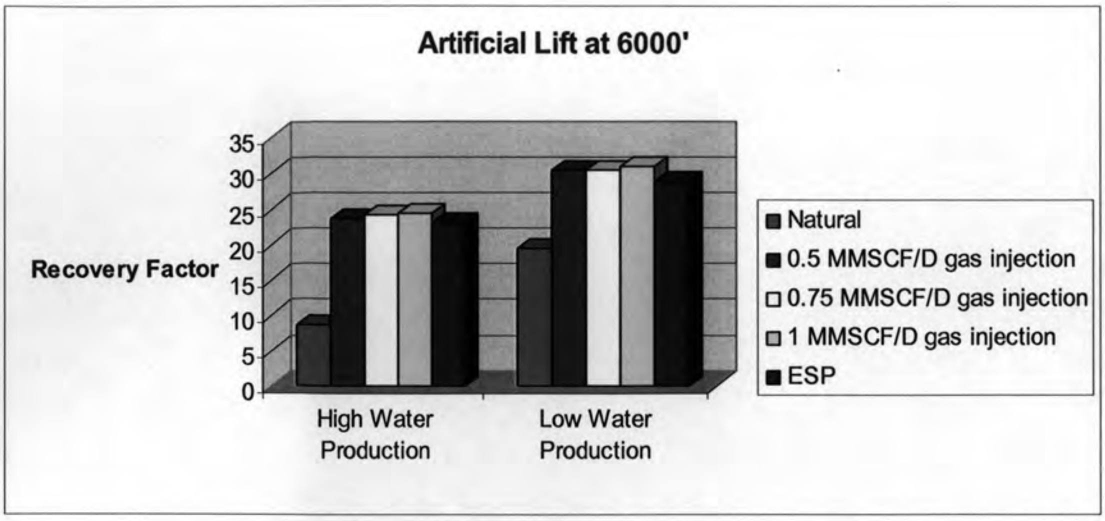

Figure 8.14 Performance comparison at 6000' MD (GOR = 500 SCF/STB and P.I. = 10 STB/psi/D)

(c) Landing Depth of 8000'MD

Figure 8.15 shows results when artificial lift setting depth is around 8000'MD:

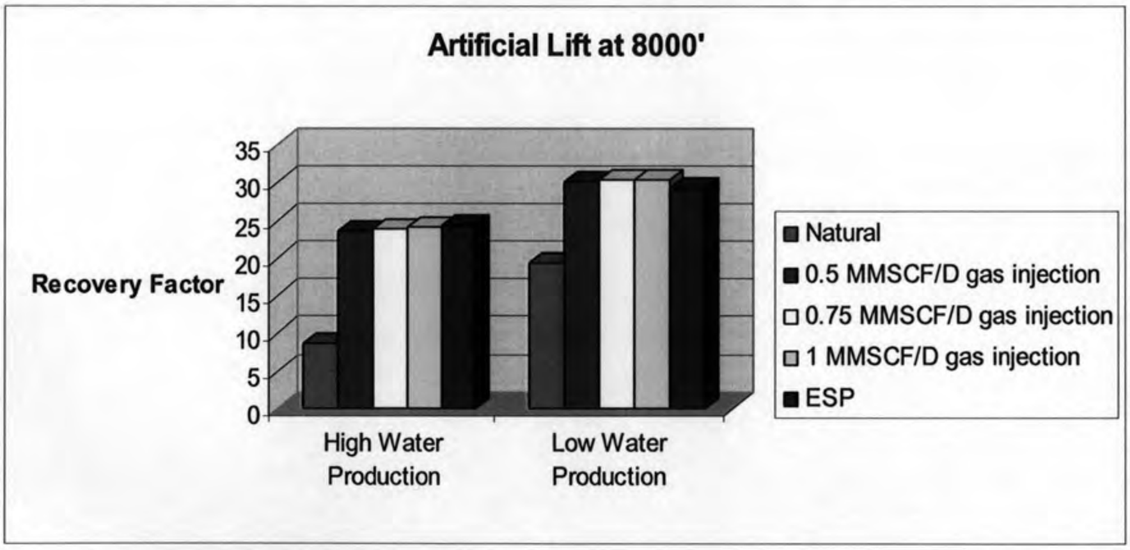

Figure 8.15 Performance comparison at 8000' MD (GOR = 500 SCF/STB and P.I. = 10 STB/psi/D)

When the ESP is landed deeper, there is a high pressure. Although there is gas in the well and at the pump intake but due to high pressure it has not expanded much while going through the stages of ESP. As the pressure increases, the gas is transformed back into the solution and does not cause gas block in the impellers. For high water cut, the results favor ESP for the reasons mentioned earlier but for lower water cut profiles gas lift performs better.

For the solution GOR of 500 SCF/STB we have observed the gas effect on the performance of one artificial lift over the other. In the next section, we can see a clear relation of gas effect individually on each artificial lift.

8.2.1 Impact of artificial lift setting depth for GOR of 500 SCF/STB

The gas lift has a certain injection depth maximum recovery beyond which a reversal effect is bound to occur. Figure 8.16 shows the results for gas injection at different depths:

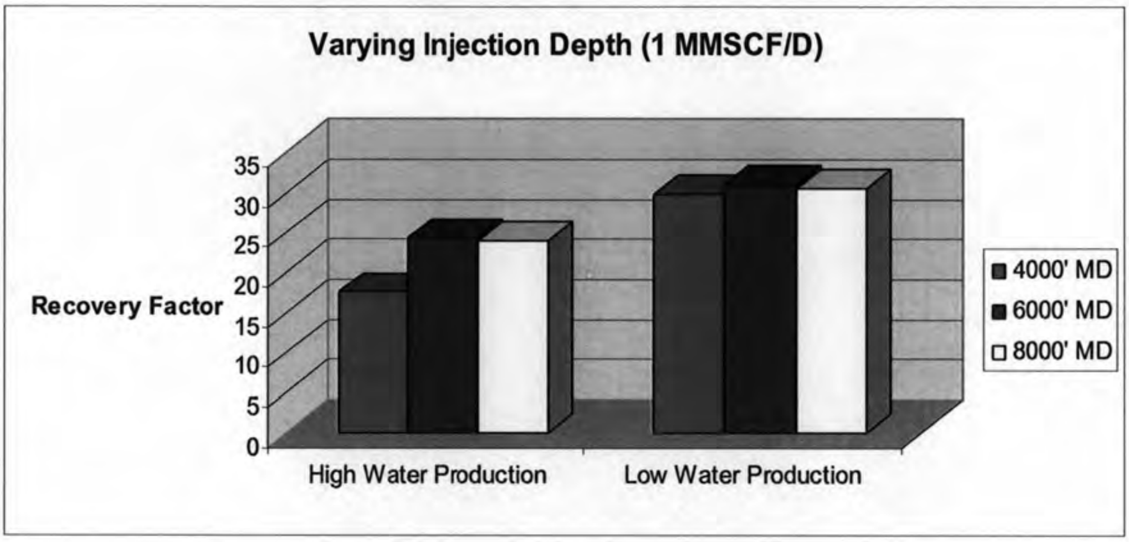

Figure 8.16 Varying injection depth for GOR of 500 SCF/STB (P.I.=10 STB/psi/D)

The reason behind the difference in the cumulative production of high and low water cut between 4000'MD and 6000'MD is that for high water production the injection rate of 1MMSCF/D could not decrease the gradient enough to drawdown the pressure of the reservoir below its bubble point but this was achieved for lower cut. For example, if the bubble point of the fluid in the reservoir is at 2200 psi and having a high water well, the injection rate of 1MMSCF/D is able to drawdown the well till 2300 psi. Hence it will not be able to deplete the reservoir below the bubble point. Whereas for low water cut wells, the injection rate of 1MMSCF/D will be able to deplete the reservoir below its bubble point after which GOR of the system increases and enables the system to deplete it even further.

Another interesting thing is that as we go deeper to 8000'MD from 6000'MD we see that there is a decrease in cumulative production and this behavior is due to the fact that there is a reversal in gradient, i.e., the excess gas in the well causing an increase in friction loss and hence a decrease in production. If we consider the impact of gas injection on the amount of oil that can be recovered and observe that the first 0.5MMSCF/D of gas injection has the greatest impact on oil recovery and increasing the gas injection rate further from it gives a very gradual increase in production. This in turn can help to maximize efficiency but it needs a different well to well and field to field approach.

Regarding to ESP landing depth, let us recall Figure 8.12, in which we have seen that there is a substantial increase in oil production for shallow to mid depth and not much of an increase from mid depth to the deepest one. But this trend does not remain the same in high GOR wells and that is because there is already gas in the well. It is just a matter of pressure which will determine the gas expansion. Figure 8.17 shows the results for varying ESP injection depth.

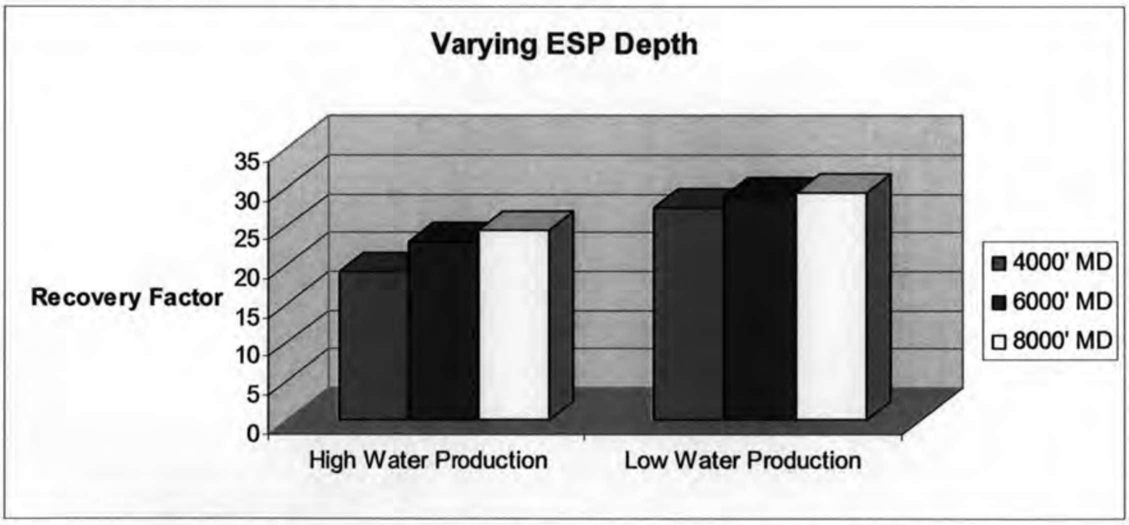

Figure 8.17 Varying Landing Depth for GOR of 500 (P.I.=10 STB/psi/D)

The results clearly indicate a gradual increase in cumulative production and somewhat proportional gas intakes at different depths for the same flowing bottom-hole pressure. So, as the solution GOR increases, the conditions under which the ESP will outperform the gas lift becomes more specific. Understanding these trends will enable us to make better use of artificial lift in the Gulf of Thailand.

8.3 Solution GOR of 800 SCF/STB and P.I of 10 STB/psi/D

The artificial lift is successful upto a certain value of solution GOR beyond which the design limitations prevent it to perform at all. The design limitations like the designed liquid rate and the designed water cut of the ESP. For a specific design rate, there can be only one flowing bottom-hole pressure. The results for the deepest landing depth is shown as the shallow and mid landing depths do not perform as well. Such a case can be observed from Figure 8.18

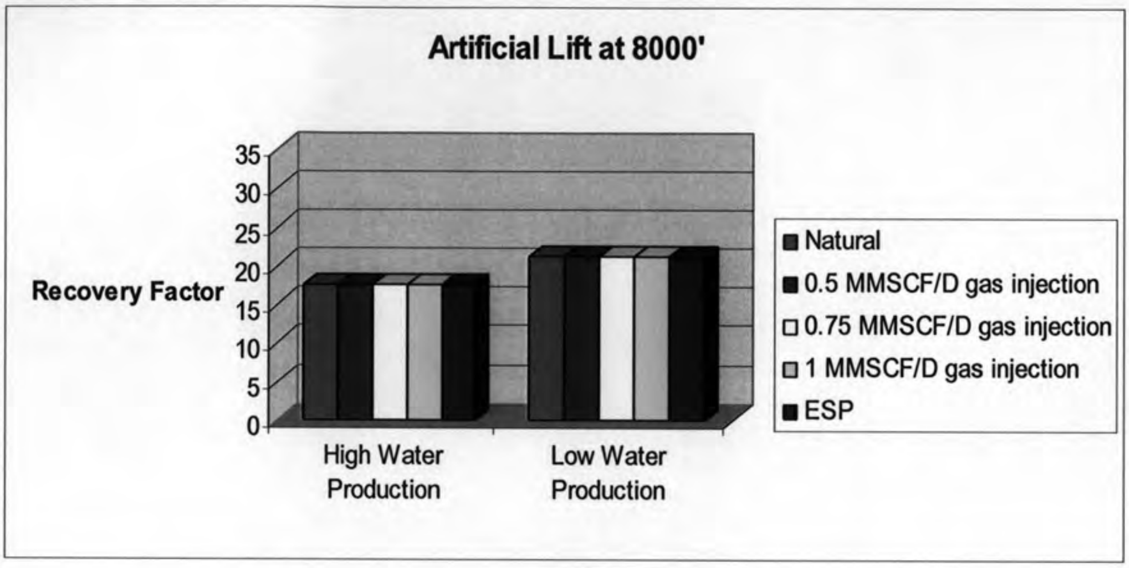

Figure 8.18 Performance comparison at 8000' MD (GOR = 800 SCF/STB and P.I.=10 STB/psi/D)

The graph clearly indicates that both gas lift and ESP does not produce any additional oil at all as the natural flow itself has a high recovery factor. This is because the solution GOR in the oil has enough energy to let the fluids flow by themselves beyond the capability of both the artificial lifts having constraints intact. If the design is altered, there may be additional oil recovery but it has not been done in this study.

8.4 Solution GOR of 200 SCF/STB and P.I. of 2 STB/psi/D

(a) Landing Depth of 4000' MD

When the productivity index of the well is low, it means the oil is recovered over a longer period of time. The cumulative oil recovered may or may not be the same as having a high productivity index but is sure in that particular range provided the difference in production timeline of the two. Figure 8.19 shows the results for shallow artificial lift installations.

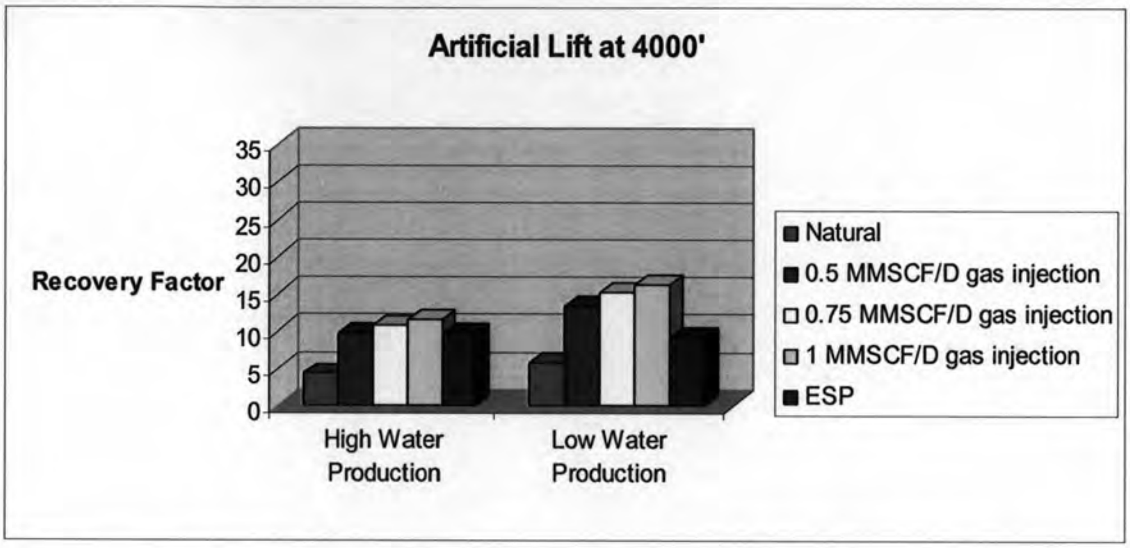

Figure 8.19 Performance comparison at 4000' MD (GOR = 200 SCF/STB and P.I. = 2 STB/psi/D)

Comparing Figure 8.19 with the results shown in Figure 8.4, we observe different magnitude of recovery factor but the trend by which there is an increase in the recovery factor, with an increase in injection rate is still the same. For ESP the level should be above its intake. Since the reservoir has low productivity index, the production rate falls off from the operating range of the ESP and hence the pump starts to pump off. As for the performance of gas lift, we see a gradual increase as the injection rate is increased.

In order to make use of the ESP in these low productivity wells, the design of the ESP should match up with the wells capability to deliver and hence the ESP should be chosen over the range which can pump for low rates and still be within its range. These ranges of rates which the ESP should be used over can be easily obtained from its pump plot.

(b) Landing Depth of 6000' MD

As the depth of the installation and the injection is increased we start to observe huge difference in the performances of the artificial lift. Figure 8.20 shows the results for the artificial lift installation depth of 6000' MD.

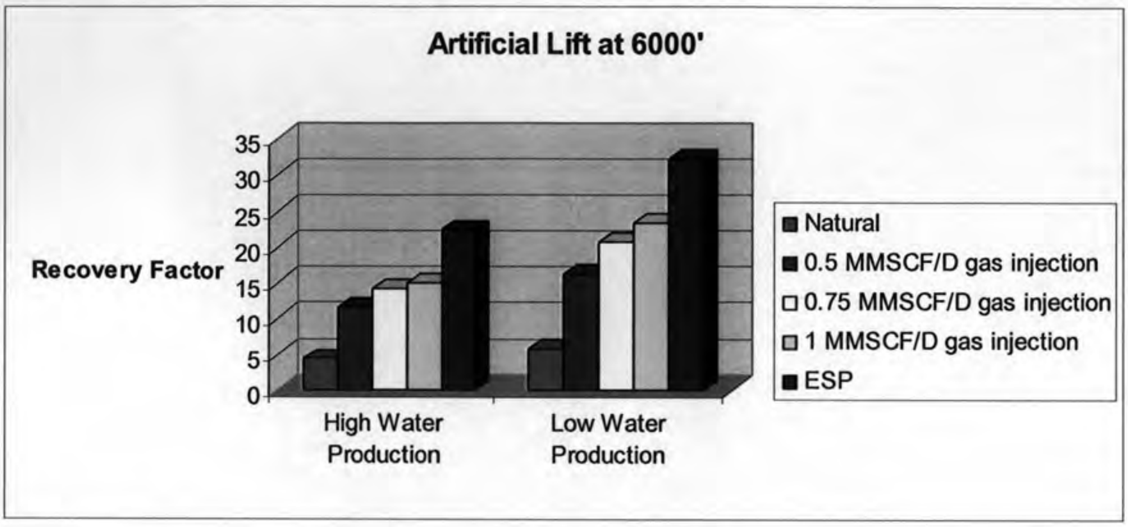

Figure 8.20 Performance comparison at 6000' MD (GOR = 200 SCF/STB and P.I. = 2 STB/psi/D)

Since increasing the depth of ESP insures that the level of the fluid in the well is above the pump intake for a longer period of time, the pump is used effectively and outperforms the cumulative production of gas lift.

There has been a case for one of the real field wells where the productivity index was low and the pump was installed at shallow depth. The well failed to keep the fluid above the pump intake and the pump had to be shut in order to avoid damage. That well is produced by for 3 days and shut for a week or so in order to bring back the fluid level up.

The two figures (Figure 8.19 and Figure 8.20) clearly show the importance of the productivity index and the corresponding landing depth of the ESP to make it run successfully. These mistakes can be avoided when we carefully examine the well in which artificial lift method is required.

The cumulative production obtained by the ESP can further be increased if the design is made for very high water cuts and high flow rates which will increase the number of stages and therefore will be able to deliver more pressure in order to lift the fluid to the surface.

(c) Landing Depth of 8000' MD

The general norm is to install the artificial lift as deep into the well as possible. But considering the same design and a well having low GOR, it is not necessary to always go that deep and increase the cable expense and also the voltage loss along the cable and hence requiring more voltage at the surface to run the pump. Figure 8.21 shows artificial lift setting at 8000'MD:

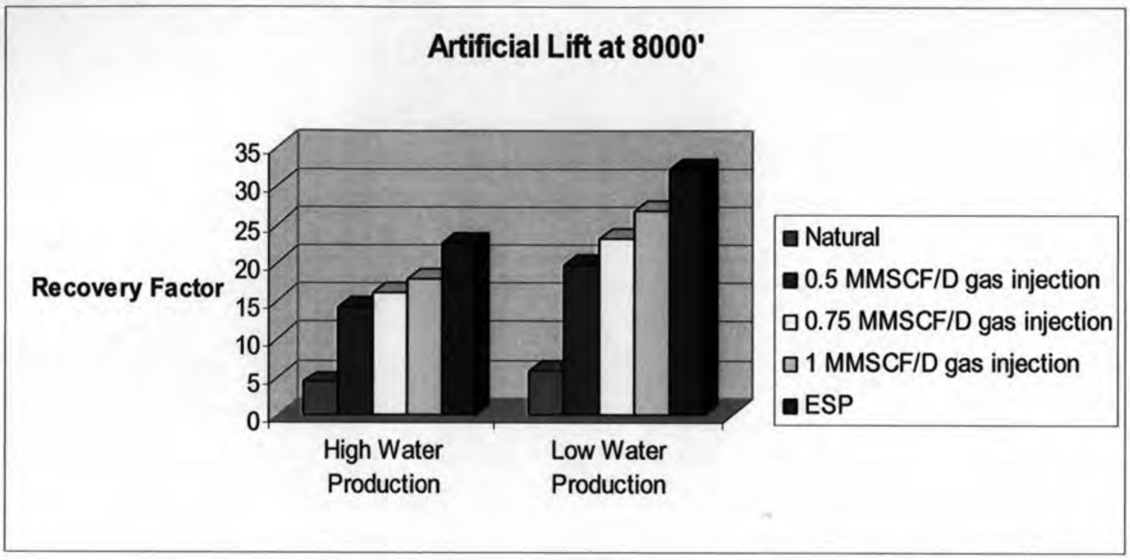

Figure 8.21 Performance comparison at 8000' MD (GOR = 200 SCF/STB and P.I. = 2 STB/psi/D)

Figure 8.21 shows an increase in production by gas lift for both high and low water cut profiles which is true due the fact that gas decreases the fluid gradient in the well and hence depletes the reservoir to a lower pressure.

8.4.1 Impact of artificial lift setting depth for GOR of 200 SCF/STB

We observed the impact of the artificial setting depth for low solution GOR for a high productivity index well but for a low productivity index well the behavior is slightly different. Having a high productivity index means there is more flow rate for the same difference in pressure between the wellbore and the reservoir but it also means that it will sustain the fluid level pretty high in the well.

For gas lift, a low productivity index impacts its performance at shallower depths when the fluid level fails to keep up to a certain level in order to make proper use of the gas injected into the well hence lowering its efficiency.

Figure 8.22 shows the results for varying injection depth for a low productivity index well.

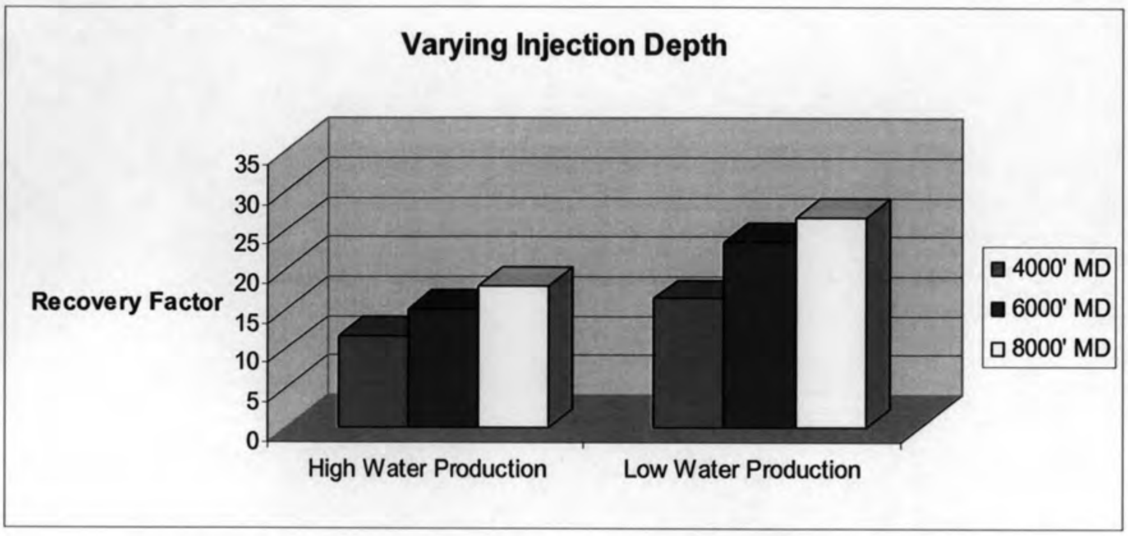

Figure 8.22 Varying Injection Depth for GOR of 200 SCF/STB (P.I.= 2 STB/psi/D)

The overall production by gas lift is lower for a lower productivity index but the main issue is about the fluid levels in the well which has already been discussed earlier. Figure 8.23 shows the impact of varying ESP depth on cumulative oil production.

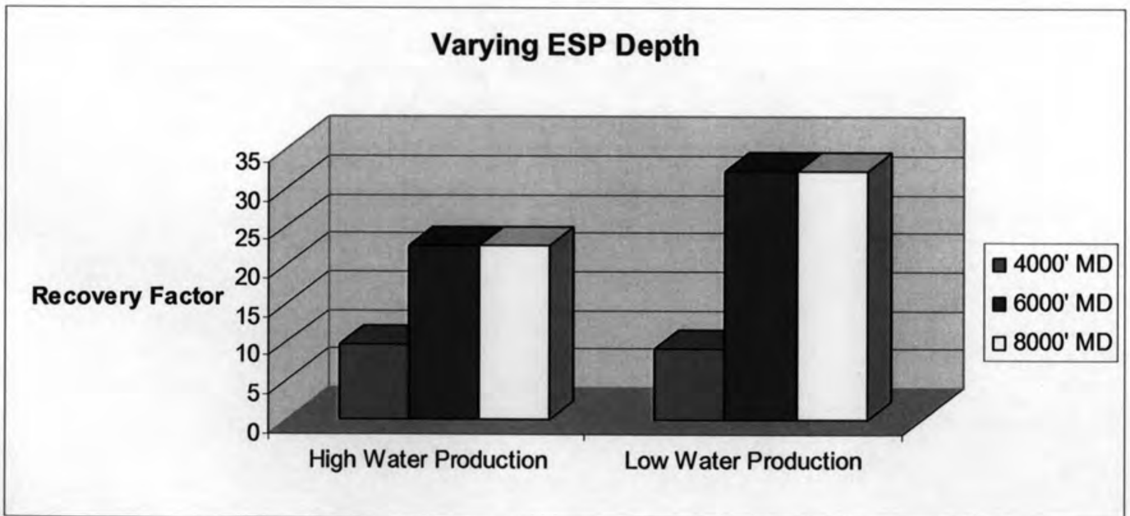

Figure 8.23 Varying Landing Depth for GOR of 200 SCF/STB (P.I.= 2 STB/psi/D)

There is a huge difference between shallow depth and mid depth because the fluid level fails to maintain above the pump intake for shallow depths.

8.5 Solution GOR of 500 SCF/STB and P.I. of 2 STB/psi/D

(a) Landing Depth of 4000' MD

As the solution GOR of the reservoir is higher, so is its lifting capability. The well itself can flow more naturally. Figure 8.24 shows the results for shallow artificial lift setting depth.

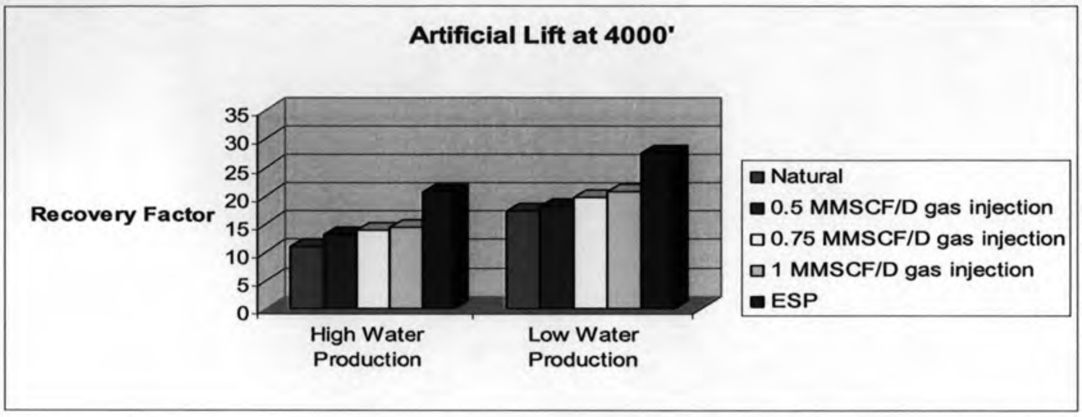

Figure 8.24 Performance comparison at 4000' MD (GOR = 500 SCF/STB and P.I. = 2 STB/psi/D)

It can clearly be seen that the ESP starts to outperform the gas lift even at shallower depths as the fluid level in the well is higher. Low productivity index means having less fluid deliverability by the well and in turn means that less gas is going through the pump which is beneficial for it.

(b) Landing Depth of 6000' MD

Figure 8.25 shows results for mid depth settings of artificial lift:

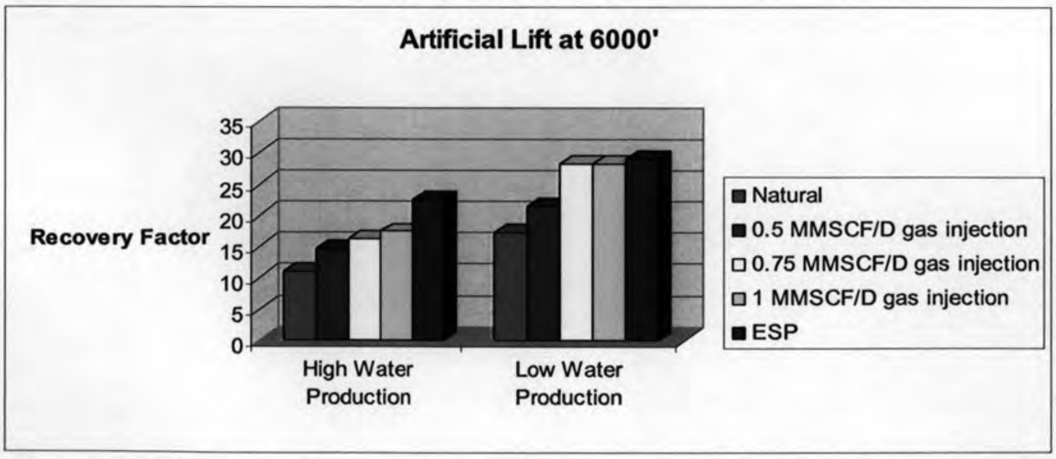

Figure 8.25 Performance comparison at 6000' MD (GOR = 500 SCF/STB and P.I. = 2 STB/psi/D)

The gas lift starts to match up in performance with the ESP for low water cut profiles as it is able to increase the GOR of the well which gives more of cumulative oil production. It can also be clearly seen that the difference between the two artificial lift performance for high and low water cuts is substantial because the ESP works better for high water cut wells. But if consider in terms of cumulative recovery, then ESP does better for low water cut wells.

(c) Landing Depth of 8000' MD

Figure 8.26 shows results for deepest setting depth for artificial lift.

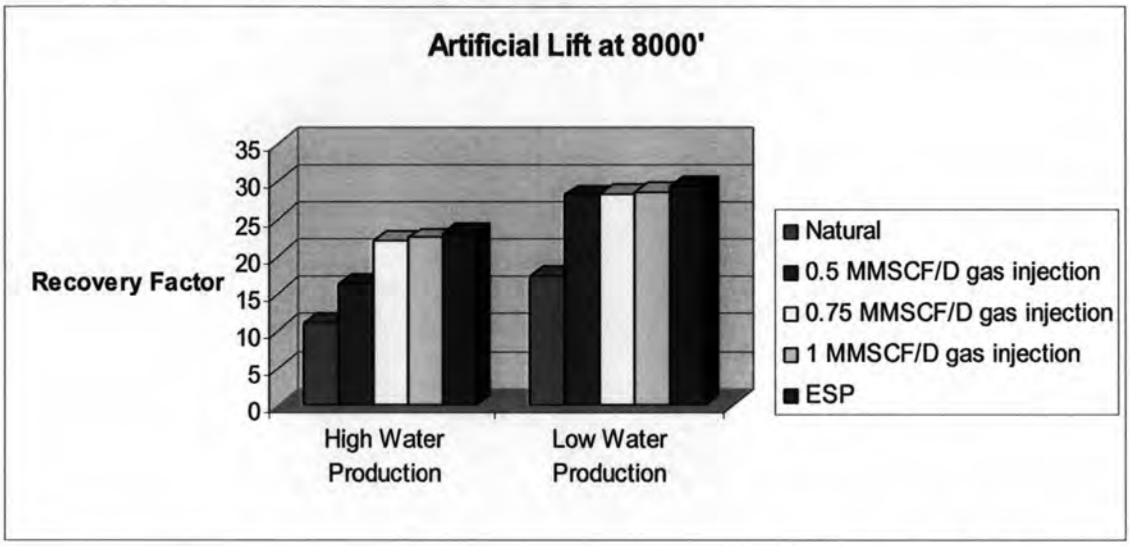

Figure 8.26 Performance comparison at 8000' MD (GOR = 500 SCF/STB and P.I. = 2 STB/psi/D)

High injection rates of gas lift delivers good results and very close to that delivered by the ESP. The thing to keep in mind is the timeline which is different between these two lift methods. As mentioned earlier, if the frequency of the ESP is increased, then the difference in the cumulative recovery will be greater.

The observation made for the gas lift is that after a certain injection rate, there is hardly an increase in the cumulative oil production. We can make use of this information and reduce the operating cost for gas injection process and find out the optimum rate which gives us the most efficient recovery.

8.5.1 Impact of artificial lift setting depth for GOR of 500 SCF/STB

Figure 8.27 shows the results for varying gas lift injection depth.

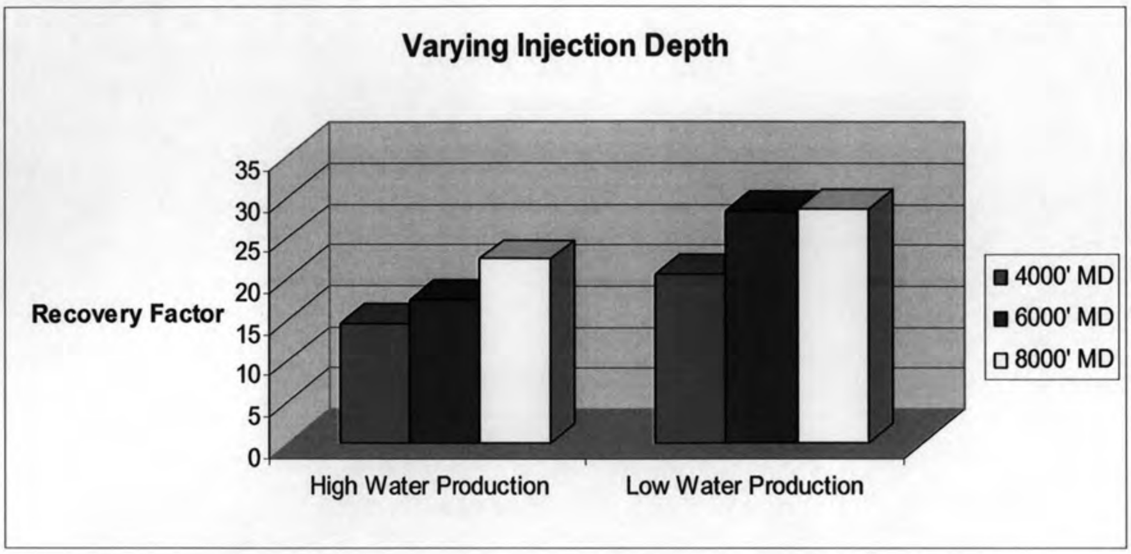

Figure 8.27 Varying Injection Depth for GOR of 500 SCF/STB (P.I. = 2 STB/psi/D)

The injection rate impacts high water cut profiles as it is necessary to have more of gas to dilute the heavy gradient of water and make it lighter. But after a certain injection rate for low water cut profile, the impact is hardly noticeable. Figure 8.28 shows results for ESP landing depths.

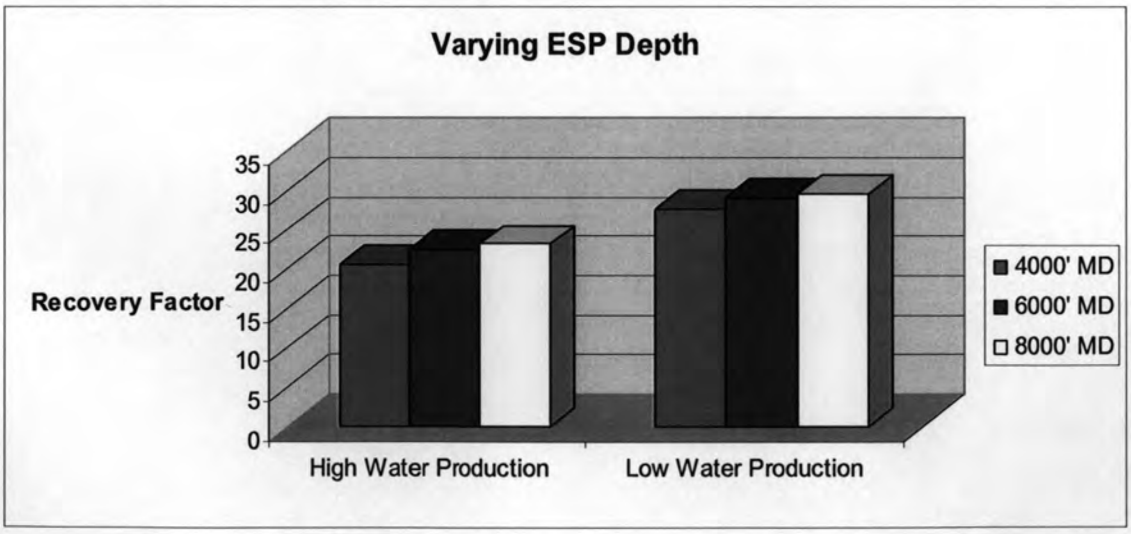

Figure 8.28 Varying Landing Depth for GOR of 500 (P.I. = 2 STB/psi/D)

The cumulative oil production has a gradual increase as the landing depth is deeper. This is inline with the fact that there is less of gas intake for low deliverability of the well.

8.6 Solution GOR of 800 SCF/STB and P.I. of 2 STB/psi/D

The energy present in the fluid in form of solution GOR determines the capability to deplete the reservoir naturally. Figure 8.29 shows the results for an artificial setting depth of 8000'MD.

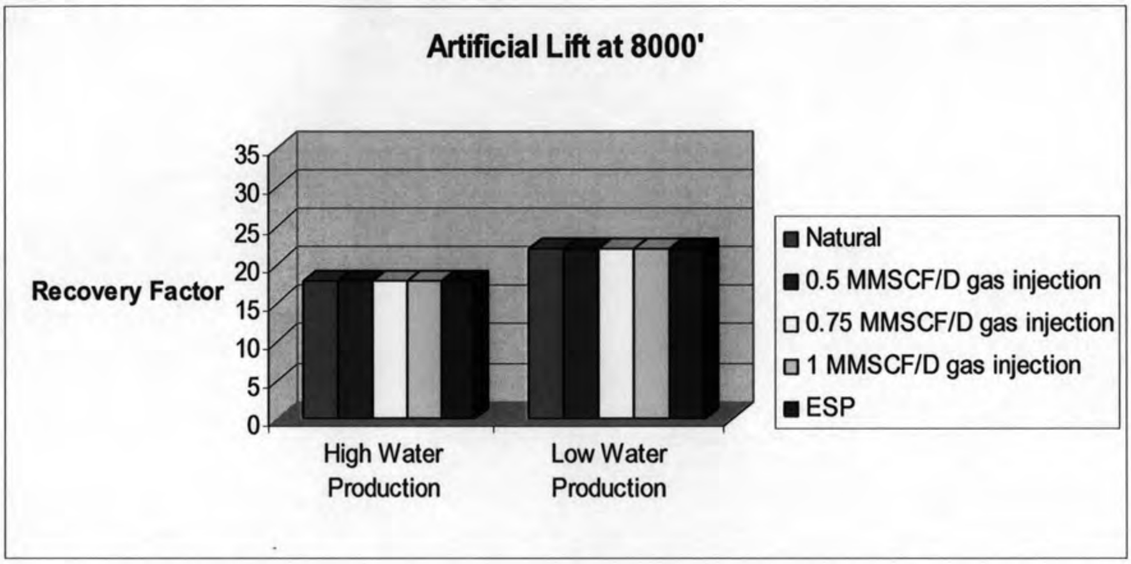

Figure 8.29 Performance comparison at 8000' MD (GOR = 800SCF/STB and P.I. = 2 STB/psi/D)

The artificial lift performance has the same recovery results as compared to high productivity well, i.e., neither of the artificial lift recovers anything after the natural flow as the high solution GOR is good enough to deplete the reservoir by itself.

8.7 Design of Experiments

The design of experiments can be beneficial for a larger picture of the trend and requires a very few runs which in turn saves cost and time in order to understand the relationship between sensitivities. The design is for 3 levels and makes use of central composite design to make surface response. The values obtained are directly fed to the various combinations required in order to make a surface response. Table 8.1 shows the various sensitivity values for electrical submersible pump.

Table 8.1 Sensitivity values

Factor	-1 (low)	0 (medium)	1 (high)
Solution GOR	200	500	800
P.I.	2	6	10
Artificial Lift Depth	4000	6000	8000
k_{rw}	0.3	0.5	0.7

Note: Units are Solution GOR = SCF/STB
P.I. = STB/D/psi
Art. Lift Depth = feet (MD)
k_{rw} = fraction

Also k_{rw} = 0.3 (means low end point and high Corey's exponent)
k_{rw} = 0.5 (means mid end point and mid Corey's exponent)
k_{rw} = 0.7 (means high end point and low Corey's exponent)

Table 8.2 Combination of low k_{rw}

	Res.Sat.	End Point	Exponent
k_{rw}	0.25	0.3	3
k_{ro}	0.25	0.8	3
k_{rg}	0.02	0.9	1

Table 8.3 Combination of mid k_{rw}

	Res.Sat.	End Point	Exponent
k_{rw}	0.25	0.5	2
k_{ro}	0.25	0.8	3
k_{rg}	0.02	0.9	1

Table 8.4 Combination of high k_{rw}

	Res.Sat.	End Point	Exponent
k_{rw}	0.25	0.7	1
k_{ro}	0.25	0.8	3
k_{rg}	0.02	0.9	1

The central composite design is chosen over other design of experiments due to the reason that it makes a better model for quantitative factors and the random combinations used to construct surface response shown in the table below:

Table 8.5 Sensitivities Combinations (Response units in MMSTB)

Exp #	*GOR*	*P.I.*	*Depth*	k_{rw}	*Response*
1	-1	1	-1	-1	1.21
2	-1	1	1	-1	1.65
3	1	-1	1	1	0
4	0	0	0	0	0.78
5	1	0	0	0	0
6	0	0	0	0	0.78
7	-1	1	1	1	2.45
8	0	-1	0	0	1.11
9	1	1	-1	1	0
10	0	0	0	-1	0.88
11	1	1	1	-1	0
12	1	-1	-1	1	0
13	-1	0	0	0	2.27
14	1	-1	-1	-1	0
15	0	0	0	1	0.69
16	0	0	0	0	0.78
17	-1	-1	1	-1	1.8
18	-1	1	-1	1	1.53
19	0	0	-1	0	0.71
20	-1	-1	1	1	2.73
21	1	1	1	1	0
22	0	0	0	0	0.78
23	-1	-1	-1	-1	0.54
24	0	1	0	0	1.13
25	0	0	1	0	0.85
26	1	-1	1	-1	0
27	1	1	-1	-1	0
28	-1	-1	-1	1	0.33

NOTE: The values of response are the actual numbers (incremental oil).

The actual number of runs required to complete Table 8.5 is only 28 but the total runs made in order to understand the behavior in more detail is around 1200 runs. We understand that there is a loss of accuracy to represent 1200 runs by just 28 runs but this helps reduce the effort and time taken if there are projects that require urgent results. The main idea is to focus on broader picture and understand the trend.

The results presented in Table 8.5 are the cumulative oil recovery made by ESP only (i.e. the incremental recovery after the natural flow by the ESP) and it needs a set of combinations in order to make surface response for the gas lift.

The quadratic model is represented by the equation below followed by coefficient values:

$$\text{Response} = b0+b1*F1+b2*F2+b3*F3+b4*F4+b5*F1*F1+b6*F2*F2 + b7*F3*F3+b8*F4*F4+b9*F1*F2+b10*F1*F3+b11*F1*F4 + b12*F2*F3+b13*F2*F4+b14*F3*F4$$

where $F1$ = *Solution GOR*
$F2$ = *P.I.*
$F3$ = *Depth*
$F4 = k_{rw}$

Table 8.6 Coefficient values

b0	0.904
b1	-0.806
b2	-0.314
b3	0.287
b4	-0.144
b5	0.148
b6	0.08111
b7	0.09167
b8	0.133
b9	-0.207
b10	-0.202
b11	-0.09000
b12	-0.115
b13	0.02500
b14	0.101

The response surface is made by two way interactions between the two factors although the equation contains all the factors in order to predict responses.

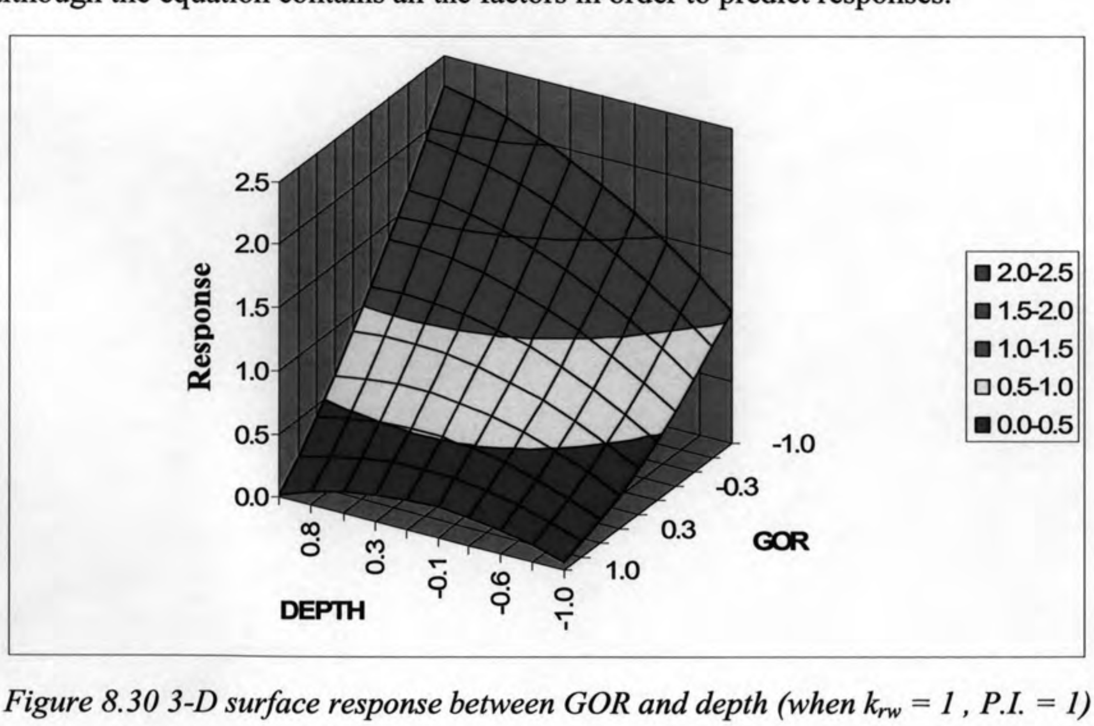

Figure 8.30 3-D surface response between GOR and depth (when $k_{rw} = 1$, P.I. = 1)

The relationship can be better observed in contour map as shown in Figure 8.31 for the same 3-D model (shown in Figure 8.30).

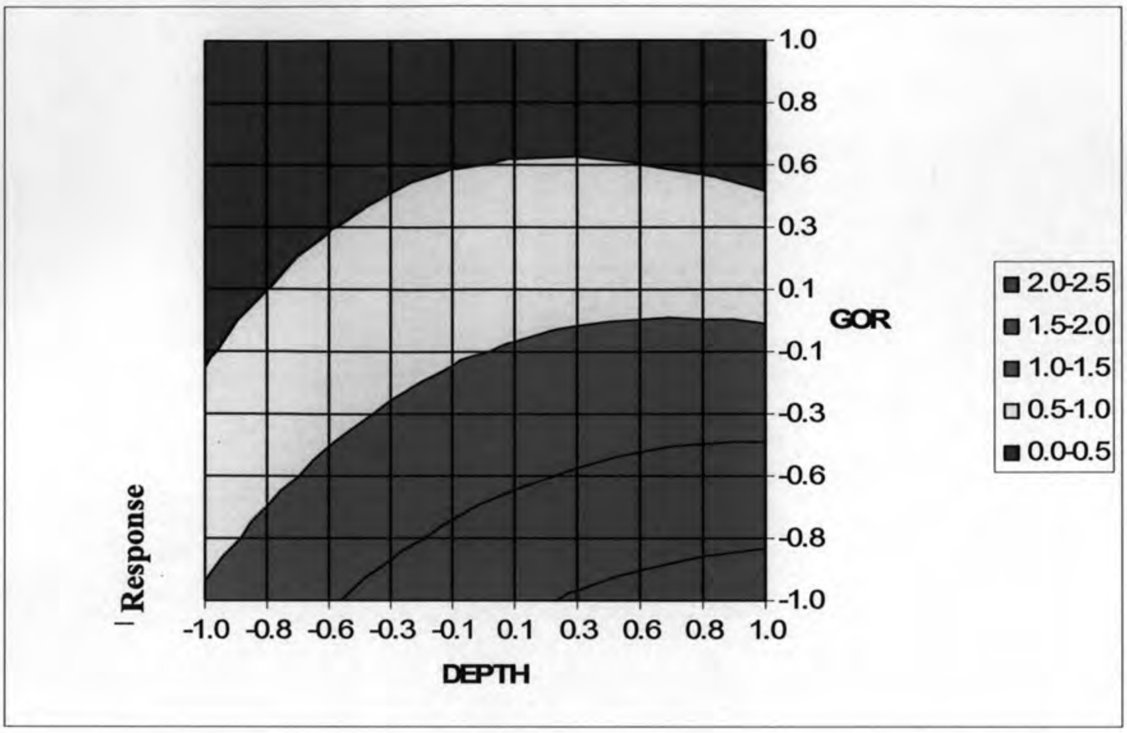

Figure 8.31 Contour map of two way interaction between GOR and depth (when $k_{rw} = 1$, P.I. = 1)

The relationship can be clearly observed that if the reservoir contains low GOR (represented by -1) and the ESP is installed at the deepest depth (represented by 1), then the recovery would be highest by the ESP. Hence, it would be a good option to install an ESP. It can be observed that for the same GOR and shallow depth, the recovery obtained by the ESP gradually decreases.

The relationship can be interpreted in a number of ways. Another instance of such is that when the ESP is installed at a fixed depth and if the well has a high GOR, there is a decline in the performance of the ESP. From the contour map, the area represented by the same colour does have a difference in cumulative oil recovered after the natural flow as the contour map does not represent the difference in the elevation like the one shown in 3-D surface response.

The next relationship is between solution GOR and the relative permeability of the reservoir which is the most important factor to create a high or low water cut profile during the natural flow as well as the artificial lift flow period.

It can be straight away assumed that with low k_{rw}, the water cut is going to be low, and for high k_{rw}, the water cut is going to be high. Figure 8.32 shows the relationship of the two factors.

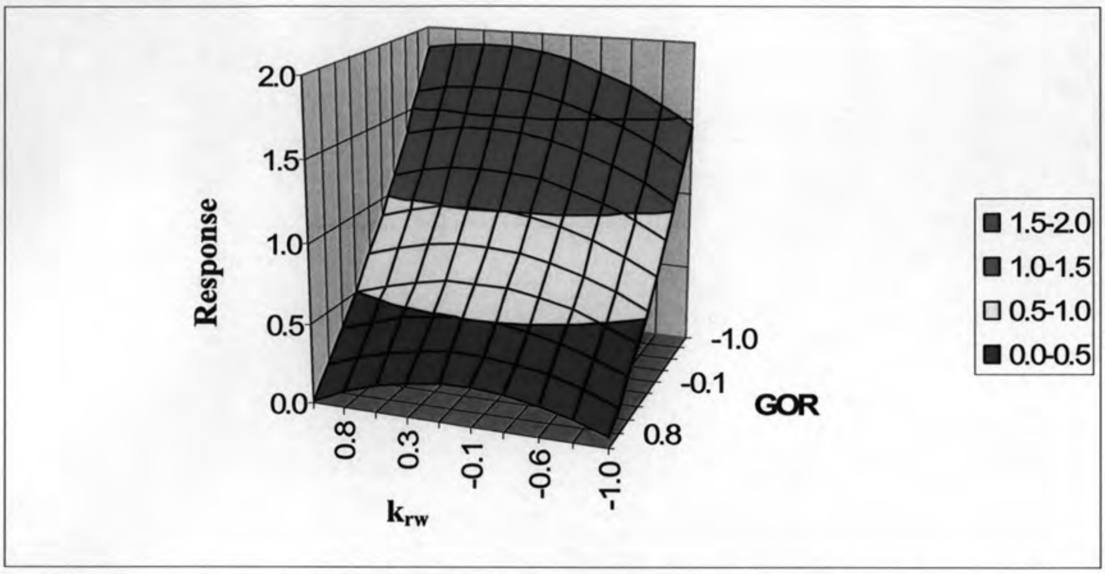

Figure 8.32 3-D Surface response between GOR and k_{rw} (P.I. =1, Depth =1)

Highest incremental oil recovery can be obtained when the well has high water cut and low solution GOR, reflected by the peak of surface response in Figure 8.32. Another way to represent Figure 8.32 is by contour map as shown in Figure 8.33.

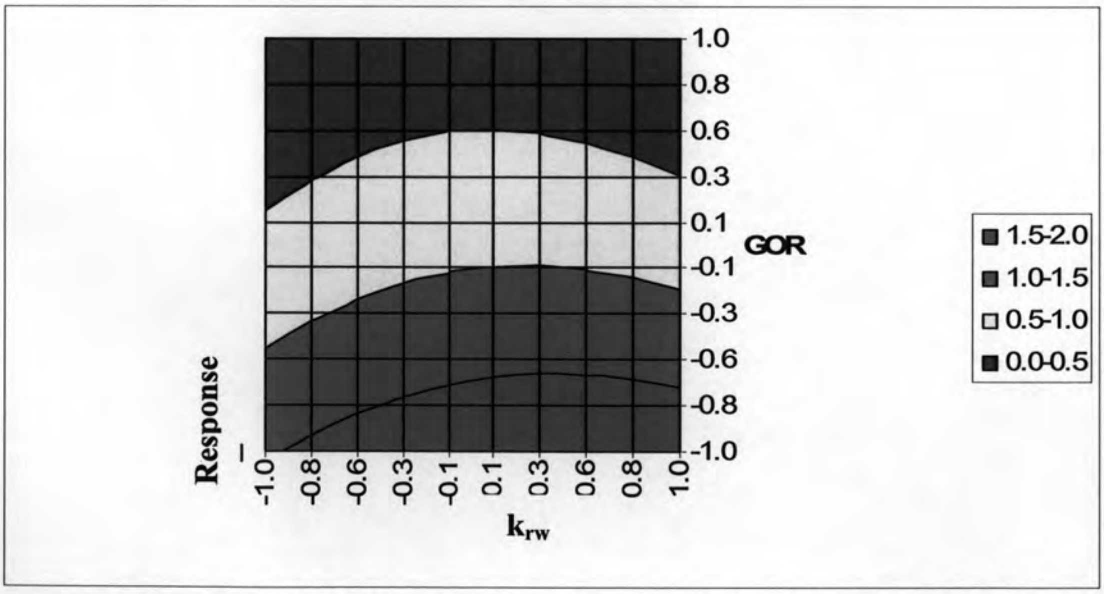

Figure 8.33 Contour map of two way interaction between GOR and k_{rw} (P.I. =1, Depth =1)

The contour map can be interpreted that for a high water cut well and low solution GOR, the ESP delivers the highest incremental oil recovery and also that for a fixed water cut well as we move up and have higher solution GOR, then the ESP does not perform well. Another important two-way relationship is between the landing depth and the water cut of the well. The surface response in Figure 8.34 shows their interactions.

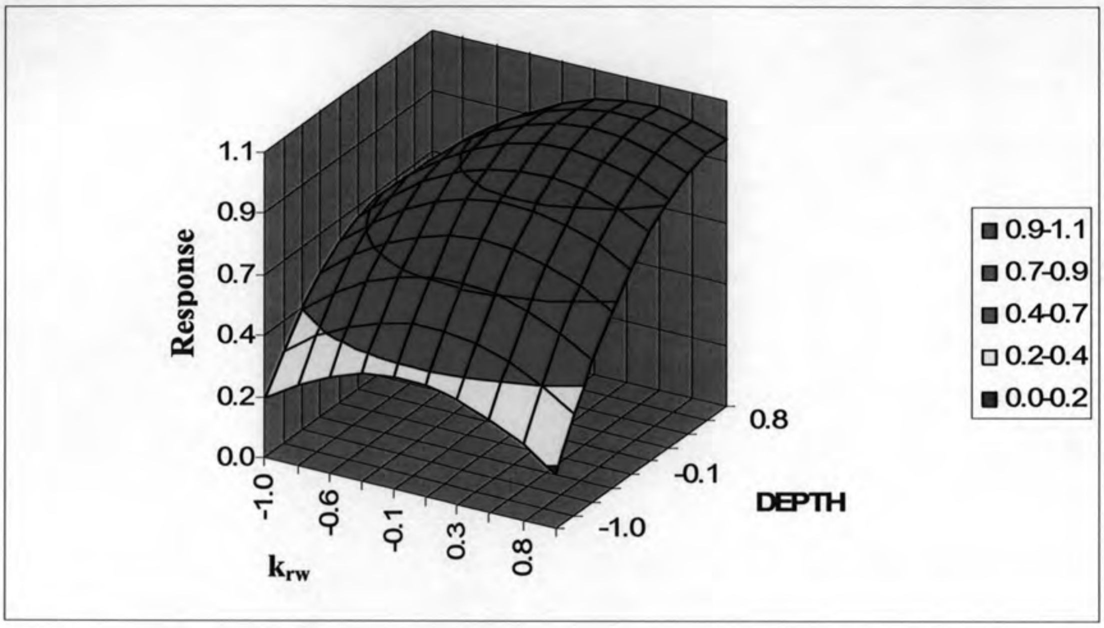

Figure 8.34 3-D Surface response between depth and k_{rw} (GOR =1, P.I. =1)

The contour map of the interaction in Figure 8.34 is shown in Figure 8.35.

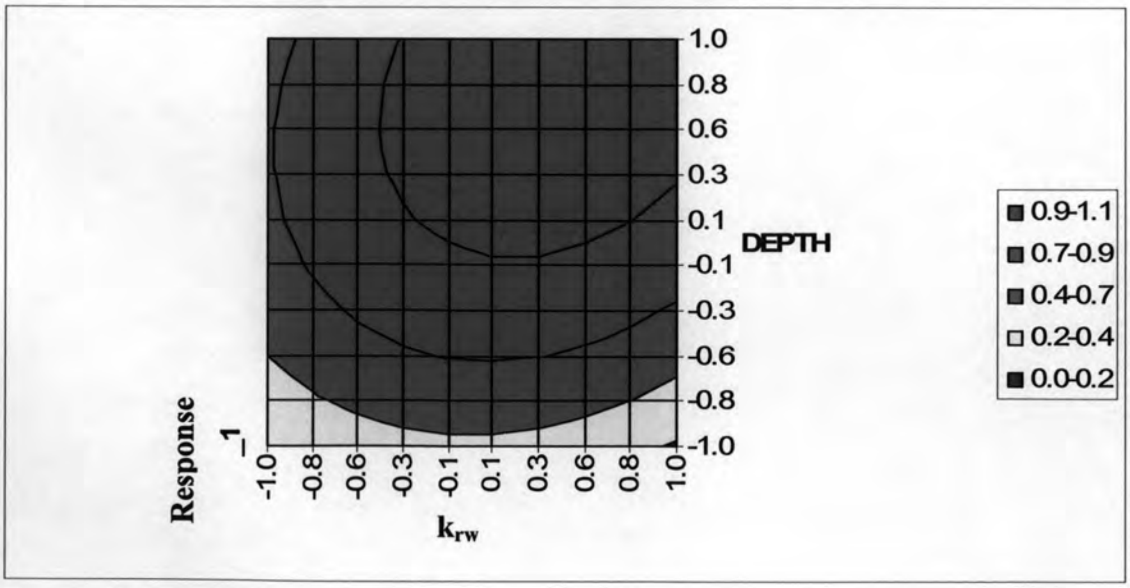

Figure 8.35 Contour map of two way interaction between depth and k_{rw} (GOR =1, P.I. =1)

The ESP is designed for fixed set of parameters such as water cut (50%) and flow rate. Hence, we can see that for a fixed landing depth of the ESP, there comes a favorable water cut profile which will maximize the incremental oil recovery as the ESP is designed for that range. It is also true the other way round that if for a fixed value of water cut or k_{rw} and we set the ESP deeper, then we see an improve in the incremental recovery.

Figure 8.36 shows the viability of the model when the response (incremental oil recovery by ESP) is plotted against the predicted response (prediction of increment by ESP).

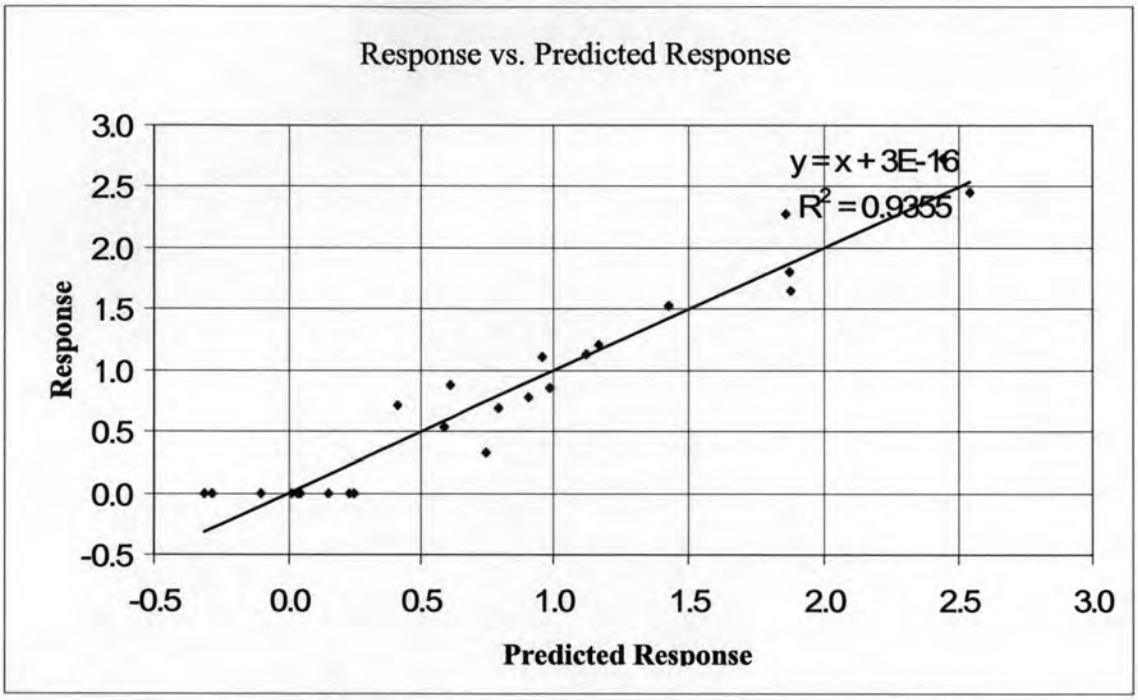

Figure 8.36 Plot of response vs. predicted response for ESP

Note: (Scale is in actual incremental oil in MMSTB)

It is seen that the model reflects the trend reasonably and is considered viable. Some of the cross checking has been done in order to see if it actually gives results reasonably close to the values obtained by the runs and it has been observed that by and large the values are in very close range of the ones obtained by the runs. Same kind of analysis is done for gas lift and the interactions of factors can be interpreted.

This technique of design of experiments which is generally used in industrial engineering seems valid for use in petroleum engineering as well in order to understanding the trends and behaviors.