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Simplified Models for Forecasting Oil Production: Niger Delta Oil Rim Reservoirs Case

By

Professor Boniface Obah*, Aniefiok Livinus, and Chima M. Ezugwu****

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Abstract

The oil and gas industry has always relied on production forecasts to predict the profitability of producing oil/gas facilities. Many factors affect both the reliability and accuracy of production forecasts; the static or geological uncertainties, the dynamic uncertainties and operational uncertainties. So, many reasons abound to performing a model study. The most important, from a commercial point of view, is the ability to generate cash flow predictions. In this work, a generic dynamic simulation study was carried out to generate oil production profiles from oil rim reservoirs in the Niger Delta. Plackett-Burman Experimental Design (ED) technique was used to capture the impact of a range of sub-surface uncertainty on oil rim recovery. Approximate models were then developed for forecasting oil production using the least square regression method. Three production forecast models for the oil rim reservoirs were obtained using Monte-Carlo simulation approach. This method enables the generation of a truly probabilistic range of forecasts that can then be used in decision making. Over the 30 years prediction period, oil recovery varies from 3.98 to 37.3 MMstb.

Introduction

In exploration and production decisions, alternatives such as development strategies, well placement, drainage strategies, artificial lift, and capital investment must be evaluated. Narayanan et al[1] examine these alternatives and uncertain geologic, engineering, and economic parameters to formulate and optimize production plans. As a result, reservoir studies may require many simulations to evaluate the effects of variables on reservoir performance measures. The oil and gas industry has always relied on production forecasts to predict the profitability of producing oil/gas facilities. Production forecasts are also used to determine the life span of a producing oil/gas facility. This is determined by estimating the time that the production forecast reaches a pre-defined economic limit. The production of an oil field tends to pass through a number of stages. This can be described by an idealized production curve. A version of this curve can be seen in figure 1. After the discovery well, an appraisal well is drilled to determine the development potential of the reservoir. Further development follows and the first oil production marks the beginning of the build up phase. Later the field enters a plateau phase, where the full installed extraction capacity is used, before finally arriving at the onset of decline, which ends in abandonment once the economical limit is reached.

*Shell Chair, Department of Petroleum Engineering, Federal University of Technology, Owerri, Nigeria.
**Research Assistants, Department of Petroleum Engineering, Federal University of Technology, Owerri, Nigeria.

[1] Narayanan, K., Cullick, A. S., Bennett, M. (2003): "Better Field Development Decisions from Multi-Scenario, Interdependent Reservoir, Well, and Facility Simulations", SPE 79703.

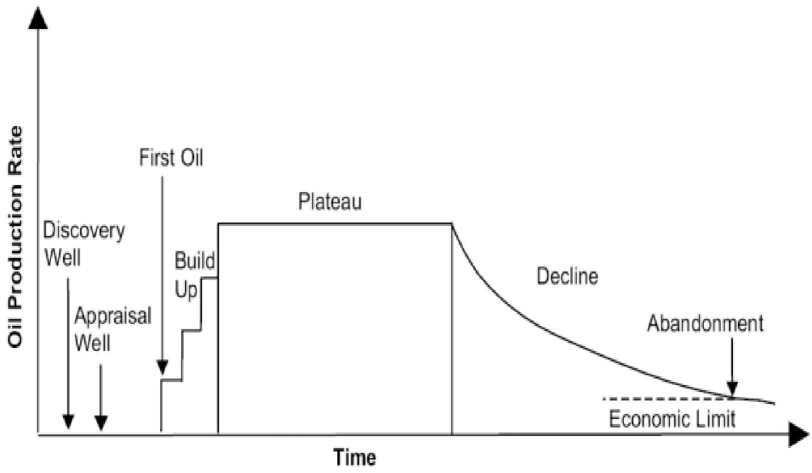

Fig. 1: A theoritical production curve, describing the various stages of maturity. Source: Robelius[2]

For many fields, especially smaller ones, the plateau phase can be very short and resemble more to a sharp peak, while large fields can stay several decades at the plateau production level. The life time of a field and the shape of the production curve are often related to the kind of hydrocarbon that is produced.

Many factors affect both the reliability and accuracy of production forecasts; the static or geological uncertainties, the dynamic uncertainties and operational uncertainties. So, many reasons abound to performing a model study. The most important, from a commercial point of view, is the ability to generate cash flow predictions. Simulation provides a production profile for preparing economic forecasts. The combination of production profile and price forecast gives an estimate of future cash flow. Despite the exponential growth of computational memory and speed, computing accurate solutions is still expensive, so that it may not be feasible to consider all alternative models. Thus, simulation runs must be chosen and analyzed as efficiently as possible. A statistical method called design of experiments addresses this problem. Experimental design and response models as reported by (White et al,[3] Peng and Gupta,[4] Peak et al,[5]) have been applied in engineering and sciences.

Though decline curve analysis is a long established tool for developing future outlooks for oil production from an individual well or an entire oilfield based on real production data but with

[2] Robelius, F., (2007): “Giant Oil Fields - The Highway to Oil: Giant Oil Fields and their Importance for Future Oil Production”, doctoral thesis from Uppsala University,

[3] White, C.D., Wills, B. J., Narayanan, K., Dutton, S.P. (2000): “Identifying Controls on Reservoir Behaviour Using Designed Simulations”, SPE 62971.

[4] Peng, C. Y., Gupta, R. (2004): “Experimental Design and Analysis Methods in Multiple Deterministic Modelling for Quantifying Hydrocarbon In-Place Probability Distribution Curve”, SPE 87002.

[5] Peake, W. T., Abadah, M., Skander, L. (2005): “Uncertainty Assessment using Experimental Design: Minagish Oolite Reservoir” SPE 91820.

reservoir simulation studies optimized by experimental designs, decline curve-based models can be generated. Arps[6] created the foundation of decline curve analysis by proposing simple mathematical curves, i.e. exponential, harmonic or hyperbolic, as tool for creating a reasonable outlook for the production of an oil well once it has reached the onset of decline. His original approach has later been developed further and is still used as a benchmark by industry for analysis and interpretation of production data due to its simplicity.

This work presents a generic dynamic simulation study. Approximate decline curve-based models are developed for forecasting oil production using the least square regression method. Three oil production forecast models for the oil rim reservoirs under study are obtained using Monte-Carlo simulation approach. This method enables the generation of a truly probabilistic range of forecasts that could then be used in decision making. The models are consistent with fundamental principles.

Data Gathering of the Oil Rim Reservoirs.

Many oil rim reservoirs have thickness less than 60-ft. The data used in the study have been obtained principally from recent field reviews and an updated OFM database in the Niger Delta region, Nigeria. The choice of reservoirs was driven by the singular purpose of understanding and unlocking reservoirs with moderate gas caps and moderate oil rims. The depth range of the selected reservoirs is 5355-ft to 10891-ft and the temperature range is 132 ^{O}F to 209 ^{O}F. The maximum viscosity is 1.65cp and a minimum viscosity of 0.41cp. The productivity of most of the reservoirs has been enhanced by the presence of light oil and good quality sands.

Reservoir Oil Rim Parameters.

There are a number of sub-surface factor that affect the recovery process of oil rim reservoirs. From a review of the performances of fifty horizontal wells in oil rim reservoirs, Vo et al[7] concluded that reservoir, completion and production parameters influence reservoir dynamics. Cronquist[8] made similar observations. Specifically, they established oil column thickness, gas-cap size, permeability, reservoir architecture, oil properties, production policy, as well as producer configuration and placement as the key factors that control recovery. In line with these findings, one would expect some of these variables to reflect in prospective screening models and heuristics. The oil rim reservoirs parameters that were inputted into the simulation comprise; Static uncertainties**,** Dynamic uncertainties and Operational uncertainties. The ranges of each of these uncertainties were drawn from the collected reservoir data and recommendations from expert who had knowledge of the reservoirs (See Table 1).

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[6] Arps, J. J.,(1945): "Analysis of Decline Curves, Transactions of the American Institute of Mining, Metallurgical and Petroleum Engineers, 1945, Volume 160. Pages 228-247

[7] Vo, D.T., Waryan, S., Dharmawan, A., Susilo, R. and Wicaksana, R. (2000). "Lookback on Performance of 50 Horizontal Wells Targeting Thin Oil Columns, Mahakam Delta, East Kalimantan". Paper 64385 presented at SPE Asia Pacific Oil & Gas Conference and Exhibition, Brisbane, 16-18 Oct

[8] Cronquist, C. (2001). "Estimation and Classification of Reserves of Crude Oil, Natural Gas, and Condensate", SPE Inc., Texas

Table 1: Parameter range for factors investigated

		LOW	MID	HIGH
Parameters	UNITS	-1	0	1
Column Height	ft	20	34	60
M factor	_	0.011	0.87	4.73
Aquifer/HC	_	2	7	15
Kh	md	100	700	2000
Kv/Kh	-	0.001	0.01	0.1
Sor	-	0.15	0.23	0.3
API^o	-	24.16 (2cp)	32.65 (1cp)	39.18 (0.4cp)
HGOC	ft	0.25 from GOC	0.5 from GOC	0.75 from GOC
HL	ft	0.125*Res length	0.25*Res length	0.5 Res*length
Krw	-	0.15	0.3	0.45
Q	stb/d	500	2500	5000

Simulation Approach.

A dynamic simulator was used to generate a 3D generic grid model with varying oil column thickness, gas cap and aquifer size. The base grid was 10 x 10 grid blocks in the x and y directions. The geometry of the model was fixed at 600ft x 600ft in the x and y directions. The grid in the z directions was varied depending on the thickness of the oil rim that was to be modelled. One of the 3D grid models is given in figure 2;

A simplistic geological description was used to focus on the underlying physics of oil rim movement. No shale barriers or faults have been introduced in the model. PVT software was used to generate a fluid model with API, gas gravity and gas solubility data from PVT reports as input parameters. Zero contamination is assumed. Based on results of performance data in the industry, horizontal wells are the better option for developing reservoirs with oil rims as to conventional wells and as such two horizontal oil production wells were placed within the oil rim section of the model. The well length was a variable in the analysis. Production system software was used to build a wellbore model to take into account the pressure drop along the horizontal section of the well.

The constraints applied to the generic oil rim model were; minimum bottom hole pressure of 1200 psi, Simulation time of 30 years, maximum allowable water cut of 90 %. A carter-Tracy analytical aquifer model was attached to the base of the model. The aquifer strength/drive indices were used as a variable in the analysis.

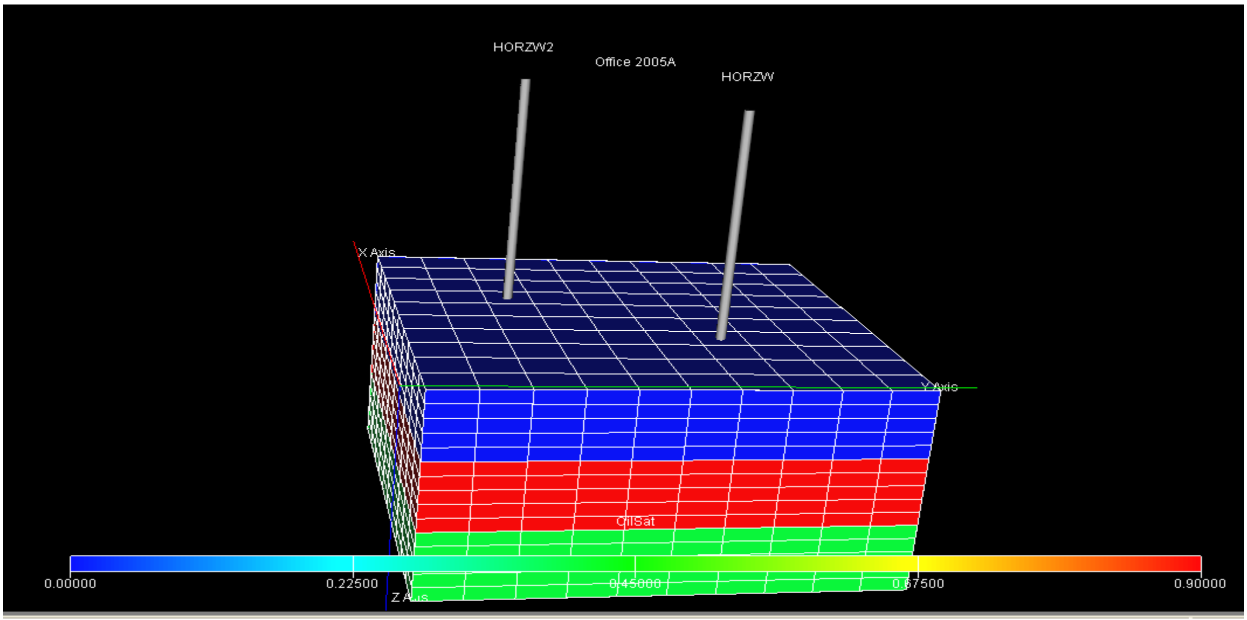

Figure 2: 3D Generic Grid Model

Design of Experiment.

A linear screening of the uncertainties was conducted using Plackett-Burman design of experiments to determine the significant uncertainties. The experiment was generated for 11 identified uncertainties in the study. In order to analyse the 11 identified uncertainties, a 2 level 11 variable Plackett-Burman design (see Table 2) was used. To increase the strength of the linear screening, the folded Plackett-Burman with a center point run consisting of all mid case was added (run 14). An extra run to define the maximum outcome was also introduced (run 13).

The simulation results of the oil production data for the fourteen runs were obtained. These production data are for a simulation time of 30 years. The cumulative productions for the simulations are shown in the Table 3.

Table 2: 11-Parameter Plackett-Burman Design

Run No.	H	Mfac	AQfac	KH	KV/KH	SORW	API	HGOC	HWL	OILR	KRW
1	1	1	-1	1	1	1	-1	-1	-1	1	-1
2	1	-1	1	1	1	-1	-1	-1	1	-1	1
3	-1		1	1	-1	-1	-1	1	-1	1	1
4	1	1	1	-1	-1	-1	1	-1	1	1	-1
5	1	1	-1	-1	-1	1	-1	1	1	-1	1
6	1	-1	-1	-1	1	-1	1	1	-1	1	1
7	-1	-1	-1	1	-1	1	1	-1	1	1	1
8	-1	-1	1	-1	1	1	-1	1	1	1	-1
9	-1	1	-1	1	1	-1	1	1	1	-1	-1
10	1	-1	1	1	-1	1	1	1	-1	-1	-1
11	-1	1	1	-1	1	1	1	-1	-1	-1	1
12	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
13	1	1	1	1	1	1	1	1	1	1	1
14	0	0	0	0	0	0	0	0	0	0	0

Approximate Model Formulation.

The simulation results (that is, oil production profiles) were used to develop decline curve-based models, which are special forms of response surface model, using the least square method that could serve as a reliable and representative production forecast tool. The early stage of production was accounted for in the proxy equations. The equations were then generalized to obtain three production forecast models for the oil rim reservoirs under study. The exponential decline curve model was chosen in this study since it has the widest application in practice.

According to Arps[9], the exponential decline is;

$$q(t) = q_i e^{-Dt} dt \qquad 1$$

Cumulative oil production is expressed as;

$$dN_p = q(t)dt \qquad 2$$

Substituting equation (1) into equation (2) gives;

$$dN_p = q_i e^{-Dt} dt \qquad 3$$

Assuming the start of decline of production, t_p marks the end of plateau production level, and the end of production is time, t;

The integration of equation (3) with respect to time results to an expression for the cumulative oil production;

$$\int_{tp}^{t} dN_p = \int_{tp}^{t} q_i e^{-Dt} dt$$

$$N_p(t) - N_p(t_p) = -\frac{q_i}{D}\left(e^{-Dt} - e^{-Dt_p}\right) \qquad 4$$

Re-arranging equation (4) for determining cumulative production at time, t, gives;

$$N_p(t) = \frac{q_i}{D}\left(e^{-Dt_p} - e^{-Dt}\right) + N_p(t_p) \qquad 5$$

Given that;

$$N_p(t_p) = q_i t_p \qquad 6$$

Substituting equation (6) into equation (5) results to;

$$N_p(t) = \frac{q_i}{D}\left(e^{-Dt_p} - e^{-Dt}\right) + q_i t_p \qquad 7$$

To approximate cumulative production from the start of production over any given time using exponential decline curve, equation 7 can be expressed as;

$$N_p(t) = \frac{q^*}{D}\left(e^{-Dt_p} - e^{-Dt}\right) + q_i t_p \qquad 8$$

Where q^* is the production rate interpreted from the Cartesian plot of natural log of flow rate against time or the semi log plot of flow rate against time. Equation 8 represents the general form of the approximate model.

[9] Op. cit

With the linear regression method of an Excel program, the calculations of the continuous decline rate constant, R-squared value of the straight line fitting, the production rate, q^*, when the straight line is extrapolated to time zero were estimated. The fourteen decline curve equations developed for the fourteen runs for predicting cumulative production differ considerably due to difference in development plans and reservoir properties. Three probabilistic production forecast models were then generated by employing Monte Carlo simulation approach. The input variables were the probability distributions of the decline curve-based equation parameters of the fourteen runs. Probabilistic P10, P50 and P90 models which are to serve as the generalized approximate models were obtained in order to be used to generate a truly probabilistic range of oil production forecast for the oil rim reservoirs under study.

Results and Discussion

Oil recovery is strongly dependent on the following; oil rim thickness, relative gas cap size (m-factor), permeability, oil viscosity and aquifer strength. Higher oil production was obtained under these favourable conditions even with smaller oil rim thickness of about 20-ft. Over the 30 years prediction period, oil recovery varies from 3.98 to 37.3 MMstb. Table gives the detail original oil in place as well as cumulative oil produced from the simulation runs. The full results of the continuous decline rate constants, the times of plateau production rates and the initial production rates, q^*, when the straight line is extrapolated to time zero are given in table 4 while figure 3, 4, 5 and 6 represent some of the Cartesian plots of the production data. The maximum and minimum values of the continuous decline rate constants are 0.00011 and 0.00089 respectively. Good R-squared values were obtained. Figure 7 represents the probabilistic analysis of the cumulative production. The selected P10, P50 and P90 models as given in Table 5 were used to generate the probabilistic range of the oil production forecasts for the oil rim reservoirs. Figure 8 shows the probabilistic production forecasts for a production rate of 1800 stb/d; this is consistent with previous modelling studies on same oil rim reservoirs.

Conclusion

Based on this study, the following conclusions are drawn;

- higher oil recovery is achieved under favourable conditions - high permeability, low oil viscosity, and strong aquifer,
- A truly probabilistic range of forecasts was obtained with this approach.
- Over the 30 years prediction period, oil recovery varies from 3.98 to 37.3 MMstb.
- The approximate models are consistent with fundamental principles.

Model Limitations

The model has the following weaknesses:

- Applicability is limited to the range of data source and two horizontal wells.
- Based solely on simulation data- no validation with production data.

Nomenclature

M-factor	Size of gas cap
Aqfac	Aquifer height to Hydrocarbon thickness ratio
Kh	Horizontal Permeability, mD
Kv	Vertical Permeability, mD
HGOC	Height to Gas-Oil Contact, ft
HL	Horizontal Well Length, ft
Krw	Relative Permeability to water
Q, q	Oil rate, stb/d
OOIP	Original Oil Initially in place
H	Hydrocarbon column thickness, ft
Sor	Residual oil saturation
t	total time of oil production
t_p	total time of plateau oil production rate level

Table3: Reservoir Parameters & Cumulative Productions of the simulation runs

Run No.	Ho	mfac	Aqfac	Kh	Kv/Kh	Sorw	API	HGOC	HWL	Q	Krw	OIIP	CumPro	RF%
1	**60**	**4.73**	**2**	**2000**	**0.1**	**0.3**	**24.16**	**24.00**	**1200**	**5000**	**0.15**	120,431,480	**23981066**	**19.91262251**
2	**60**	**0.268**	**15**	**2000**	**0.1**	**0.15**	**24.16**	**48.00**	**2400**	**5000**	**0.45**	120,431,480	**30210432**	**25.08516212**
3	**20**	**4.73**	**15**	**2000**	**0.001**	**0.15**	**24.16**	**8.00**	**1200**	**5000**	**0.45**	40,172,541	**12883713**	**32.07094368**
4	**60**	**4.73**	**15**	**100**	**0.001**	**0.15**	**39.18**	**48.00**	**2400**	**5000**	**0.15**	111,120,250	**37360964**	**33.62210218**
5	**60**	**4.73**	**2**	**100**	**0.001**	**0.3**	**24.16**	**48.00**	**2400**	**1300**	**0.45**	120,431,480	**22546422**	**18.7213692**
6	**60**	**0.268**	**2**	**100**	**0.1**	**0.15**	**39.18**	**48.00**	**1200**	**5000**	**0.45**	111,120,250	**23389388**	**21.04871794**
7	**20**	**0.268**	**2**	**2000**	**0.001**	**0.3**	**39.18**	**8.00**	**2400**	**5000**	**0.45**	39,338,272	**11036516**	**28.05541636**
8	**20**	**0.268**	**15**	**100**	**0.1**	**0.3**	**24.16**	**16.00**	**2400**	**5000**	**0.15**	40,172,567	**5331299**	**13.27099411**
9	**20**	**4.73**	**2**	**2000**	**0.1**	**0.15**	**39.18**	**16.00**	**2400**	**1300**	**0.15**	39,338,272	**6966806**	**17.70999499**
10	**60**	**0.268**	**15**	**2000**	**0.001**	**0.3**	**39.18**	**48.00**	**1200**	**1300**	**0.15**	111,120,250	**28470000**	**25.62089268**
11	**20**	**4.73**	**15**	**100**	**0.1**	**0.3**	**39.18**	**8.00**	**1200**	**1300**	**0.45**	39,338,272	**3981925**	**10.12226719**
12	**20**	**0.268**	**2**	**100**	**0.001**	**0.15**	**24.16**	**8.00**	**1200**	**1300**	**0.15**	40,172,568	**4954105**	**12.33205953**
13	**60**	**4.73**	**15**	**2000**	**0.1**	**0.3**	**39.18**	**48.00**	**2400**	**5000**	**0.45**	111,120,250	**38495104**	**34.64274423**
14	**34**	**1**	**7**	**1000**	**0.01**	**0.23**	**32.65**	**20.40**	**1800**	**2500**	**0.3**	69,453,673	**15169987**	**21.84187869**

Table 4: Input variables into the proxy equation for the Simulation runs

Runs	q*(stb/d)	qi(stb/d)	D(1/day)	tp (days)
1	1696	5000	0.00011	498
2	1999	5000	0.00013	1247
3	1988	5000	0.00031	213
5	5621	1300	0.00025	5596
6	2244	5000	0.00015	252
7	3850	5000	0.00089	730
8	656	5000	0.00020	43
9	943	1300	0.00020	1727
11	559	1300	0.00017	568
12	1339	1300	0.00033	304
13	1978	2400	0.00015	2676
14	2615	1800	0.00033	1399

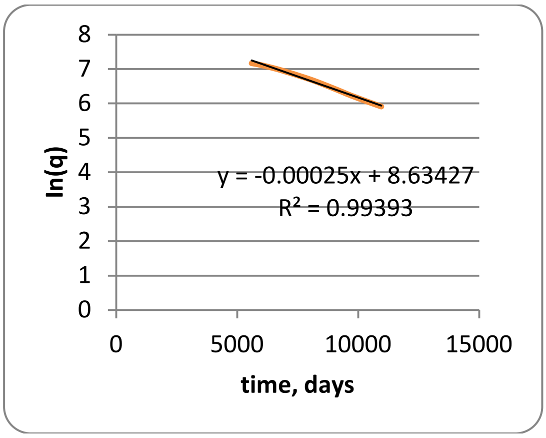

Fig. 3: A Cartesian plot of In (q) against time for run 5

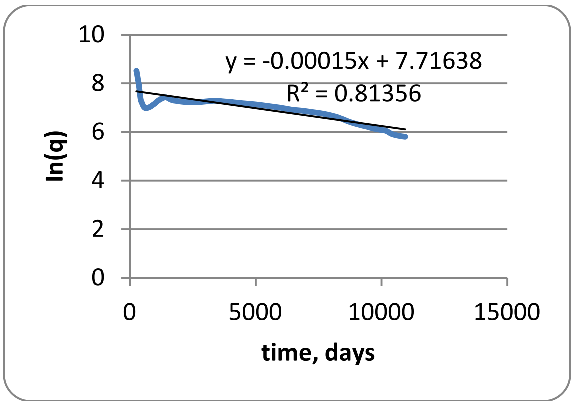

Fig. 4: A Cartesian plot of In (q) against time for run 6

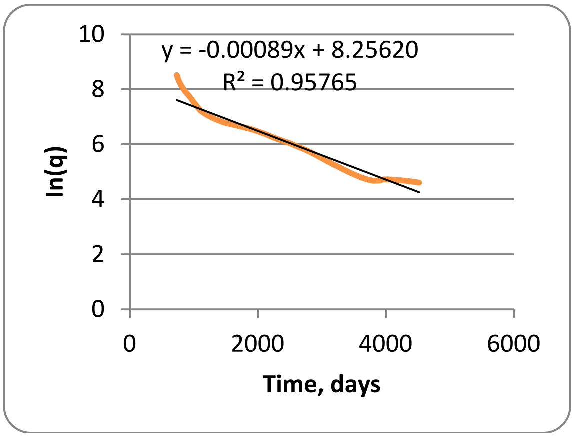

Fig. 5: A Cartesian plot of In (q) against time for run 7

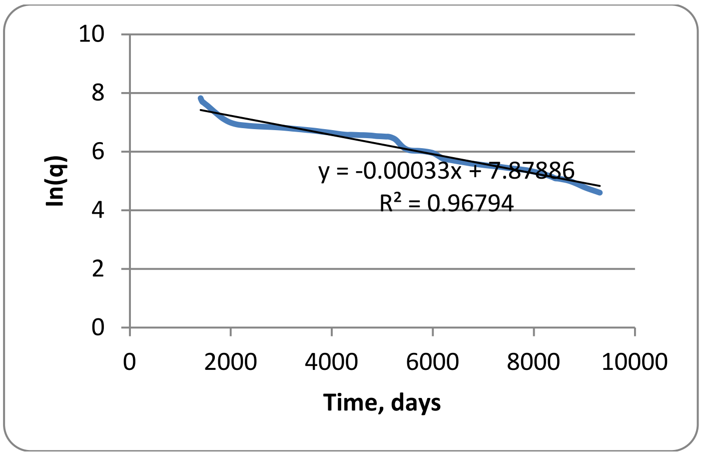

Fig. 6: An Cartesian plot of In (q) against time for run 14

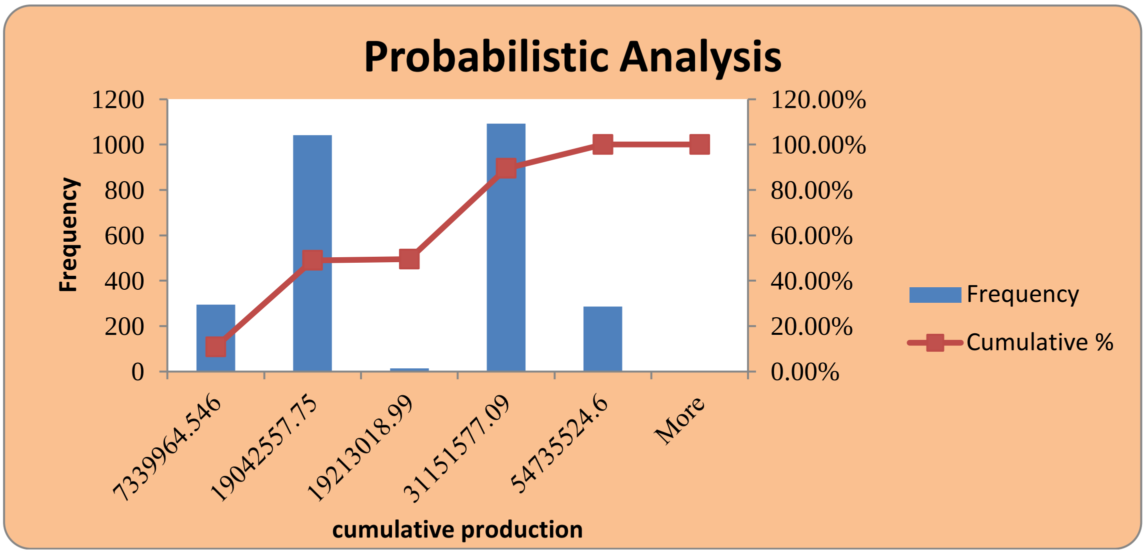

Figure 7: Probabilistic Analysis of the Cumulative production.

Table 5: Probability distribution of the input variables of the proxy equation

Percentile	q*(stb/d)	D(1/day)	tp(days)
P10	1053	0.000189	598
P50	3121	0.000496	2779
P90	5160	0.000808	5059

The general form of the approximate model;

$$N_p(t) = \frac{q^*}{D}\left(e^{-Dt_p} - e^{-Dt}\right) + q_i t_p \quad .... 8$$

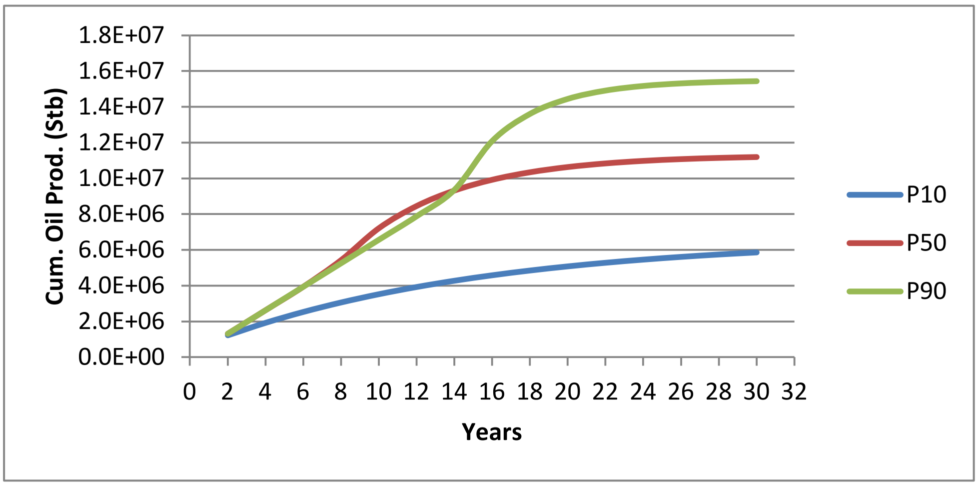

Figure 8: Probabilistic Production Forecast for oil rate of 1800 stb/d