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Statistical Method of Estimating Nigerian Hydrocarbon Reserves

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ABSTRACT:- *Hydrocarbon reserves are basic to planning and investment decisions in Petroleum Industry. Therefore its proper estimation is of considerable importance in oil and gas production. The estimation of hydrocarbon reserves in the Niger Delta Region of Nigeria has been very popular, and very successful, in the Nigerian oil and gas industry for the past 50 years. In order to fully estimate the hydrocarbon potentials in Nigerian Niger Delta Region, a clear understanding of the reserve geology and production history should be acknowledged. Reserves estimation of most fields is often performed through Material Balance and Volumetric methods. Alternatively a simple Estimation Model and Least Squares Regression may be useful or appropriate. This model is based on extrapolation of additional reserve due to exploratory drilling trend and the additional reserve factor which is due to revision of the existing fields. This Estimation model used alongside with Linear Regression Analysis in this study gives improved estimates of the fields considered, hence can be used in other Nigerian Fields with recent production history.*

KEYWORDS:*Additional Reserves, Completed Wells, Estimation Model, Linear Squares Regression, Nigerian Hydrocarbon Reserves).*

I. INTRODUCTION

The process of estimating oil and gas reserves for a producing field continuesthroughout the life of the field. There is always uncertainty in making such estimates. The level of uncertainty is affected by the following factors: Reservoir type, source of reservoir energy, quantity and quality of the geological, engineering, and geophysical data, assumptions adopted when making the estimate, available technology, and experience and knowledge of the evaluator ***Arps, (1956)***. The magnitude of uncertainty, however, decreases with time until the economic limit is reached and the ultimate recovery is realized ***Arps, (1956)***. Petroleum (or any other natural resource) reserves cannot be measured directly. They are estimates of future production under certain conditions which may or may not be well specified, but which include economic assumptions, knowledge of the feasibility of projects to extract the resources, and geological information. Judgment is involved and different estimates for the same field are legitimately possible***Ross, (2001)***.

Statistical estimation of oil and gas reserves is the estimation of petroleum reserves using historical records of production, exploratory drilling, pressure history and other factors that influence reserves ***SPE, (1979).*** Reserve estimation is useful in evaluation of exploration and development expenditures, to determine the market value of a field in connection with possible purchase or sale. It is also used to determine the feasibility of secondary recovery projects and other special recovery projects. Reserves can be divided into primary and secondary reserves. Primary reserves is the estimated future commercial production recoverable by normal or primary method as a result of energy availability in the reservoir while secondary reserve is the estimated future commercial production which will be recovered in addition to the primary reserves as a result of pressure maintenance, water flooding or other secondary methods ***Cronquist, (2001)***. Unproved reserves are less certain to be recovered than proved reserves and may be sub-classified as probable or possible to denote increasing uncertainty. Proved reserves can be estimated with reasonable certainty to be recoverable under current economic conditions which include prices and costs prevailing at the time of the estimate ***SPE/WPC/AAPG, (2001).*** Proved reserves may be developed or under developed. It must have facilities to process and transport those reserves to markets that are operational at the time of the estimate or there is commitment or reasonable expectation to install such facilities in the future ***SPE/WPC/AAPG, (2001).***.

The additional reserve each year is dependent on reserves found by exploratory drilling in new pools, in new fields and reserves done to re-evaluate the basic geological and engineering data of existing fields. A discovery during one year will result in the drilling of additional wells during subsequent production and these wells add productive acreage to the previously estimated proved area ***Jacks, (1990).*** Other reserves estimation methods includes: Analogy, Volumetric, Decline analysis, Material balance, and Reservoir simulation ***Dake, (1989)***. Most of the field data required are not obtainable until the reservoir has produced for substantial period, therefore evaluated reserve of new field using other reserves estimation methods are not reliable.

Aims of the study : The aims of this study are to Estimate the Nigerian hydrocarbon reserve and to measure the crude oil potential of Nigerian fieldsusing Least Squares Regression (LSR).

Objective of the study : A mathematical model "(Estimation Model) for petroleum reserves estimate based on extrapolation of exploratory drilling trend was developed. Additional reserve factor due to revision of existing field is included in the model. Method of Least Square Regression is employed to solve the constants in the developed model and to compare the estimated reserves from the actual reserves.

Geological Settings of the Niger Delta Region of Nigeria : Niger Delta is a large arcuate Tertiary prograding sedimentary complex deposited under transitional marine, deltaic, and continental environments since Eocene in the North to Pliocene in the South. Located within the Cenozoic formation of Southern Nigeria in West Africa, it covers an area of about 75,000 Km ***Arps, (1967)***from the Calabar Flank and Abakaliki Trough in Eastern Nigeria to the Benin Flank in the West, and it opens to the Atlantic ocean in the South where it protrudes into the Gulf of Guinea as an extension from the Benue Trough and Anambra Basin provinces ***Burke et al*****., (1972).** The Niger Delta as a prograding sedimentary complex is characterized by a coarsening upward regressive sequences. The overall regressive sequence of clastic sediments was deposited in a series of offlap cycles that were interrupted by periods of sea level change ***Etu-Efeotor, (1997).*** These periods resulted in episodes of erosion or marine transgression. Stratigraphically, the Tertiary Niger Delta is divided into three Formations, namely Akata Formation, Agbada Formation, and Benin Formation ***Ekweozor et al, (1984).*** The Akata Formation at the base of the delta is predominantly undercompacted, overpressured sequence of thick marine shales, clays and siltstones (potential source rock) with turbidite sandstones (potential reservoirs in deep water). It is estimated that the formation is up to 7,000 meters thick ***Bouvier et al, (1989).*** The Agbada Formation, the major petroleum-bearing unit about 3700m thick, is alternation sequence of paralic sandstones, clays and siltstone and it is reported to show a two-fold division ***Doust, and Omatsola, (1990).*** The upper Benin Formation overlying Agbada Formation consists of massive, unconsolidated continental sandstones.

Why "Linear Regression Analysis (LRA)" for Hydrocarbon Reserves? : The "Method of Least Squares" that is used to estimate parameters estimates was independently developed in the late 1700's and the early 1800's by the mathematician Karl Friedrich Gauss, Adrien Marie Legendre and Robert Adrain ***Stigler, (1978)], Harter, (1976), Stigler, (1986)*** working in Germany, France and America respectively. In the least squares method the unknown parameters are estimated by minimizing the sum of the squared derivatives between the data and the model. The minimization process reduces the over-determined system of equations formed by the data to a sensible system of p (where p is the number of parameters in the functional part of the model) equations in p unknowns. This new system of equations is then solved to obtain the parameter estimates ***Stigler, (1986)***. Linear Regression Analysis (LRA) is by far the most widely used modeling method adapted to a broad range of situations that are outside its direct scope. It plays a strong underlying role in many other modeling methods like Non Linear Least Squares Regression Method, Weighted Least Squares Regression, and LOESS ***Stigler, (1978).*** Linear Regression Analysis (LRA) can be used directly with an appropriate data set to fit complex data. It has earned its place as the primary tool for process modeling because of its effectiveness and completeness. Though there are types of data that are better described by functions that are non-linear in the parameters, many process in science and engineering are well described by linear models. This is because either the processes are inherently linear or because, over short range, any process can be well-approximated by a linear model. The estimates of the unknown parameters obtained from linear regression are the optimal estimates from a broad class of possible parameter estimates under the usual assumptions used for process modeling. Practically speaking, Linear Regression Analysis (LRA) makes very efficient use of the data. Good results can be obtained with relatively small data sets ***Larry, (1998).***

II. RESEARCH METHODOLOGY

a). Model Development Procedure : The model is based on the principle that the reserve at the end of any year will be the sum of the reserve at the beginning of that year and additional reserve minus productions during that year. Additional reserves of hydrocarbons in any year are broken down into two established categories: Those attributable to recoveries as a result of exploratory effort in new pools in new fields. Reserves attributed to revisions as a result of re-evaluation on the existing fields. Newly discovered petroleum reservoirs, even in existing fields are always fully developed during the year of recovery ***John, (2004).*** Therefore, the year and reserve estimates of discoveries generally represent only a part of the reserves that will ultimately be assigned to these new reservoirs. A discovery during one year will usually result in the drilling of additional wells during subsequent years and generally these new wells will increase the previously estimated productive area ***Mistrot, (1998).*** Additional producing wells in a reservoir not only add to the estimated productive area but also help to improve the basic geologic and engineering data. Early estimates of porosity, interstitial water, pay thickness and other important reservoir factors may be reviewed therefore from future wells. As field development continues, production history accumulates and the most accurate methods of pressure maintenance and secondary recovery factor are formulated ***McMichael, and Spencer, (2001).***

b). Estimation Model Derivation

Reserve at the end of any year is defined as:

$$\mathbf{R_x = R\,(x-1) + R_x^{+} - Q_x + A_x} \qquad \mathbf{(1.1)}$$

Where,

X is the number of terms in years

$\mathbf{R_x}$ is the estimated reserve at the end of xth year.

R (x–1) is the estimated reserve at the end of (x–1)th year.

$\mathbf{R_x^{+}}$ is the additional reserve during the xth year due to exploratory drilling.

$\mathbf{Q_x}$ is the production in the xth year

$\mathbf{A_x}$ is the additional reserve in the xth year due to revision of existing fields.

Additional reserve due to exploratory drilling R_x^{+} based on historical trend is defined as:

$$\mathbf{R_x^{+} = (m + nP_x) - C_{x-1}} \qquad \mathbf{(1.2)}$$

Where,

m is the intercept of regression line of plot of cumulative additional reserve against cumulative number of completed wells.

n is the rate of change of cumulative additional reserve with cumulative number of completed wells.

$\mathbf{P_x}$ is the cumulative number of completed wells at the end of xth year.

$\mathbf{C_{x-1}}$ is the cumulative additional reserve at the end of (x-1)th year.

In general, $(m + nP_x)$ represents cumulative additional reserve due to exploratory effort in the xth year. Thus, it can be represented by C_x.

$$\mathbf{C_x = m + nP_x} \qquad \mathbf{(1.3)}$$

Where,

$\mathbf{C_x}$ is the cumulative additional reserve in the xth year. The Estimation Model can therefore be approximated as:

$$\mathbf{R_x = R\,(x-1) + C_x - C_{x-1} - Q_x + A_x} \qquad \mathbf{(1.4)}$$

$$\mathbf{= R\,(x-1) + (m + nP_x) - C_{x-1} - Q_x + A_x} \qquad \mathbf{(1.5)}$$

$$\mathbf{= R\,(x-1) + (m + nP_x) + A_x - (C_{x-1} + Q_x)} \qquad \mathbf{(1.6)}$$

Constants **m** and **n** can be calculated by Linear Regression Analysis (LRA). **Equation (1.6)** represents the general form of the Estimation Model.

c). Linear Regression Analysis (LRA)

The concept of linear regression is concerned with an investigation of the dependence of one variable on a linear combination of independent variable. When the dependent variable is expressed linearly in terms of one independent variable, the linear expression is said to be simple while it is said to be multiple when the dependent variables is expressed linearly in terms of several independent variables. In this study, the linear regression is simple since only one independent variable is involved.

From **Equation (1.3):**

$$\mathbf{C_x = m + nP_x}$$

C_x from this equation is the calculated C_x which may not correspond to the observed C_x.

Let $C_x^{'}$ = observed C_x.

Then the error term, T_x is calculated as:

$$\mathbf{T_x = C_x - C_x^{'}} \qquad \mathbf{(1.7)}$$

$$\mathbf{T_x = (nP_x + m)} \qquad \mathbf{(1.8)}$$

To minimize the error, a relation of the form is introduced:

$$\mathbf{S = \sum T_x^2} \qquad \mathbf{(1.9)}$$

Using least squares to minimize S, so that

$$\frac{ds}{dT} = 0; \frac{ds}{dm} = 0$$

$\frac{ds}{dn} = 2\sum t \frac{dTx}{xdn} = 0$

$= 2\sum(nP_x + m - C_x)P_x = 0$

$= n\sum P_x^2 + m\sum P_x - \sum C_xP_x = 0$

Therefore,

$\sum C_xP_x = m\sum P_x + n\sum P_x^2$ **(2.0)**

Similarly,

$\frac{ds}{dm} = 2\sum T_x \frac{dTx}{xdn} = 0$

$= 2\sum(nP_x + m - C_x) \times 1 = 0$

$= n\sum P_x + m - \sum C_x = 0$

$= n\sum P_x + km - \sum C_x = 0$

Therefore,

$\sum C_x = km + n\sum P_x$ **(2.1)**

Where,

k is the number of data used in trend analysis. **Equations (2.0) and (2.1)** can then be solved simultaneously to obtain **m** and **n.**

$\sum C_x = km + n\sum P_x$

$\sum C_xP_x = m P_x + n\sum P_x + n\sum P^2_x$

Or

$\sum P_x C_x = m k\sum P_x + n(\sum P_x)^2$ **(2.2)**

$k\sum C_x P_x = m k\sum P_x + n\sum P_x^2$ **(2.3)**

$k\sum C_x - (\sum P_x)(\sum C_x) = (k\sum P_x^2 - (\sum P_x)^2)$

$n = \frac{k\sum CxPx - \sum PxCx}{(k\sum Px^2 - (\sum Px)^2)}$ **(2.4)**

Substitute **equation (2.4) in equation** **(2.1)**

$\sum C_x = km + \frac{k\sum Px\ \sum CxPx - (\sum Px)^2\ \sum Cx}{(k\sum Px^2 - (\sum Px)^2)}$

$m = \frac{\sum Cx}{k} - \frac{1}{k}\frac{k\sum Px\sum CxPx - (\sum Px)^2\sum Cx}{(k\sum Px^2 - (\sum Px)^2)}$ **(2.5)**

$C_x = m + nP_x$ represents equation of regression line on C_x and P_x.

d). Estimated Model Equation Application in Nigerian Fields

The developed estimation model can be used to evaluate the total petroleum reserves in Nigeria.

Recall that:

$R_x = R(x-1) + (m + nP_x) + A_x - (C_{x-1} + Q_x)$ **(1.6)**

Assuming $A_x = 0$, that is no revision of the existing fields used in the reserve estimation, the estimation model will reduce to:

$R_x = R(x-1) + (m + nP_x) + (C_{x-1} + Q_x)$ **(2.6)**

e). Concept of Correlation and Standard Error of Estimate

Correlation is the degree of relationship between variables, in this case, the cumulated additional reserves and cumulated number of completed wells. The coefficient of correlation can be determined using the Pearson's Product-Moment Method.

$R = k\frac{k\sum PxCx - (\sum Px)\sum Cx}{\sqrt{(k\sum Px^2 - (\sum Px)^2)\ (k\sum Px^2 - (\sum Cx)^2)}}$ **(2.7)**

Standard error of estimate S is a measure of the scatter about the regression line and is supplied by the quantity.

$S = \sqrt{\frac{\sum Cx^2 - m(\sum Cx) - n\sum CxPx}{k}}$ **(2.8)**

III. RESULTS AND DISCUSSION

Results

The general form of the estimation model is given by:

$R_x = R(x-1) + C_x - C_{x-1} - Q_x + A_x$

Where,

R_x = Estimated reserve at the end of xth year.

R (x–1) = Estimated reserve at the end of (x–1)th year.

C_x = Cumulative additional reserve during the xth year due to exploratory drilling at the end of xth year.

C_{x-1}= Cumulative additional reserve at the end of (x-1)th year.
Q_x= Production during the year.
A_x= Additional reserve in the xth year due to revision of existing fields.
$C_x = (m + nP_x)$
Where,
P_x is the intercept of regression line of plot of cumulative additional reserve against cumulative number of completed wells.
m and n are constant determined from linear regression model.

Estimation of Fields X and Y Reserves in Nigeria
Two fields considered in Nigeria were assigned X and Y fields due to the sensitive nature of the data***(DPR, 2014).*** The generalized form of the estimation model is:
$R_x = R\,(x–1) + (m + nP_x) + A_x – (C_{x-1} + Q_x)$.
A_x was assumed to be zero, i.e. no revision of the existing fields used in the reserve estimation.
The above equation reduces to:
$R_x = R\,(x–1) + (m + nP_x) - (C_{x-1} + Q_x)$. **(2.6)**

Coefficient of Correlation
The correlation between the cumulative additional reserve and cumulative number of completed wells can be estimated from **equation (2.6)** using the data shown in **Tables 2** and **3.**

Table 1: Coefficient of Correlation for Field X and Y (2014)

Field	Coefficient of Correlation, r
X	0.999817
Y	0.993728

The result from **Table 1** shows that there is a perfect correlation between cumulative additional reserve and cumulative number of completed wells in the positive direction for both fields.

Table 2: Production History of Field X (2014)

Year	Annual Production (mmmbbls)	Reserves (mmmbbls)	Additional Reserve (mmmbbls)	Cumulative Additional Reserve (mmmbbls)	Cumulative No. of Completed Wells
1978	0.0301	0.615	0.0348	0.3048	18
1979	0.0304	0.594	0.0098	0.0446	24
1980	0.0363	0.560	0.0022	0.0468	25
1981	0.0217	0.597	0.0587	0.1055	55
1982	0.0318	0.571	0.0053	0.1108	58
1983	0.0258	0.554	0.0090	0.1198	62
1984	0.0286	0.529	0.0041	0.1239	64

Table 3: Production History of Field Y (2014)

Year	Annual Production (mmmbbls)	Reserve (mmm bbls)	Additional reserves (mmmbbls)	Cumulative additional reserve (mmmbbls)	Cumulative No. of completed wells
1978	0.0150	0.116	0.0201	0.0201	1.0
1979	0.0153	0.142	0.0413	0.0614	31

19980	0.0133	0.144	0.0148	0.0762	38
1981	0.0088	0.138	0.0026	0.0788	41
1982	0.0057	0.133	0.0009	0.0797	42
1983	0.0064	0.128	0.0012	0.0809	44
1984	0.0054	0.123	0.0008	0.0817	45

Determination of constants n and m from Table 2 and 3 using equation (2.4) and (2.5) respectively

Field	n	m
X	0.1949×10^7	$- 0.1440 \times 10^7$
Y	0.1807×10^7	0.3607×10^7

Applying the constants generated from **equation (2.4)** and **(2.5)** respectively to the developed estimation model of **equation (1.6)** for **Field X** and **Y** gives the results in **Tables 4** and **5** respectively.

Table 4: Annual Estimated Reserves and Actual Reserves for Field X (2014)

Year	Estimated Reserve (mmmbbls)	Actual Reserves (mmmbbls)	Difference
1979	0.596092	0.59420	0.001892
1980	0.561740	0.56010	0.001640
1981	0.598499	0.59710	0.001399
1982	0.527544	0.57060	0.000739
1983	0.554539	0.55380	0.000739
1984	0.529836	0.52930	0.000536

Table 5: Annual Estimated Reserve and Actual Reserve for Field Y (2014)

Year	Estimated Reserve (mmmbbls)	Actual Reserves (mmmbbls)	Difference
1979	0.138946	0.142300	0.003354
1980	0.138295	0.143300	0.005505
1981	0.134915	0.137600	0.002684
1982	0.131022	0.132800	0.001778
1983	0.128236	0.127600	0.000636
1984	0.124643	0.123000	0.001643

Concept of Correlation Coefficient and Standard Error of Estimate : The correlation between the cumulative additional reserve and cumulative number of completed wells as well as standard error of estimate were evaluated from **equation (2.7)** and **(2.8)** respectively using the data in **Table 6:**
The obtained results of **$r = 0.9996208$ and $S = 0.6980 \times 10^6$** for **Field X**, and **$S = 0.2323 \times 10^7$ for Field Y** shows that there is perfect correlation between cumulative additional reserve and cumulative number of completed wells in the positive direction.

Determination of constants n and m for Nigerian hydrocarbon reserves

Applying data in **Table 4** to constants n and m expressions gives:

$n = 0.7527 \times 10^{7}$ bbls/well and $m = 0.3128 \times 10^{9}$bbls/well

The general equation of estimated model therefore becomes:

$$R_x = R\,(x-1) + (0.3128 \times 10^{9} + 0.7527 \times 10^{7}\, P_x) - (C_{x-1} + Q_x). \quad (2.9)$$

The result obtained from **equation (2.9)** using data in **Table 6** is shown in **Table 7.**

Table 6: Production History of a Named Nigerian field (2014)

Year	Annual Production (mmmbbls)	Reserve (mmmbbls)	Additional reserve (mmmbbls)	Cumulative additional reserve (mmmbbls)	Cumulative no. of completed wells (mmmbbls)
1970	0.3958	10.400	0.4458	0.4958	105
1971	0.5596	11.200	1.3596	1.8554	223
1972	0.6666	12.100	1.5666	3.420	368
1973	0.7484	12.700	1.3484	4.7704	520
1974	0.8231	12.800	0.9231	5.6935	652
1975	0.6514	13.000	0.8514	6.5449	819
1976	0.7568	12.800	0.5568	7.1017	936
1977	0.7646	12.600	0.5648	7.6665	1033

Table 7: Annual Estimated Reserves and Actual Reserves for Nigeria (2014)

Year	Estimate Reserves (mmmbbls)	Actual Reserves (mmmbbls)	Variation
1971	10.728625	11.20000	0.471375
1972	11.153489	12.10000	0.946511
1973	11.549245	12.70000	1.150755
1974	11.719751	12.80000	1.080249
1975	12.325417	13.00000	0.674583
1976	12.449317	12.80000	0.350683
1977	12.414868	12.60000	0.185132

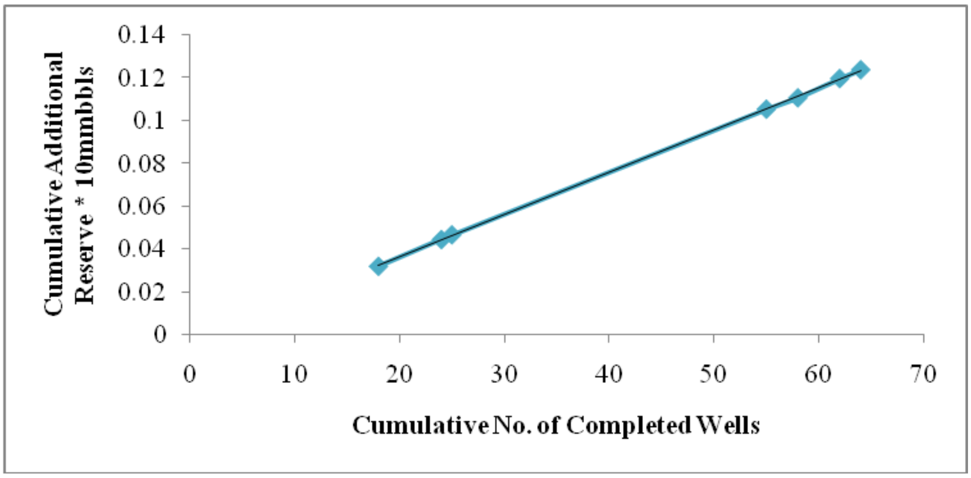

Fig. 1: Cumulative Additional Reseves vs. Cumulative No. of Completed Wells for Field X

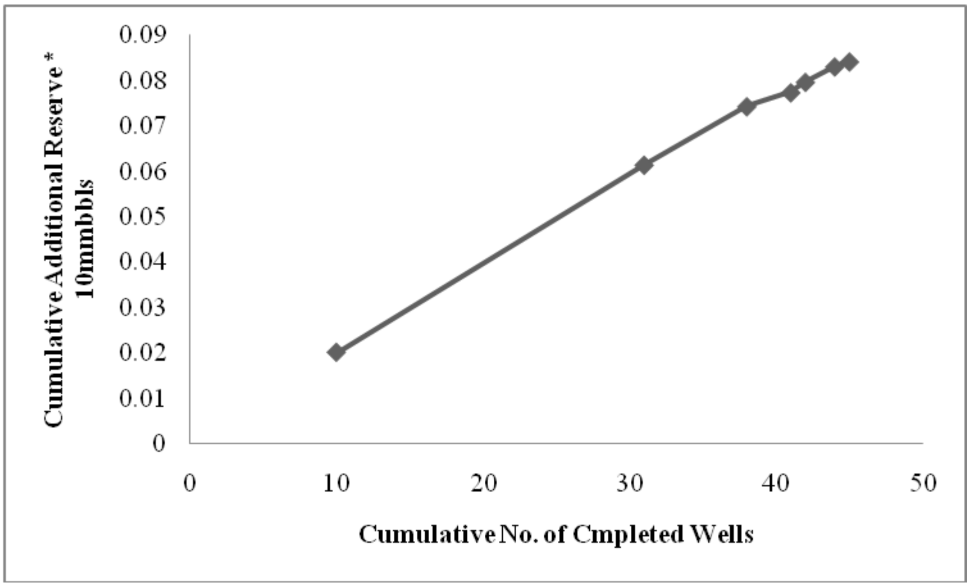

Fig. 2: Cumulative Additional Reseves vs. Cumulative No. of Completed Wells for Field Y

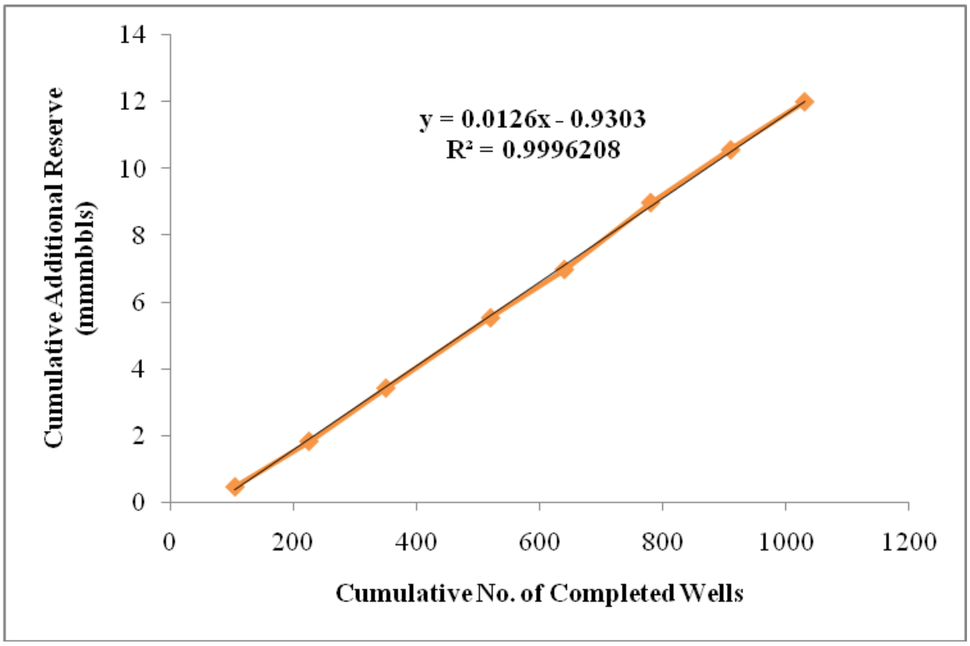

Fig. 3: Cumulative Additional Reseves vs. Cumulative No. of Completed Wells for Nigeria

III. DISCUSSION

Thecumulative additional reserve with cumulative number of completed wells varies from one field to the other and it is a function of hydrocarbon potential of each field. A field with high hydrocarbon potential has a high rate of change of cumulative number of completed wells. For example the rate of change of cumulative additional reserves with cumulative number of completed wells of **Field Y** is larger than that of **Field X**. It shows that **Field Y** has a huge crude oil potential than **Field X**. Therefore the developed Estimation Model could be used as a benchmark to measure the hydrocarbon potential of a given field.The variation between the estimated reserve and the actual reserve could be attributed to the assumption made in the application of the estimation model that no revision of the field samples has been used which makes the additional reserve due to the revision of the field to be zero. The additional reserve when added by way of revision could alter the reserve potential when increased knowledge of the field changes the field fractional recovery.

IV. CONCLUSION AND RECOMMENDATIONS

Conclusion

The following conclusions could be drawn from the findings:

- The Estimation model is useful in that better and more reliable reserve estimates are evaluated since the most recent data are used.
- The model gives an improved performance when compared between cumulative additional reserve and cumulative number of completed wells.
- The model depends on sound, accurate and up to date production data. Direct estimation of reserves in future will not be possible without first estimating the production during the year and reserve at the end of the preceding year.
- Reserves estimates of some existing fields could be considerably improved upon if such fields are revised by way of re-evaluating their basic geology and engineering data.

Recommendations

- The model only investigated the reserves in existing wells. Effort should be geared towards evaluating reserves of unexpected fields.
- A mathematical expression that would relate the rate of change of cumulative additional reserve to cumulative number of completed wells be developed and incorporated into the model to replace the one evaluated from linear regression analysis.

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