Effect of water influx on the inventory of underground gas storage developed in a depleted oil reservoir

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Effect of water encroachment into an underground gas storage reservoir on its storage capacity (verification of inventory) is presented. Inventory verification is to determine the amount of natural gas to be injected into a particular underground reservoir. Reservoir and production history of a depleted oil reservoir, Z-16T, located in the Niger Delta region were obtained for the analyses. A volumetric equation was used to estimate the storage capacity of the reservoir in two cases ($W_e = 0$ and $W_e \neq 0$, for fifteen different pressures). Microsoft Visual Basic computer model developed based on the same volumetric equation was applied for the same purpose. It was confirmed that the amount of gas to be injected at any given pressure is higher when there is no water influx into the storage reservoir. This has shown that water influx reduces the storage space of an underground storage reservoir.

Key words: storage, capacity, water influx, inventory, encroachment, gas, underground.

INTRODUCTION

Underground natural gas storage acts as the swing capacity due to the seasonal variations in demand. Natural gas is injected into the underground gas reservoirs for the purpose of storage for future use during the second and third quarters when supply exceeds demand (Dietert and Pursell, 2008). This injected gas is withdrawn from these reservoirs during the first and fourth quarters when demand is at the peak and exceeds supply. There are 3 types of reservoirs commonly used for underground gas storage: depleted oil/gas reservoir; aquifer and salt cavern; each of the storage reservoirs has very specific producing parameters (Anyadiegwu, 2012).

Statement of the Problem

It is a challenge for the natural gas producers in Nigeria to remove the bottleneck of meeting up with the gas demand by relying on the pipeline supply alone especially now that natural gas price is put at $4.45 per 1000scf, the obvious and urgent need by the oil and gas producing companies to be compliant with the new gas flares out/down target which is put at 2012. Also, the recent increase in gas flare penalty is currently put at $3.5 per 1000scf and the environmental degradation and green house emission caused by gas flaring. Furthermore, supply of natural gas stopped even though there is high...
demand in the event of national or local producing community unrests when gas production is disrupted and/or when there is breakdown in heavy equipment for gas production, which takes a long time to restart. Natural gas price/supply instability leads to poor monitoring of gas sales transactions.

To date, there is no record of underground gas storage in the country in spite of the strategic importance of petroleum resources in Nigeria. Therefore, it is very vital to turn to underground storage as a viable solution due to the above-listed problems.

Storage in depleted reservoirs is an underground gas storage that occurs in porous and high deliverability depleted reservoirs, which are close to the consumption centre. The conversion of the oil fields from the production to storage duty takes advantage of the existing wells, gathering systems and pipeline connections. Depleted oil reservoirs are used for underground gas storage due to their wide availability and well known geology. The requirements for each of the reservoirs vary since no two reservoirs are the same, typically these types of reservoirs require 50% base gas (that is, equal amount of working gas) and one cycle per season (EIA, 2002).

Below are the 3 basic requirements in underground storage of natural gas:

1. Verification of inventory
2. Retention against migration
3. Assurance of deliverability

The particular characteristic of an underground storage reservoir taken into consideration in this research is the Storage Capacity (Verification of Inventory). Storage Capacity of a depleted reservoir refers to the volume of gas that can be stored in the reservoir in accordance with its design. There had been methods and models for the estimation of the storage capacity of an underground gas storage reservoir, but most of the models estimate the storage capacity of the reservoir without taking into consideration the effect of underlying aquifer on the storage capacity.

In this work, the effect of an underlying aquifer in the storage capacity of a storage reservoir is studied. Models are developed for this study and the results are presented.

Research Objective

There is no underground storage of natural gas in the numerous depleted oil and gas wells available in Nigeria. This is in spite of the fact that underground storage of natural gas is a developed industry elsewhere in the world necessary for effective gas delivery.

Nigeria needs to urgently expand its gas storage capability to include underground storage in depleted crude oil wells. It is therefore vital to evolve the development and performance analysis of depleted crude oil reservoirs for underground natural gas storage.

In order to address these problems, the specific objectives of this research are:

1. To evaluate the storage capacity of an available depleted crude oil reservoir for underground natural gas storage. The intention is to provide basic knowledge of the verification of inventory (storage capacity) for the depleted reservoir.
2. To obtain suitable equations from the existing material balance equations that will estimate the reservoir capacity with and without water encroachment respectively.
3. To apply visual basic computer model for characterizing the depleted reservoir in (2) above.

Natural water encroachment is commonly seen in many oil and gas reservoirs. In fact, some times, there is more water than oil produced from oil reservoirs, much of this is natural water influx. Thus, it is clear that an understanding of reservoir/aquifer interaction can be an important aspect of reservoir management to optimize recovery of hydrocarbons (William, 1997).

There are more uncertainties attached to the subject of water influx than to any other in reservoir engineering. This is simply because one seldom drills wells into aquifer to gain the necessary information about the porosity, permeability, thickness and fluid properties. Instead, these properties have frequently been inferred from what has been observed in the reservoir. Even more uncertain, however, is the geometry and real continuity of the aquifer itself. Due to these inherent uncertainties, the aquifer fit obtained from history matching is seldom unique and the aquifer model may require frequent updating as more production and pressure data becomes available. This is unsteady state water influx theory (Van Everdingen and Hurst, 1949).

The recovery from many oil reservoirs is affected by water influx, either from the perimeters of the oil reservoirs, from below, or from both. An understanding of the interplay between aquifers and the oil reservoirs is important to properly perform oil recovery calculations (William, 1997). A large water influx decreases recovery because a large amount of gas is trapped by the rise of the gas-water interface, and the water reaching the wells means a higher abandonment pressure (high water-cut), and hence a shorter production period while a moderate water influx increases recovery (Cosse, 1993). The water inflows resulting from gradual expansion of the aquifer continue in transient conditions over a relatively long period. Since the pressure at oil/water interface drops as a function of time, the superimposition theorem is used to obtain an equation given below for the estimation of water influx (Van Everdingen and Hurst, 1949):

$$W_w (P, t) = B \sum_{i=0}^{n} C (t_i - t_{0i}) DP_i$$

(1)
B = Constant = 2πR²hΦ (C_w + C_p)

C = tabulated aquifer function (from time t to time t - i)
DP = half pressure drop at interface from time (t - i) to (t - i - 1).

Also, the maximum theoretical water influx is obtained with the following equation (Van Everdingen and Hurst, 1949):

\[
W_{em} = V_w (C_w + C_p) (P_i - P)
\]

V_w = estimated volume of aquifer water

Water influx into storage reservoir reduces the storage volume of the reservoir and in turn affects the total investment cost and the expected revenue.

**EXPERIMENTAL PROCEDURE**

**Estimation of storage capacity (Inventory Verification)**

To determine the volume of gas to be injected at different pressures of the storage reservoir, pressure is varied for fifteen different cases. At each pressure variation, new reservoir parameters, B_o, B_d, and R_i were obtained. Table of values was generated for the plot of gas versus reservoir pressure which represents the volume to be injected at different pressures.

The steps for the reservoir engineering calculation of the gas storage capacity of the reservoirs are as shown below:

From gas material balance equations

\[
\text{Production (scf)} = G \times (HCPV) \times E
\]

\[
G_o = G \times (HCPV) \times E
\]

\[
G = G \times (HCPV) \times E
\]

Where \(G_o\) = Gas Production (scf)
\(G\) = Gas initially in place, HCPV (scf)
E = Gas Expansion Factor = standard volume of n moles of gas / reservoir volume of n moles of gas

\[
E = V_{sc}/V
\]

For real gas, \(PV = znRT\)

\[
S_o = \frac{V_{sc}}{V} = P/P_{sc} \times T_{sc}/T \times z_{sc}/z
\]

In field units, \(V_{sc}/V = P/14.7 \times 520/T \times 1/z = 35.37 \times P/(zT)
\]

Where \(V_{sc}\) = Volume at standard condition
\(V\) = Reservoir volume
\(P\) = Storage pressure
\(P_{sc}\) = Pressure at standard condition
\(T_{sc}\) = Temperature at standard condition
\(T\) = Temperature
\(z_{sc}\) = Compressibility factor at standard condition
\(z\) = Compressibility factor

Therefore, \(E = 35.37 \times P/(zT)\)

\[
E_i = 35.37 \times P/(zT)
\]

Where \(E_i\), \(P_i\), \(z\), and \(T_i\) are expansion factor, pressure, compressibility factor and temperature at the initial state before gas storage.

Substituting Equations (10) and (11) in Equation (5), putting \(T = T_i\), and making \(G\) the subject:

\[
G = G_o/[1 - Pz/(Pz)]
\]

\[
V_i = G_o/[1 - Pz/(Pz)]
\]

Where \(V_i\) = Total Storage capacity, scf.
This is the volume of gas required to replace the produced oil. It is also called the total storage capacity.

Since working gas is 50% of the total storage for a depleted reservoir, the working gas capacity is estimated using:

\[
V_{sc} = 0.5*V_i
\]

\[
V_{sc} = 0.5*G_o/[1 - Pz/(Pz)]
\]

Where \(V_{sc}\) = Working gas capacity, scf
\(N_b\) is expressed in gas terms as \(G_o\) from \(G_o B_o = N_b B_o\) as:

\[
G_o = N_b B_o/B_o
\]

\(N_b\) = Cumulative oil production, scf
\(B_o\) = Oil formation volume factor, rb/stb
\(B_o\) = Gas formation volume factor, rcf/scf
\(P_i\) = Initial pressure, psia
\(T_i\) = Initial temperature, °R
\(Z_i\) = Initial compressibility factor
\(P\) = Pressure, psia
\(T\) = Temperature, °R
\(Z\) = Compressibility factor

As stated in this section, the storage capacities at various pressures represent the volume of gas to be injected into the storage reservoir at the various pressures. It guides the operator of the gas storage facility in choosing the initial injection pressure.

A Microsoft Visual Basic Program (MVBP) was developed using Equations (13) and (15), and was used to obtain the volume of gas injected into the reservoirs at various pressures and presented in a table which was used to make a plot of volume of gas injected against Reservoir pressure.

**Estimation of storage capacity of reservoir with water influx**

Recalling Equation (5) and considering water encroachment (net water influx) into the reservoir becomes:

\[
G_o = G - (G/E_i - W_0)\times E
\]

Where \(W_0\) = Net water influx, scf
\(W_e\) is expressed in gas terms from \(W_{eq} B_o = W_e B_o\) as:

\[
W_{eq} = W_e B_o/B_o
\]

Making \(G\) the subject and putting Equations (10) and (11) into the equation:

\[
G = [G_o - (W_{eq} \times 35.37P/(zT))]\times [1 - Pz/(Pz)]
\]

Then total storage capacity is given as:

\[
V_i = [G_o - (W_{eq} \times 35.37P/(zT))]\times [1 - Pz/(Pz)]
\]

And working gas capacity is given as:

\[
V_{sc} = 0.5*[G_o - (W_{eq} \times 35.37P/(zT))]\times [1 - Pz/(Pz)]
\]
Equations (20) and (21) were used to develop a Microsoft Visual Basic computer program and were applied in generating the volume of gas to be injected into the storage reservoir at different pressures considered. The sample of the MVBP sheet is shown in Figure 1.

**Description of the Study Area**

The test field is located onshore in the eastern part of the Niger Delta oil producing fields. Niger Delta covers the nine states where the oil producing fields are located in Nigeria, they include: Abia, Akwa Ibom, Bayelsa, Cross Rivers, Delta, Edo, Imo, Ondo and Rivers state. It stretches from east to west, as shown in Figure 2 below. Oil and gas production from the Niger Delta fields started in the late fifties till date. The reservoir selected for the study is a depleted crude oil reservoir. It was selected due to:

1. Geologic features: Having retained oil/gas for millions of years and produced same before depletion, hence good porosity and permeability.
2. Geographical location: The field is located near the region where population and industries are located, this will make supply easier.

**RESULTS**

**CASE 1: No Water Influx (We = 0), Table 1.**

**Estimation of the storage capacity (Inventory Verification)**

The storage capacity is computed using Equation (14) as:

\[
V_{sc} = 0.5 \times 0.82554Bscf / [1 - (3634 \times 0.86)/(3955 \times 0.84)]
\]

= 6.96 Bscf

The total storage capacity is computed using eq 2.10a as:

\[
V_t = 0.82254Bscf / [1 - (3634 \times 0.86)/(3955 \times 0.84)] = 13.92 Bscf
\]

The storage capacities of reservoir Z-16T at various pressures were estimated and the results are shown in Table 1.

**Estimation of storage capacity using MVBP**

The volume of gas to be injected into the reservoir was estimated using the MVBP as shown in Figure 3. The results are presented in Table 2, which is used to obtain the plot of the volume of gas injected at various injection pressures as shown in Figure 4.

**CASE 2: With Water Influx (We ≠ 0)**

**Estimation of the storage capacity of the reservoir with water influx**

Recall Equation (19):

\[
V_{sc} = 0.5 \times (G_p - (W_{eg} \times 35.37P/zT)) / [1 - Pz/(P_i z)]
\]

In computing \( B_w \), Figure 5 was employed, considering the discovery pressure and temperature of the reservoir:

At a pressure of 3634 psig and temperature of 210°F, \( B_w = 1.0359 \)
Table 1. Reservoir and Fluid Data for Reservoir Z-16T.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial pressure, $P_i$</td>
<td>3955 psig</td>
</tr>
<tr>
<td>Initial storage pressure, $P$</td>
<td>3634 psig</td>
</tr>
<tr>
<td>Saturation pressure, $P_{sat}$</td>
<td>3290 psig</td>
</tr>
<tr>
<td>Reservoir temperature, $T$</td>
<td>210°F</td>
</tr>
<tr>
<td>Initial Gas compressibility factor, $Z$</td>
<td>0.86</td>
</tr>
<tr>
<td>Initial oil formation volume factor, $B_{oi}$</td>
<td>1.405</td>
</tr>
<tr>
<td>Specific gravity, SG</td>
<td>25.7°API</td>
</tr>
<tr>
<td>Height, $h$</td>
<td>80 ft</td>
</tr>
<tr>
<td>Porosity, $\phi$</td>
<td>0.25</td>
</tr>
<tr>
<td>Initial water saturation, $S_{wi}$</td>
<td>20 %</td>
</tr>
<tr>
<td>Permeability, $k$</td>
<td>30 MD</td>
</tr>
<tr>
<td>Well depth, $d$</td>
<td>11 000 ft</td>
</tr>
<tr>
<td>Net Water Influx, $W_w$</td>
<td>0.004582 MMscf</td>
</tr>
<tr>
<td>Initial Water formation volume factor, $B_{wi}$</td>
<td>1.0359</td>
</tr>
</tbody>
</table>

The Storage capacity of the reservoir is given as:

\[
V_{sc} = 0.5*[0.82254Bscf - (0.001084Bscf \times 35.37*3634/(0.84*210))/(1 - (3634*0.86)/(3955*0.84))] = 4.87 Bscf
\]

The total storage capacity is given as:

\[
V_t = [0.82254Bscf - (0.001084Bscf \times 35.37*3634/(0.84*210))/(1 - (3634*0.86)/(3955*0.84))] = 9.74 Bscf
\]

Estimation of storage capacity of Z-16T using MVBP

Figure 6 is a Microsoft Visual Basic Program used in estimating the storage capacity of reservoir Z-16T at any given pressure. It was used in generating new volume of gas to be injected into the reservoir at different pressures considered. The volume of gas that can be injected at various reservoir pressures are presented in Table 3 and used to obtain the plot of the volume of gas injected at various injection pressures as shown in Figure 7.

RESULTS AND DISCUSSION

One basic requirement in underground storage of natural gas which is the verification of inventory was evaluated for the reservoir. The storage capacity of the reservoir was estimated using the models and the MVBP. The total
The storage capacity of the reservoir without water influx was computed as 13.92 Bscf while the working gas capacity was generated as 6.96 Bscf which is exactly 50% of the total storage capacity as required for storage in depleted reservoirs. Considering water influx into the reservoir, the total storage capacity of the reservoir was estimated as 9.74 Bscf, while the working gas capacity was gotten as 4.87 Bscf, which is also 50% of the total storage capacity as required for storage in depleted reservoirs. The results show that water influx reduced the total storage capacity of the reservoir by 4.18 Bscf and the working gas capacity by 2.09 Bscf.

**Conclusion**

The following conclusions were drawn at the end of this study:

1. That it is possible to rework a depleted oil reservoir for use as an underground gas storage vessel provided the water is controllable.
2. Water influx into an underground storage reservoir reduces its storage capacity, hence the storage capacity of Z-16T in both cases were estimated to be 6.96 Bscf and 4.87 Bscf respectively.
Figure 3.2: A plot of volume of gas to be injected at various pressures for reservoir Z-16T.

Table 3. Volume of gas injected at various pressures of Z-16T with water influx.

<table>
<thead>
<tr>
<th>P (psia)</th>
<th>( N_p ) (MMstb)</th>
<th>( B_w ) (bbl/stb)</th>
<th>( W_e ) (MMscf)</th>
<th>( W_{eq} ) (MMscf)</th>
<th>( V_{sc} ) (Bscf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3634</td>
<td>468.1514</td>
<td>1.0359</td>
<td>0.004582</td>
<td>1.084122</td>
<td>4.874171</td>
</tr>
<tr>
<td>3561</td>
<td>487.1965</td>
<td>1.0360</td>
<td>0.00478</td>
<td>1.115</td>
<td>4.069682</td>
</tr>
<tr>
<td>3534</td>
<td>489.6978</td>
<td>1.0361</td>
<td>0.005057</td>
<td>1.185</td>
<td>4.237888</td>
</tr>
<tr>
<td>3350</td>
<td>545.5654</td>
<td>1.0365</td>
<td>0.005357</td>
<td>1.205</td>
<td>2.985076</td>
</tr>
<tr>
<td>3288</td>
<td>558.4096</td>
<td>1.0367</td>
<td>0.005446</td>
<td>1.225</td>
<td>3.041601</td>
</tr>
<tr>
<td>3212</td>
<td>584.6983</td>
<td>1.0369</td>
<td>0.005674</td>
<td>1.255</td>
<td>2.742906</td>
</tr>
<tr>
<td>3043</td>
<td>655.326</td>
<td>1.0373</td>
<td>0.005997</td>
<td>1.265</td>
<td>2.243078</td>
</tr>
<tr>
<td>2922</td>
<td>712.4505</td>
<td>1.0376</td>
<td>0.006302</td>
<td>1.285</td>
<td>2.030907</td>
</tr>
<tr>
<td>2911</td>
<td>717.5029</td>
<td>1.0377</td>
<td>0.006342</td>
<td>1.29</td>
<td>2.018785</td>
</tr>
<tr>
<td>2857</td>
<td>746.8523</td>
<td>1.0378</td>
<td>0.006478</td>
<td>1.295</td>
<td>1.937715</td>
</tr>
<tr>
<td>2767</td>
<td>798.3728</td>
<td>1.0380</td>
<td>0.006713</td>
<td>1.305</td>
<td>1.83668</td>
</tr>
<tr>
<td>2427</td>
<td>1049.995</td>
<td>1.0387</td>
<td>0.007553</td>
<td>1.3055</td>
<td>1.619197</td>
</tr>
<tr>
<td>2237</td>
<td>1253.034</td>
<td>1.0391</td>
<td>0.00847</td>
<td>1.35</td>
<td>1.539652</td>
</tr>
<tr>
<td>2145</td>
<td>1373.683</td>
<td>1.0393</td>
<td>0.008974</td>
<td>1.37</td>
<td>1.51552</td>
</tr>
<tr>
<td>2057</td>
<td>1505.177</td>
<td>1.0394</td>
<td>0.009541</td>
<td>1.395</td>
<td>1.500443</td>
</tr>
</tbody>
</table>

In computing \( B_w \), Fig 3.3 was employed, considering the discovery pressure and temperature of the reservoir:

Figure 3.3: Spreadsheet for the Computation of water formation volume factor, \( B_w \)

Figure 4. A plot of volume of gas to be injected at various pressures for reservoir Z-16T.

Figure 5. Spreadsheet for the Computation of water formation volume factor, \( B_w \)
3.2.1 Estimation of storage capacity of Z-16T using Microsoft Visual Basic Program

Figure 3.4: Storage Capacity of Z-16T with water influx at 3634 psia.

Figure 6. Storage Capacity of Z-16T with water influx at 3634 psia.

Figure 7. A plot of Volume of gas injected at various pressures for reservoir Z-16T with water influx.

(3) In choosing reservoirs for the purpose of gas storage, considerations should be made on the amount of water influx into the system and preference is given to the reservoir with less $W_e$, reason given in 1 above.

Conflict of Interest
The author(s) have not declared any conflict of interests.

NOMENCLATURE

- $B = \text{Constant} = 2\pi R^2 h \Phi (C_w + C_p)$
- $B_o = \text{Oil formation volume factor}$
- $B_g = \text{Gas formation volume factor}$
- $B_{gi} = \text{Initial gas formation volume factor}$
- $B_w = \text{Water formation volume factor}$
- $B_{scf} = \text{Billion standard cubic foot}$
Bcf = Billion cubic foot
C = Tabulated aquifer function (from time t to time t+1)
$D_{Pi} =$ Half pressure drop at interface from time \((i-1)\) to \((i+1)\).
E = Gas Expansion Factor
$E_{i}$ = Gas Expansion Factor at initial state
EIA = Energy Information Administration
Eq = Equation
$Ft^3$ = Cubic foot
G = Gas initially in place, GIIP (scf)
$G_{p}$ = Gas Production (scf)
MMscf = Million standard cubic foot
MVBP = Microsoft Visual Basic Program
N = Initial oil in place
$N_{p}$ = Cumulative oil production
P = Storage pressure
$P_{i}$ = Pressure at the initial state
$P_{sc}$ = Pressure at standard condition
Res = Reservoir
$R_{p}$ = Gas oil ratio
$R_{s}$ = Gas solubility
T = Temperature
$T_{i}$ = Temperature at initial state
$T_{sc}$ = Temperature at standard condition
V = Reservoir volume
$V_{sc}$ = Volume at standard condition
$V_{sc}$ = Working gas capacity, scf
$V_{t}$ = Total storage capacity, scf
$V_{w}$ = Estimated volume of aquifer water
$W_{e}$ = Net water influx
$W_{eq} = W_{e}$ in gas terms, scf
z = Compressibility factor
$z_{i}$ = Compressibility factor at the initial state
$z_{sc}$ = Compressibility factor at standard condition

**REFERENCES**


