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Full Length Research Paper

Causes of water inundation on the stock of underground gas storage developed in an evacuated 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 This injected gas is withdrawn from these reservoirs during the first and fourth quarters when demand is at the peak and exceeds supply.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):

$$W_e(P, t) = B \sum_{i=0}^{n} \overline{C}\,(t_D - t_{D\,i})\, DP_i \quad (1)$$

B = Constant = $2\pi R^2_i h\Phi (C_w + C_p)$
C = tabulated aquifer function (from time t to time t_i)
DP_i = half pressure drop at interface from time (i-1) to (i+1).
Also, the maximum theoretical water influx is obtained with the following equation (Van Everdingen and Hurst, 1949):

$$W_{em} = V_w (C_w + C_p) (P_i - P) \quad (2)$$

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_g, and R_s 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

$$\text{Production (scf)} = \text{GIIP (scf)} - \text{Unproduced Gas (scf)} \quad (3)$$

$$G_p = G - (HCPV) \times E \quad (4)$$

$$G_p = G - G/E_i \times E \quad (5)$$

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

$$E = V_{sc}/V \quad (6)$$

$$\text{For real gas, } PV = znRT \quad (7)$$

$$\text{So, } V_{sc}/V = P/P_{sc} \times T_{sc}/T \times z_{sc}/z \quad (8)$$

$$\text{In field units, } V_{sc}/V = P/14.7 \times 520/T \times 1/z = 35.37 \times P/(zT) \quad (9)$$

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

$$\text{Therefore, } E = 35.37 \times P/(zT) \quad (10)$$

$$E_i = 35.37 \times P_i/(z_iT_i) \quad (11)$$

Where E_i, P_i, z_i 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:

$$G = G_p/[1 - Pz_i/(P_iz)] \quad (12)$$

$$V_t = G_p/[1 - Pz_i/(P_iz)] \quad (13)$$

Where V_t = 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:

$$V_{sc} = 0.5 * V_t \quad (14)$$

$$V_{sc} = 0.5 * G_p/[1 - Pz_i/(P_iz)] \quad (15)$$

Where V_{sc} = Working gas capacity, scf
N_p is expressed in gas terms as G_p from $G_pB_g = N_pB_o$ as:

$$G_p = N_pB_o/B_g \quad (16)$$

N_p = Cumulative oil production, scf
B_o = Oil formation volume factor, rb/stb
B_g = 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:

$$G_p = G - (G/E_i - W_e) \times E \quad (17)$$

Where W_e = Net water influx, scf
W_e is expressed in gas terms from $W_{eg}B_g = W_eB_w$ as:

$$W_{eg} = W_eB_w/B_g \quad (18)$$

Where W_{eg} = W_e in gas terms, scf
Making G the subject and putting Equations (10) and (11) into the equation:

$$G = [G_p - (W_{eg} * 35.37P/zT)]/[1 - Pz_i/(P_iz)] \quad (19)$$

Then total storage capacity is given as:

$$V_t = [G_p - (W_{eg} * 35.37P/zT)]/[1 - Pz_i/(P_iz)] \quad (20)$$

And working gas capacity is given as:

$$V_{sc} = 0.5*[G_p - (W_{eg} * 35.37P/zT)]/[1 - Pz_i/(P_iz)] \quad (21)$$

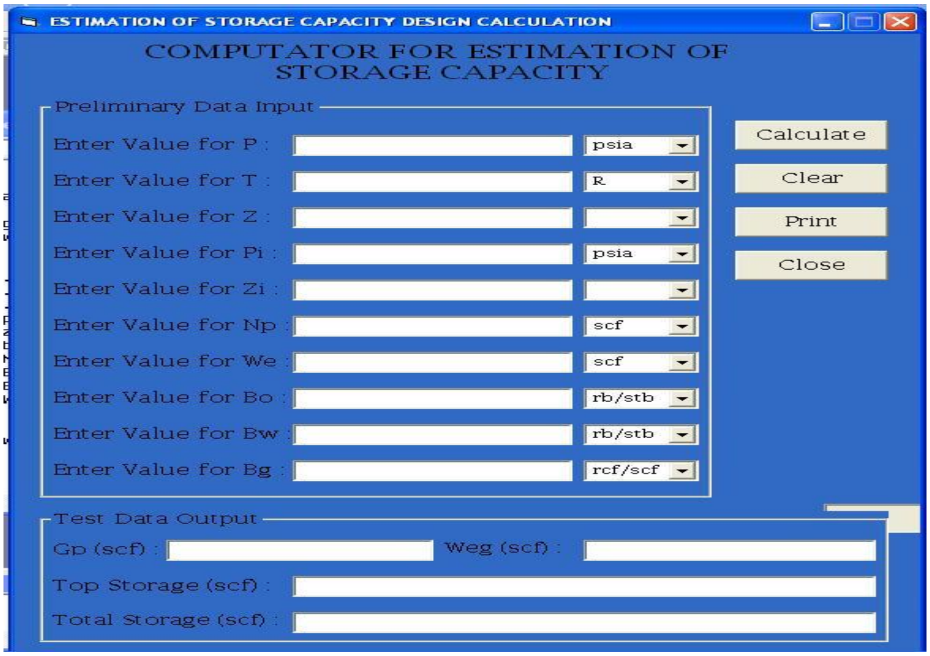

Figure 1. Microsoft Visual Basic Program for Estimating Storage Capacity.

Fig 2.1: Microsoft Visual Basic Program for Estimating Storage Capacity

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 * 0.82554Bscf / [1 – (3634 * 0.86)/(3955 * 0.84)] = 6.96 Bscf

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

V_t = 0.82254Bscf / [1 – (3634 * 0.86)/(3955 * 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):
$V_{sc} = 0.5*[G_p – (W_{eg} * 35.37P/zT)]/[1 – Pz_i/(P_iz)]$

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

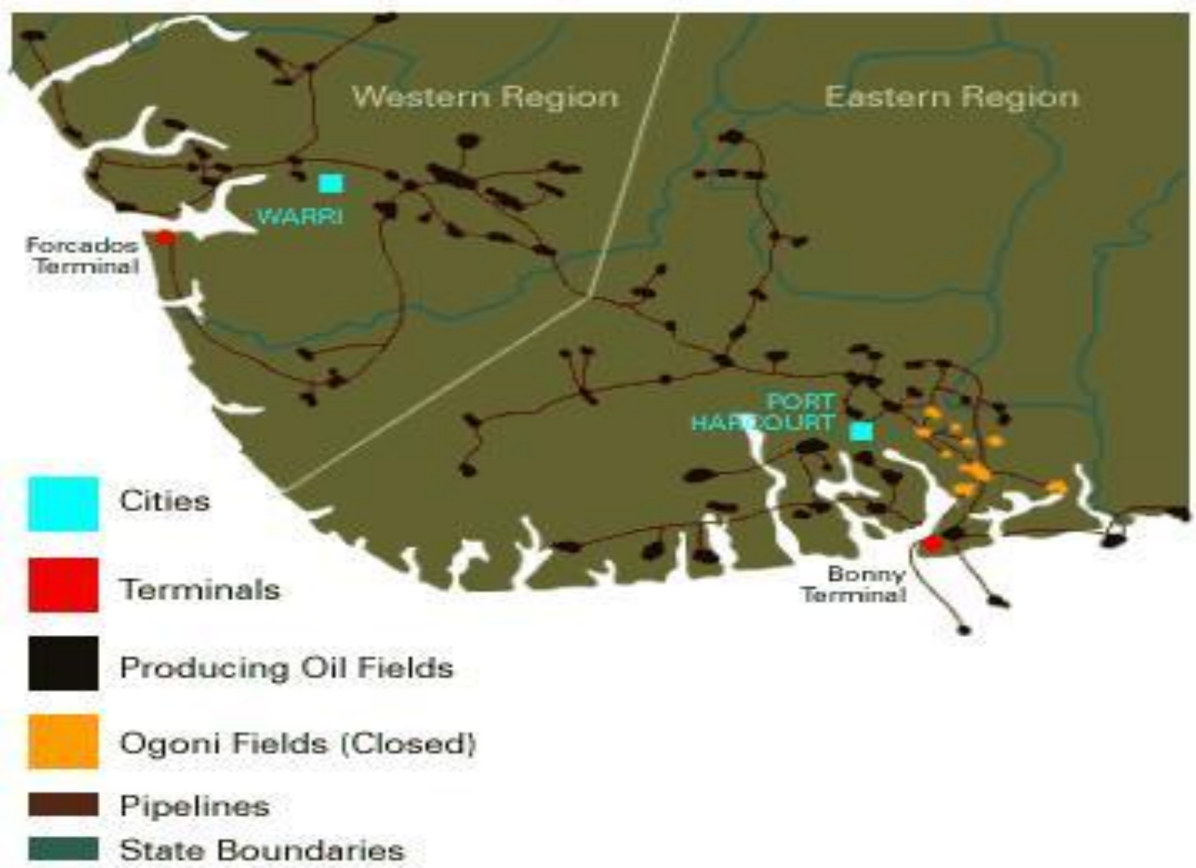

Figure 2. A map of Niger Delta showing oil fields and pipelines
*Source: Ministry of Lands and Urban Planning, Owerri.

Fig. 2.2: A map of Niger Delta showing oil fields and pipelines

Source: Ministry of Lands and Urban Planning, Owerri.

Table 1. Reservoir and Fluid Data for Reservoir Z-16T.

Initial pressure, P_i	3955 psig
Initial storage pressure, P	3634 psig
Saturation pressure, P_{sat}	3290 psig
Reservoir temperature, T	210°F
Initial Gas compressibility factor, Z	0.86
Initial oil formation volume factor, B_{oi}	1.405
Specific gravity, SG	25.7°API
Height, h	80 ft
Porosity, Ø	0.25
Initial water saturation, S_{wi}	20 %
Permeability, k	30 MD
Well depth, d	11 000 ft
Net Water Influx, W_e	0.004582 MMscf
Initial Water formation volume factor, B_{wi}	1.0359

The Storage capacity of the reservoir is given as:

V_{sc} = 0.5*[0.82254Bscf – (0.001084Bscf * 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 * 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 plot of the volume of gas injected at various injection pressures as shown in Fig 3.2.

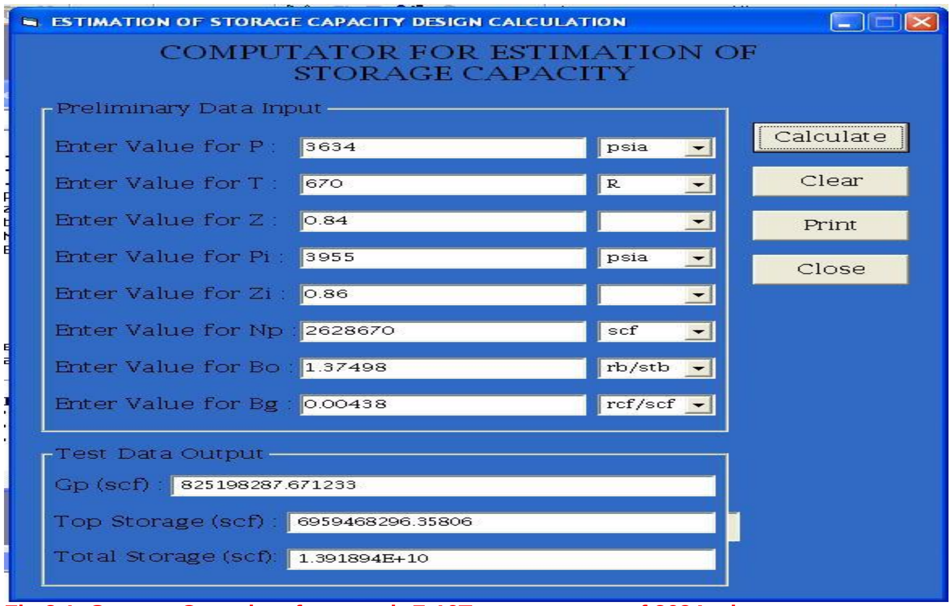

Fig 3.1: Storage Capacity of reservoir Z-16T at a pressure of 3634psia

Figure 3. Storage Capacity of reservoir Z-16T at a pressure of 3634psia.

Table 2. Volume of gas injected at various pressures of Res Z-16T.

P (psia)	N_p (MMstb)	B_g (scf/scf)	B_o (rb/stb)	R_s (scf/rb)	G_p (Bscf)	V_{sc} (Bscf)
3634	468.1514	0.00438	1.37498	769.3446	0.82554	6.962322
3561	487.1965	0.00444	1.36776	750.8924	0.84246	5.797014
3534	489.6978	0.00442	1.3651	744.087	0.8489	6.192776
3350	545.5654	0.00461	1.34708	697.9943	0.89552	4.21611
3288	558.4096	0.00461	1.34105	682.5773	0.91241	4.291837
3212	584.6983	0.00469	1.33369	663.7595	0.934	3.844802
3043	655.326	0.00492	1.31746	622.2407	0.98587	3.034957
2922	712.4505	0.00509	1.30595	592.7992	1.02669	2.693303
2911	717.5029	0.0051	1.30491	590.1348	1.03057	2.67515
2857	746.8523	0.00519	1.29981	577.0848	1.05005	2.541455
2767	798.3728	0.00534	1.29135	555.4463	1.08421	2.371164
2427	1049.995	0.00601	1.2599	475.0178	1.23609	1.96442
2237	1253.034	0.00652	1.24271	431.0394	1.34108	1.820755
2145	1373.683	0.00681	1.23448	410.0111	1.3986	1.770191
2057	1505.177	0.00711	1.22669	390.0672	1.45843	1.733702

storage capacity of the reservoir without water influx was computed as 13.92Bscf while the working gas capacity was generated as 6.96Bscf 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 9.74Bscf, while the working gas capacity was gotten as 4.87Bscf, 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 4.18Bscf and the working gas capacity by 2.09Bscf.

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.

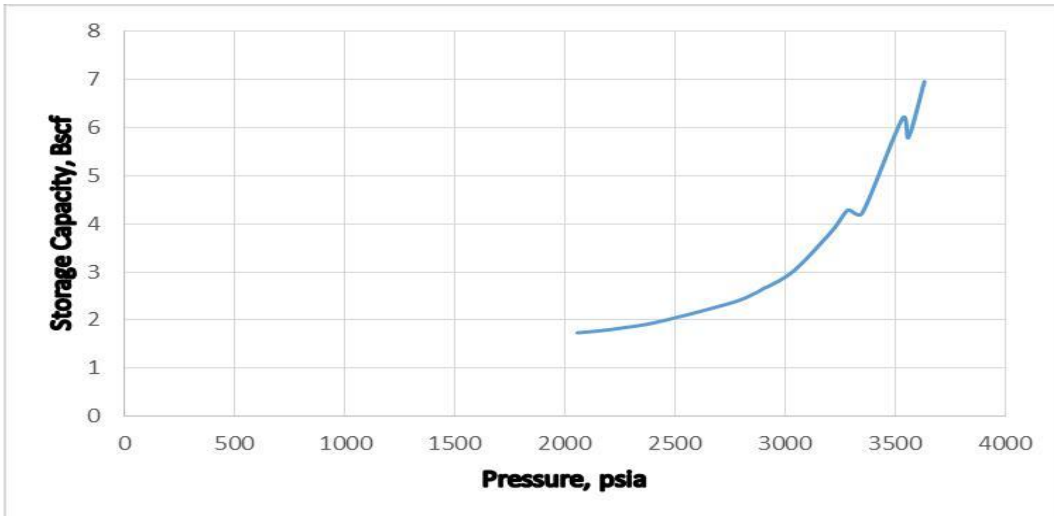

Figure 4. A plot of volume of gas to be injected at various pressures for reservoir Z-16T.

Fig 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.

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

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

Figure 5. Spreadsheet for the Computation of water formation volume factor, Bw
*Source: Liu, (2009).

Fig 3.3: Spreadsheet for the Computation of water formation volume factor, B_w

Source: Liu, (2009).

Gas.1 Estimation Eng. of storage capacity of Z-16T using Microsoft Visual Basic Program

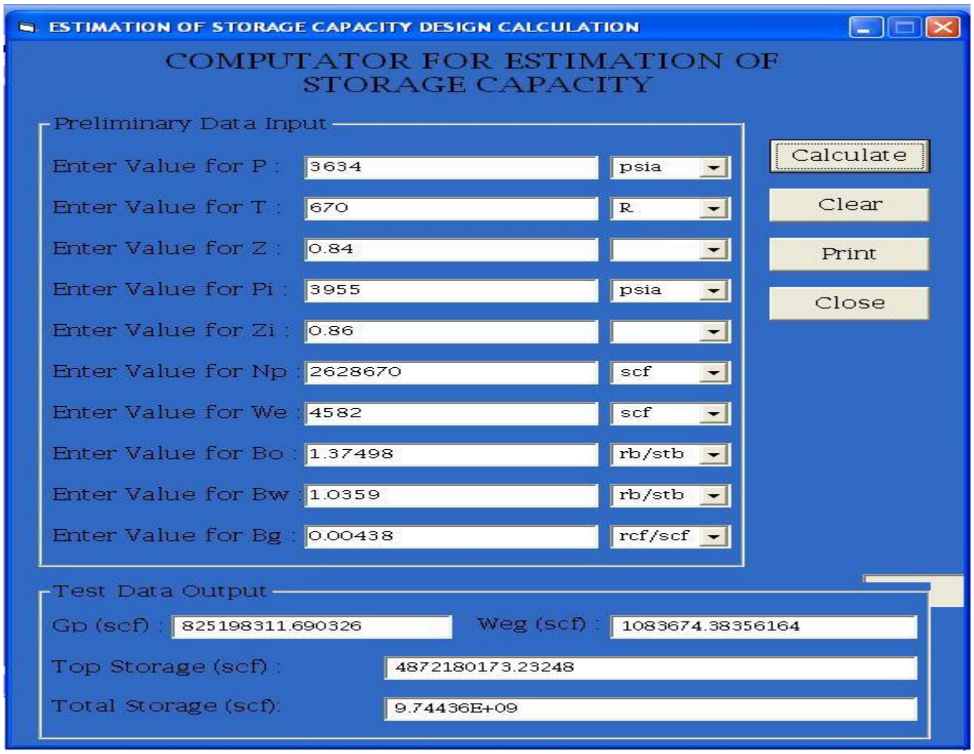

Figure 6. Storage Capacity of Z-16T with water influx at 3634psia.

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

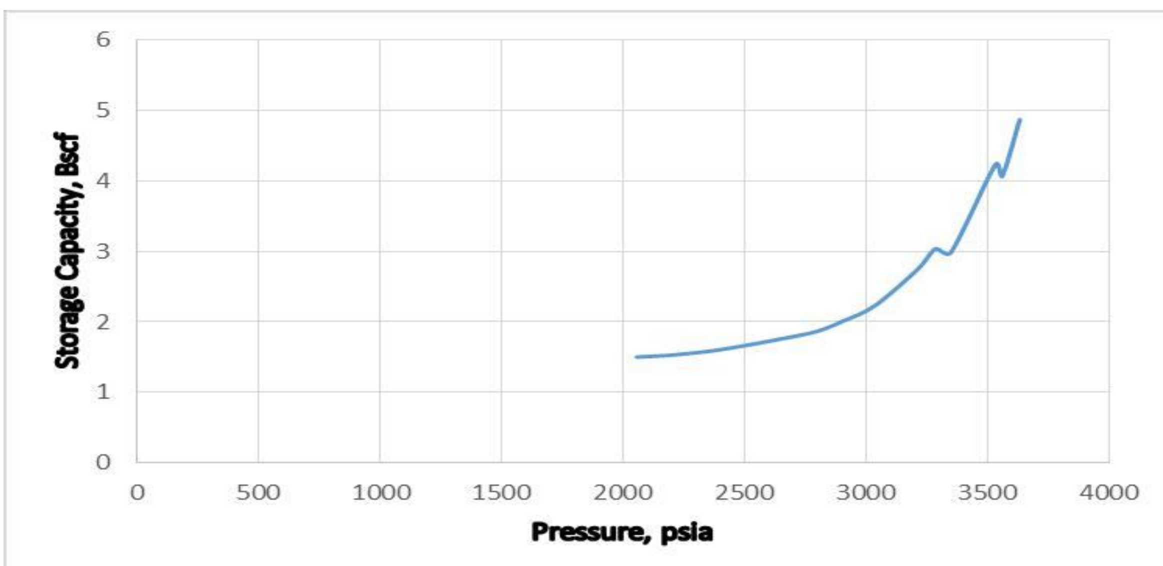

Figure 7. A plot of Volume of gas injected at various pressures for reservoir Z-16T with water influx.

Fig 3.5: 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 = Constant = $2\pi R^2_i h\Phi$ ($C_w + C_p$) B_o = Oil formation volume factor
B_g = Gas formation volume factor
B_{gi} = Initial gas formation volume factor B_w = Water formation volume factor Bscf = Billion standard cubic foot
Bcf = Billion cubic foot
C = Tabulated aquifer function (from time t to time t_i)
DP_i = 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_{eg} = W_e in gas terms, scf
z = Compressibility factor
z_i = Compressibility factor at the initial state
z_{sc} = Compressibility factor at standard condition

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