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Optimizing the Benefits of Conversion of Depleted Oil Reservoirs for Underground Natural Gas Storage in Nigeria

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Abstract

Underground natural gas storage in depleted oil reservoir was examined with reservoir Z-16T located onshore in Nigeria. The geological information and the production history of the reservoir were gathered, which aided in the computation of the storage capacity at a given pressure as well as at various pressures. The plot of well flowing pressure, Pwf against flow rate, Q shows the deliverability of the reservoir at various pressures. The study which its *objectives are to check the suitability of reservoir Z-16T for underground gas storage and to determine the benefits of operating the reservoir as a storage system, shows that the reservoir is ideal for the purpose. The benefits which were derived from the process of operating the storage system include: (1) utilization of the abandoned oil wells of known production histories; (2) recovery of substantial quantities of oil that otherwise might not have been recovered; (3) converting partially depleted oil reservoirs to total depletion types; (4) secondary recovery practice through continuous gas repressuring and repeated gas cycling; (5) producing vaporized oil as natural gas liquids or condensates; (6) preventing the huge wastage of gas through flaring; (7) stopping the greenhouse emission and attracted penalty; (8) utilising already existing facilities*

Key words: Natural gas, depleted reservoir, storage, deliverability, leakage, injection, pressure, benefits, secondary recovery, gas flaring

Introduction

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 J. and Pursell D, 2008). This injected gas is withdrawn from these reservoirs during the first and fourth quarters when demand is at the peak and exceeds supply. Underground natural gas storage acts as the swing capacity due to the seasonal variations in demand.

There are 3 types of reservoirs commonly used for underground gas storage 1) depleted oil/ gas reservoir; 2) aquifer and 3) salt cavern. Each of the storage reservoirs has very specific producing parameters.

Storage in depleted oil reservoirs

This underground gas storage occurs in porous and high deliverability depleted reservoirs, which are close to the consumption centres. 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 (Energy Information Administration, 2002). The requirements for each of the reservoirs vary since no two reservoirs are the same, typically these type of reservoirs require 50% base gas (i.e. equal amount of working gas) and one cycle per season.

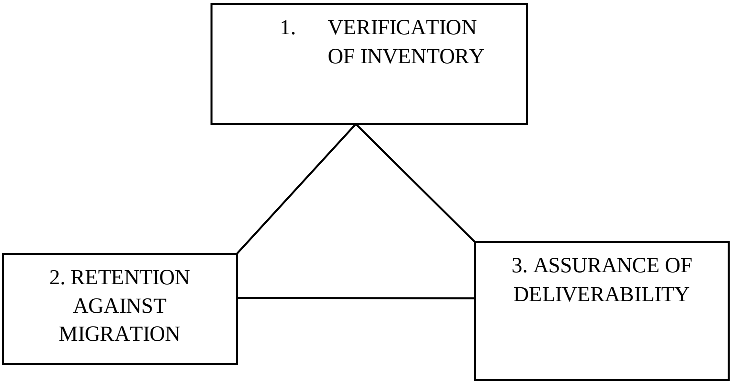


Fig 1: The three basic requirements in underground gas storage, Katz and Tek (1981).

Fig 1 shows the 3 basic requirements in underground storage of natural gas.

1. Verification of inventory: Estimation of the maximum theoretical volume of natural gas that can be cycled in the storage reservoir
2. Retention against migration: Monitoring of the storage system to verify where the gas resides and ensure that losses are not occurring.
3. Assurance of deliverability: To know the measure of the amount of gas that can be withdrawn from the reservoir on a daily basis during withdrawal from the storage capacity

The following steps are followed in designing the storage facility.

- Gathering of geological and engineering information
- Assessing the mechanical condition of the well
- Determining the working storage content (storage capacity) of the reservoir
- Considering compression, field lines, and conditioning of the gas

In order to find the working storage content of the reservoir, range of pressures used must be selected. The upper pressure selected is based upon the information available, particularly the mechanical condition of the well. The pressure range also has much to do with the flow capacity of the well.

According to Katz and Tek (1981), the most essential features of the underground storage facility to be determined by equation (models) are

- Storage capacity (verification of inventory)
- Quantity to be injected at different pressures
- Storage retention against migration and determination of the amount of leakage
- Assurance of deliverability

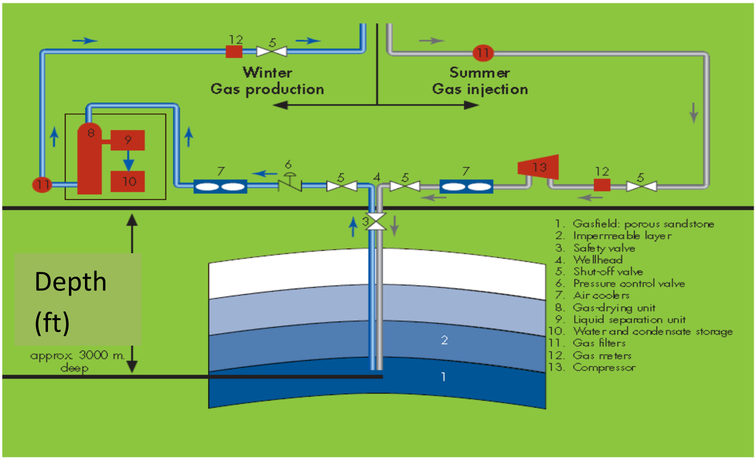
The storage container is a porous solid with a cap rock overhead to prevent vertical migration. Water in the storage zone underlies all or part of the gas-filled sand. Wells designated I/W (Injection and Withdrawal) are completed in the storage zone.

Depleted gas reservoirs are prime candidates for conversion to storage. The size of the reservoir is determined by calculations from geological data or from the oil production reservoir pressures. In considering a depleted oil field, it should be recognized that the gas withdrawal take about 120days in a given year. This requires more wells than used during oil production, and enlarged gathering and injection pipeline system from the well to the central station (Okwananke et al, 2011).

A delivery system can be installed to cover the market demand for the year. Some flexibility is needed, since variation in weather causes varying demands. Storage field pipelines may require some period of reduced load in summer for testing. Natural gas is injected into the porous sandstone through the surface facilities during the period when the demand is low and withdrawn for use during the period when the demand for gas is high. For temperate countries the periods correspond to summer and winter periods respectively.

A delivery system is installed to cover the market demand for the year. The typical injection and withdrawal trend in an oil-depleted underground gas storage reservoir is shown in the Fig 2 below.

Fig 2: Schematic of Natural Gas Storage



Schematic representation of natural gas storage.

Source: Dietert, J. and Pursell D. (2008)

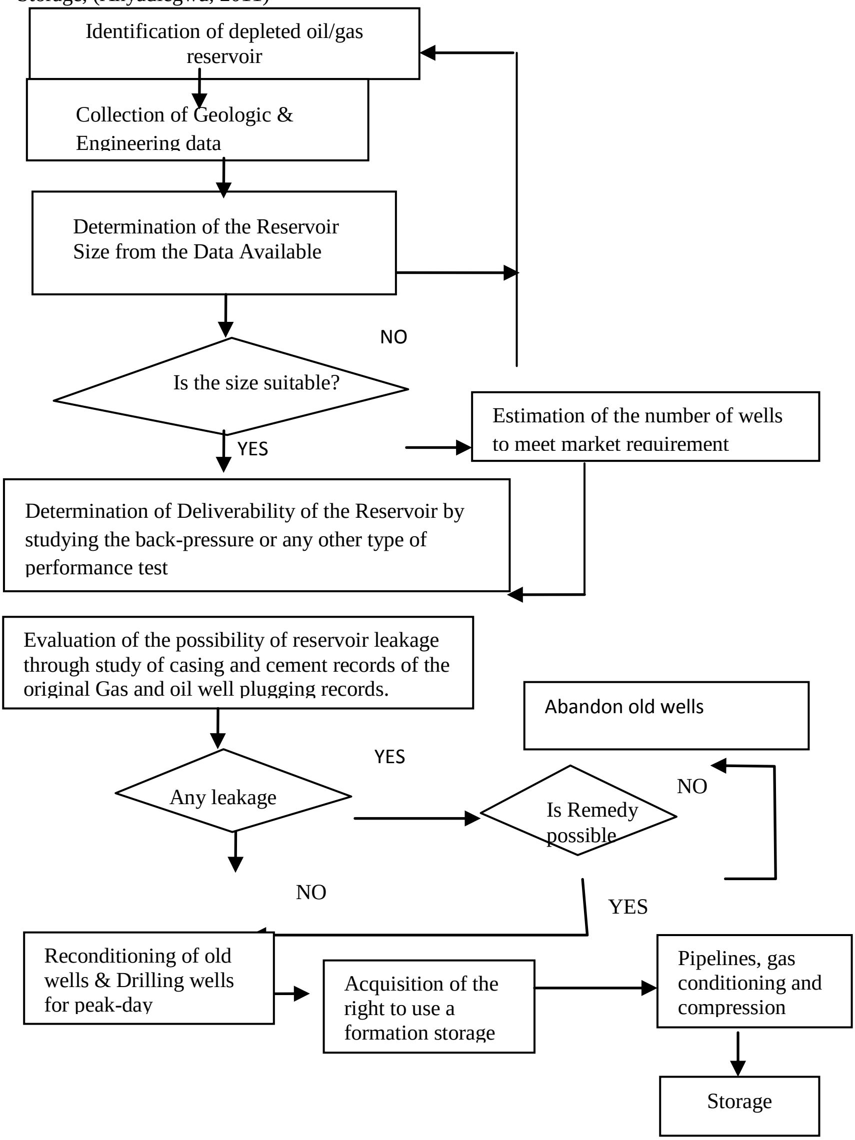
The objective of this work includes the following:

1. Outlining the principles involved in choosing a depleted oil reservoir for underground storage
2. Determining the basic characteristics of the chosen reservoir for underground gas storage
3. Indicating the various benefits derived from operating the storage system obtained through (1) and (2) above.

Procedures for choosing a candidate well for underground gas storage

Fig 3 shows the step-by-step procedure for re-working a depleted reservoir to be utilized for underground gas storage. It involves identification of the reservoir, determination of the reservoir size from the geologic and engineering data, determination of the deliverability and possible leakage from the reservoir, installation of pipelines and compression facilities.

Fig 3: Flow Chart for the Conversion of a Depleted Gas or Oil Reservoir for Natural Gas Storage, (Anyadiegwu, 2011)



Estimation of the volume of gas to be injected into the reservoirs at given pressure (storage capacity)

To determine the volume of gas to be injected at different pressures of the storage reservoir, a volumetric equation as shown below and was used to develop a Microsoft visual basic program for performing the calculation. At each pressure variation, new reservoir parameters, B_o, B_g, R_s and R_p 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 determined below. The total cumulative fluid production from depleted crude oil reservoir is given by the sum of the produced oil, dissolved gas, free gas and produced water. This is represented mathematically as:

Total cumulative production = produced oil + dissolved gas + free gas + produced water 1

The produced oil and dissolved gas are assumed to be produced together as a component given by:

Produced oil + dissolved gas = N_pB_o 2

The other terms of the RHS of equation 1 are defined as

Free gas = $N_p(R_p - R_s)B_{gi}$ 3

Produced water = W_pB_w 4

Substituting equations 2, 3 and 4 into Eqn 1 gives the total cumulative fluid (oil + gas + water) production as:

$$P_{CUM} = N_pB_o + N_p(R_p-R_s)B_{gi} + W_pB_w \quad 5$$

The total cumulative fluid production is in units of barrels of fluid (bbl) and may be converted to standard cubic feet (scf) using Eqn 6

1bbl = 5.615scf 6

For the purpose of underground natural gas storage, the depleted oil/gas reservoir must be reconditioned to contain a volume of gas equal to the volume of total cumulative fluid production (Brown and Sawyer, 1999). This is the amount of natural gas to be injected into the reservoir for storage.

Therefore, the volume of gas to be injected in units of standard cubic feet (scf) into depleted reservoir to fill the space created from withdrawal of oil is given by:

Volume of gas to be injected = V_{inj} x B_{gi} 7

This represents the cumulative production of natural gas from the reservoir. Equating volume of gas injected to total cumulative fluid production to obtain

$$V_{inj}B_{gi}\,(scf) = 5.615(N_pB_o + N_p(R_p\text{-}R_s)B_{gi} + W_pB_w) \quad 8$$

Dividing through by B_{gi}

$$V_{inj}\,(scf) = 5.615(N_pB_o/B_{gi} + N_p(R_p\text{-}R_s) + W_pB_w/B_{gi} \quad 9$$

Storage capacity of the reservoir at a given pressure represents the amount of gas that can be injected into the storage reservoir at that pressure. It helps in the analysis of reservoir storage economics. It also guides the operator to know when the pressure of the storage vessel is at its maximum capacity for inventory verification. This helps in proper monitoring of injection and withdrawal program.

In estimating the storage capacity of the reservoir, reservoir pressure in psig is converted to pressure in psia using Eqn 10

P(psia) = P(psig) + 14.7 10

The reservoir temperature is also converted to degrees Rankine (^{0}R) as in Eqn 11

$^0R = {}^0F + 460$ 11

According to Katz and Lee, (1990), the determination of gas compressibility factor, Z, of the natural gas in storage depends the pseudo-reduced properties of the gas are used.

The pseudo-reduced properties are pseudo-reduced temperature and pseudo-reduced pressure. The values of Z for natural gas mixtures have been experimentally correlated as functions of pressure, temperature and composition. This correlation is based on the well-known Theorem of Corresponding States which states that the ratio of the volume of a particular substance to its volume at its critical point is the same for all substances at the same ratio of absolute pressure to critical pressure, and absolute temperature to critical temperature. This theorem is not completely true but may satisfactorily be applied to compounds of similar molecular structure such as the light paraffins and natural gases. In preparing a correlation for hydrocarbon mixtures, the ratios of actual pressure and temperature to the modal average critical or pseudo-critical pressure, (P_{pc}) and pseudo-critical temperature, (T_{pc}) have been used. These ratios are called pseudo-reduced pressures, (P_{pr}) and pseudo-reduced temperatures, (T_{pr}). Fig 4 is a correlation of Z as a function of these quantities (Ikoku, 1984).

The pseudo-critical pressure and temperature are evaluated using Eqns 12 and 13 respectively.

$$P_{pc} = 709.604 – 58.718 * SG \quad 12$$

$$T_{pc} = 170.491 – 307.344 * SG \quad 13$$

Accordingly, the pseudo-reduced pressure and temperature are determined from Eqns 14 and 15 respectively

$$P_{pr} = P/P_{pc} \quad 14$$

$$T_{pr} = T/T_{pc} \quad 15$$

The following equations were used to estimate B_g, B_o and R_s. The gas formation volume factor is given by Eqn 16 and the oil formation volume factor is given by Eqn 17.

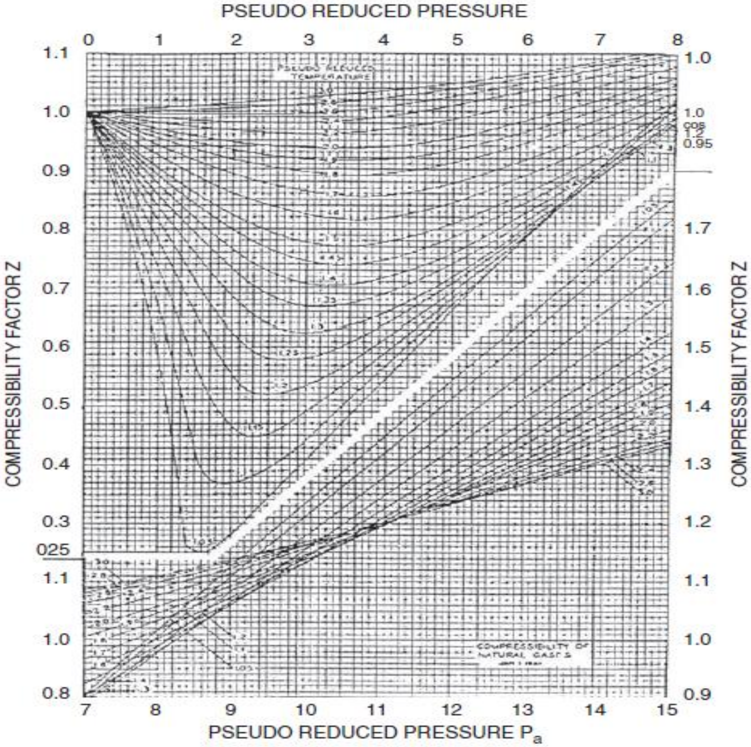


Figure 1-2. Compressibility of natural gases as a function of reduced pressure and temperature (Standing and Katz, 1942).

The gas formation volume factor, B_g, is estimated from Eqn 16

$$B_g = 0.02827\frac{zT}{p}$$

The oil formation volume factor, B_o, is estimated from Eqn 17 (Vasquez and Beggs, 1980).

$$B_o = 1.0 + C_1R_s + (T - 520)\left(\frac{API}{\gamma_{gs}}\right)[C_2 + C_3R_s]$$

The gas-oil-ratio, R_s, is estimated from Eqn 18

$R_s = \square\ \square\ \square_g [(P / 18.2 + 1.4)10^{X}]^{1.2048}$ 18

Where $\square_g$ = gas specific gravity

$\square_{gs}$ = solution-gas specific gravity

With x = 0.0125 API – 0.00091 (T – 460) 19

There is no water production, ie Wp = 0, Eqn 9 becomes:

$V_{inj} = 5.615[N_pB_o/B_{gi} + N_p(R_p\text{-}R_s)]$ 20

This is the volume of gas required to replace the produced oil. It is also called the working gas capacity.

Eqn 20 which is the equation for estimating working gas capacity is converted to the equation for total storage capacity by replacing the cumulative production term, N_p with stock tank oil in place, N.

Volume of gas required to replace the entire producible oil in the reservoir which is the total storage capacity is given below:

$V_{total} = 5.615N[B_o/B_{gi} + (R_p\text{-}R_s)]$ 21

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 as developed using the derived volumetric equation, Eqn, 20 is shown in Fig 5. The program was used to obtain the volume of gas injected into the reservoir at various pressures and presented in Table 2 which was used to make a plot of volume of gas injected against Reservoir pressure.

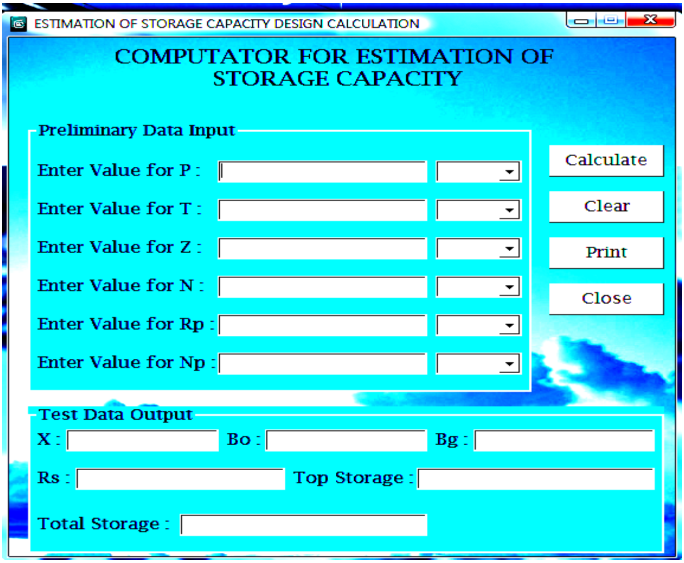


Fig 5: Program computator for estimation of Storage Capacity of reservoir at given pressure

Storage retention against migration and determination of the amount of leakage for the reservoirs

A system of observation wells permits measurements to verify if the injected gas is confined to the designated area and has not migrated away.

When there is leakage, the amount of leaked gas is estimated by applying the Eqn 22 below.

$$\text{Amount of Leakage} = [P_1/Z_1 - P_2/Z_2] * V_1Z_1/P_1 \qquad 22$$

Initial volume, V_1 here represents maximum storage capacity of depleted reservoir. Pressure was varied for several cases to obtain new Z-factors (Z_1 and Z_2) in each case.

A Microsoft Visual Basic Program was developed using Eqn 22 for the amount of leakage. The sample of the Microsoft visual basic program for the determination of amount of leakage from reservoirs is as shown in Fig 6

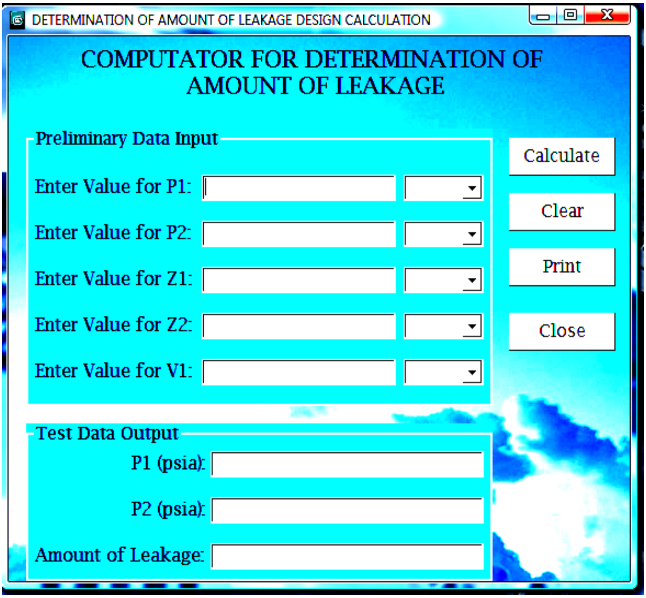


Fig 6: Program computator for determination of amount of leakage at given pressure drop

Performance and deliverability of reservoir

In evaluating the performance of a storage reservoir, a deliverability test (back pressure test) is carried out on the reservoir for the prediction of well flow rate against any pipeline back pressure. It has been observed that a plot of $P_R^2 - P_{WF}^2$ (difference of the squares of reservoir pressure and well flowing pressure) versus Q_{sc}, (flow rate at standard condition) yields a straight line on logarithm plot, which represents the reservoir performance curve.

The straight line relationship for a particular well applies throughout the lifetime of the well, as long as the production remains in single phase (gas or liquid). The back-pressure (deliverability) equation as developed by Rawlins and Schellhardt (1935) is expressed as:

$$Q_{sc} = C\,[P_R^2 - P_{WF}^2]^n = C\,[\square\,\square\,P^n] \quad (23)$$

C is the reservoir flow coefficient and

n is the inverse of the slope of the curve.

By extending the performance curve, the absolute open flow, (AOF) is obtained. Although this AOF does not reflect reality, it does approximate the capacity of the well.

The slope of the plot of Log $(P_R^2 - P_{WF}^2)$ versus Log Q is computed and used to obtain the back-pressure exponent as:

$$n = 1 / slope \qquad 24$$

Also the flow capacity at standard condition is given as:

$$Q_{sc} = C\,[P_R^2 - P_{WF}^2]^n \qquad 25$$

At $P_{WF} = 0$, equation 25 reduces to:

$$Q_{sc} = C\,[P_R^2]^n \qquad 26$$

But the reservoir flow coefficient, C is expressed as:

$$C = \frac{Q}{[P_R^2 - P_{WF}^2]^n}$$

According to Katz and Coats (1968), flow tests on individual wells are employed for gas storage obtained as in gas production operations. From gas inventory and/or reservoir pressure measurements plus deliverability data, it is possible to predict the field flow at several stages of the storage cycle. The performance of storage reservoirs become less predictable during high withdrawal rates due to pressure sinks which develop as a result of heterogeneities. Another problem of continuing interest relates to interference by water reaching the wellbore. The presence of water not only reduces the permeability to gas but also effectively cuts down the bottomhole pressure drawdown available for gas flow due to increased density of well fluid. For aquifers, water interference problems are likely to subside as the gas bubbles thicken with growth in stored gas. Each reservoir and set of wells must be tested to give assurance for future years with regard to which well will have water intrusion at a given stage of the withdrawal cycle. Deliverability of storage wells after several years of repetitive use decreases as a result of sand face contamination.

In gas storage reservoirs, injection pressures of approximately 0.55 psi/ft are often used, but pressures as high as 0.7 psi/ft have been used. In other words, an approximate injection rate can be estimated using the relationship below (Katz and Coats, 1968).

$P_{inj} \propto I_{rate}/hk,$ 28

A Microsoft Visual Basic Program was developed using Eqn 23, and was used to obtain the deliverabilities of the depleted reservoir, Q (MMscf/d) at different well flowing pressures, P_{wf} (psig) and presented in Table 3 which was used to make a plot of P_{wf} against Q. The sample of the Microsoft visual basic program for the evaluation of deliverability from reservoirs is as shown in Fig 7.

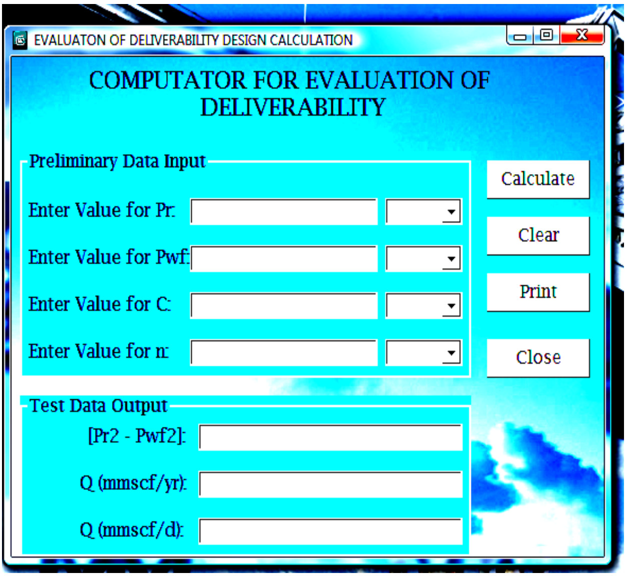


Fig 7: Program computator for evaluation of deliverability at given well flowing pressure

Depleted Reservoir Z-16T

Reservoir Z-16T is a depleted crude oil reservoir located onshore, South-East, Nigeria. The reservoir and fluid data is shown in Table 1 below.

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

Discovery pressure, P	3955 psig
Saturation pressure	3002 psig
Reservoir temperature, T	216^{o}f
Stock tank oil initial in place, N	1.2444 MMstb
Cumulative oil produced, Np	0.5825 MMstb
Initial oil formation volume factor, Boi	1.405
Specific gravity, SG	0.9
Thickness, h	80 ft
Porosity, Ø	0.25
Initial oil water saturation	20 %
Permeability, k	30 MD
Well depth, D	11 000 ft
Oil API gravity	26 ^{0}API
Remaining gas in formation	7.01 Bscf

Estimation of Storage Capacity of Reservoir Z-16T using Microsoft Visual Basic Program

The values of Pressure (P), Temperature (T), Stock tank oil in place (N) and Cumulative oil production (Np) and Gas-oil ratio (Rp)were obtained from Tables 1 and 2 while the compressibility factor (Z) is the compressibility factor of the gas at the given pressure of 3955psig. These values were input into the program to obtain the storage capacity of reservoir Z-16T as shown in Fig 8.

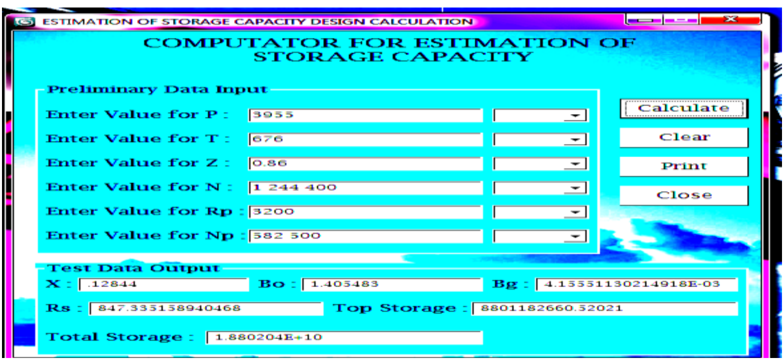


Fig 8: Storage Capacity of reservoir Z-16T at a pressure of 3955psig

The volume of gas to be injected at various reservoir pressure are presented in Table 2 which is used to obtain the plot of the storage capacities at various injection pressures as shown in Fig 9.

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

P (psig)	Np (MMstb)	Bg (scf/scf)	Bo (rb/stb)	Rs (scf/rb)	Rp (scf/rb)	Vinj (Bscf)
3955	0.582458	0.004156	1.405446	847.2412	3200	8.8008221
3900	0.607124	0.004214	1.399941	833.157	3440	10.16050424
3782	0.811398	0.004346	1.388184	803.0767	3960	16.5628319
3534	0.908459	0.004651	1.363718	740.4834	4980	25.87601973
3350	1.406055	0.004906	1.34579	694.6139	6030	52.2869859
3288	1.823687	0.004998	1.339793	679.2715	10010	118.2306619
3212	2.468388	0.005117	1.332473	660.5449	11540	190.1140618
3199	2.847551	0.005138	1.331225	657.3506	11980	228.9435032
2922	3.187355	0.005625	1.304872	589.9283	12570	295.8255308
2881	3.590383	0.005705	1.301013	580.0558	13990	377.4371605
2857	4.099377	0.005753	1.298759	574.29	15000	466.8585916
2767	4.852182	0.00594	1.290342	552.7562	17560	670.7650069
2427	5.463045	0.006772	1.259058	472.7173	18980	934.4265758
2237	5.878718	0.007347	1.241952	428.9518	20870	1202.798298
2145	6.446661	0.007662	1.233772	408.0254	21880	1443.844736
2057	6.957614	0.00799	1.226015	388.1781	23190	1724.267519

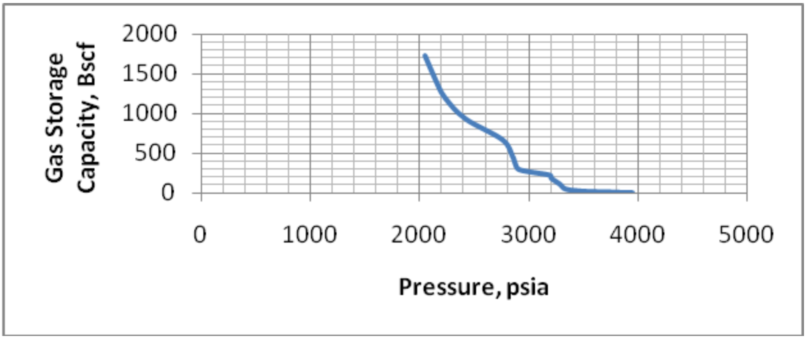


Fig 9: A plot of volume of gas to be injected at various pressures for reservoir Z-16T.

Determination of Amount of Gas Leakage at various Pressure drops of Reservoir Z-16T using Microsoft Visual Basic Program

The values of Initial Pressure (P_1), Final Pressure (P_2) and Initial Volume (V_1) were obtained from Table 2 while the compressibility factors Z_1 and Z_2 are the compressibility factors of the gas at the pressures of 3955psig and 3900psig respectively. These values were input into the program to determine the amount of leakage from reservoir Z-16T as shown in Fig 10.

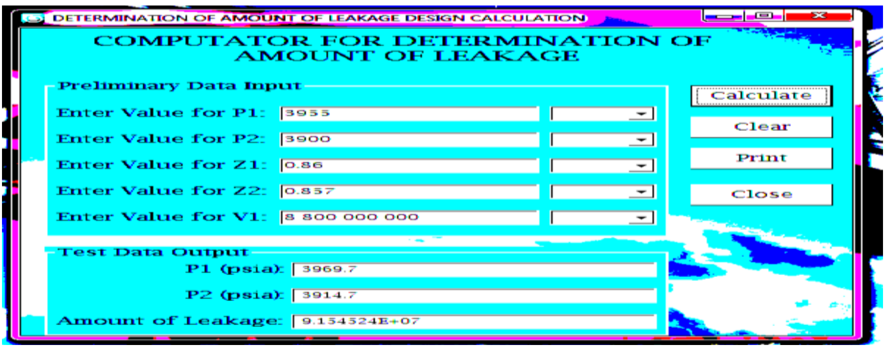


Fig 10: Amount of Leakage at a pressure drop from 3955psig to 3900psig

Evaluation of the Deliverability of Reservoir Z-16T at Given Well Flowing Pressure using Microsoft Visual Basic Program

The values of Reservoir Pressure (P_r), Well Flowing Pressure (P_{wf}) were obtained from Tables 1 and 3 while the values of the Reservoir Flow Coefficient (C) and Back-pressure Exponent (n) are the flow coefficient and back-pressure exponent at well flowing pressure of 3900psig. These values were input into the program to determine the deliverability of reservoir Z-16T as shown in Fig 11.

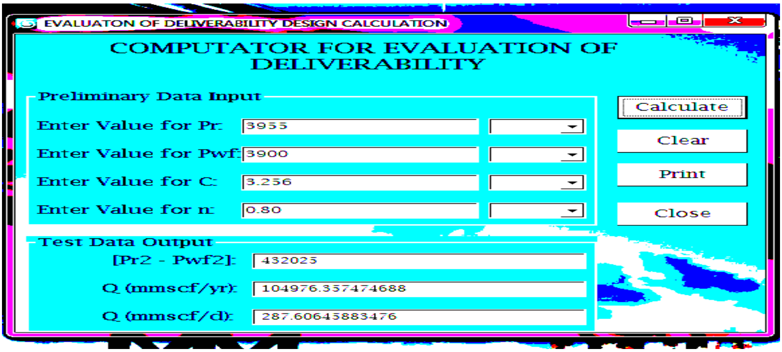


Fig 11: Deliverability at well flowing pressure of 3900psig

Table 3: Deliverability of Reservoir Z-16T

P_{wf} (psig)	P_{wf}^2 (psig^2)	P_R^2-P_{WF}^2 (psig^2)	Q (MMscf/yr)	Q (MMscf/d)
3900	15210000	432025	104976.3575	287.6064588
3700	13690000	1952025	350810.5913	961.1249075
3500	12250000	3392025	545822.7482	1495.40479
3300	10890000	4752025	714804.651	1958.368907
3100	9610000	6032025	865077.2729	2370.07472
2900	8410000	7232025	1000212.623	2740.308556
2700	7290000	8352025	1122322.901	3074.857263
2500	6250000	9392025	1232797.622	3377.527733
2300	5290000	10352025	1332614.842	3650.999567
2100	4410000	11232025	1422495.317	3897.247444
1900	3610000	12032025	1502987.528	4117.774049
1700	2890000	12752025	1574518.329	4313.748846
1500	2250000	13392025	1637424.926	4486.095689

1300	1690000	13952025	1691975.978	4635.550625
1100	1210000	14432025	1738385.994	4762.701353
900	810000	14832025	1776825.406	4868.01481
700	490000	15152025	1807427.721	4951.856769
500	250000	15392025	1830294.625	5014.505821
300	90000	15552025	1845499.589	5056.163257
100	10000	15632025	1853090.327	5076.959799

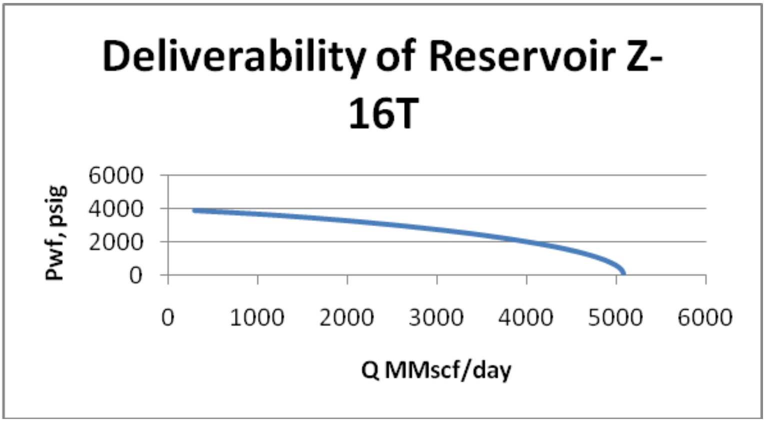


Fig 12: A Plot of Well Flowing Pressure versus Deliverability

The deliverabilities of reservoir Z-16T at various withdrawal pressures are presented in Table 2 which is used to obtain the plot of the deliverabilities at various well flowing pressures as shown in Fig 12.

Results

Fig 9 represents the volume of gas to be injected at various pressures for Z-16T that is the storage capacity of the reservoir as estimated using the visual basic program as shown in Fig 8. At the discovery pressure of 3955 psig, the volume of gas to be injected into Z-16T is 8.8 Bscf as indicated in Table 2. Between the pressures of about 2700 psia and 3364 psia, the volume of gas to be injected were 720 Bscf and 52.29 Bscf respectively. It is shown that at these pressures, the shape of the graph changed which maybe as a result of the oil produced, Np not increasing consistently at those pressure intervals.

Fig 10 represent the Microsoft Visual Basic Program used in determining the amount of leakage in reservoir Z-16T. When the pressure of reservoir Z-16T dropped from its discovery pressure of 3955 psig to 3900 psig, the amount of gas leaked out of the reservoir is 91.5 MMscf.

Fig11 represent the deliverability of Z-16T during gas withdrawal. At the initial well flowing pressure of 3900 psig the amount of gas to be delivered from the reservoir is 287.606 MMscf/d as shown in Table 3. The deliverability of Z-16T at any pressure was determined using the developed Microsoft Visual Basic computer program as shown in Fig 12.

Benefits of Underground Natural Gas Storage in Depleted Oil Reservoirs

1. Use of reservoirs of known production histories

Using depleted oil reservoirs for underground storage of natural gas is beneficial since it makes use of oil reservoirs that have already been produced. The production history of the reservoir is also known. These known histories include static and flowing bottom hole pressures, Gas-oil ratio (GOR), oil flow rate, permeability and storage retention, deliverability etc. With these data known to the project manager or the engineer, there would be little or no need for well test analyses, pressure tests, production tests, core analysis and many other tests conducted in new wells before operation. This will reduce the costs of exploration and production of new wells for underground natural gas storage.

2. Recovery of oil that might not have been recovered

Another benefit of underground storage of natural gas in depleted oil reservoir is that it helps in the recovery of substantial quantities of oil that otherwise might not have been recovered. Generally, when the natural energy in the reservoir derivable from aquifer expansion, oil expansion or gas expansion, is no more sufficient to produce oil from the reservoir, the reservoir is abandoned as a depleted oil reservoir together with the remaining amount of oil in the reservoir. About 0.6615 MMstb of oil still remains in reservoir Z-16T as unrecoverable oil (Anyadiegwu, 2011). As it is then converted to facility for underground storage of gas, gas would be injected into the reservoir for storage, as injection of gas occurs some quantity of oil is displaced from the reservoir. This quantity of oil could not have been produced if the reservoir were not considered for underground storage of natural gas.

3. Increased storage capacity of reservoir

Using depleted oil reservoir for underground gas storage also helps in the achievement of large storage capacity for natural gas. The oil reservoir considered for storage of gas is partially depleted because not all the stock tank oil in place had been produced. As gas is being injected into the reservoir and withdrawn, oil is produced along, at a time the whole oil would have been produced, the partially depleted oil reservoir would then be totally depleted and more space is created for more storage of gas. This means an increase in the storage capacity of the reservoir for gas storage

4. Secondary oil recovery

Using depleted oil reservoir for underground gas storage is also a secondary oil recovery practice if viewed from another angle. The injection of gas into the reservoir for storage causes gas repressuring, this gas repressuring and repeated gas cycling in the reservoir results in the production of highly volatile crude oil from the reservoir. Repressuring is the method by which the pressure inside a crude oil well is increased so as to increase the output of the well. Producing crude oil from a reservoir causes its pressure to drop, which further reduces productivity. Returning or injection of the natural gas or other inert gases to the oil well increases the productivity of the crude present inside the well by decreasing its viscosity and density. The viscosity and density of the oil decreases to an extent that it becomes highly volatile. Highly volatile oil is also called light crude oil. Light crude oil is liquid petroleum that has a low density and flows freely at room temperature. It has a low viscosity, low specific gravity and high API gravity due to the presence of a high proportion of light hydrocarbon fractions. It generally has a low wax content. Light crude oil receives a higher price than heavy crude oil on commodity markets because it produces a higher percentage of gasoline and diesel fuel when converted into products by an oil refinery.

5. Recovery of condensate or Natural Gas Liquids

As the viscosity of the oil in the reservoir is reduced, part of the volatile oil vapourises and it is produced and recovered at the surface as natural gas condensate. Natural gas condensate is a low-density mixture of hydrocarbon liquids that are present as gaseous components This gas is separated into its components of this gas condensate are natural gas liquids (NGL). NGL's are an aggregate of heavier gaseous hydrocarbons: ethane (C_2H_6), propane (C_3H_8), normal butane (n-C_4H_{10}), isobutane (i-C_4H_{10}), pentanes and even higher molecular weight hydrocarbons. Natural gas liquids have wide uses, such as: cooking gas, vehicle fuel (LPG) and ethane which is used as petrochemical feedstock for ethylene production, butane can also be used as refrigerant, and so forth.

6. Check greenhouse emission

Conversion of depleted oil reservoirs to underground storage facility helps to prevent huge loss of gas through flaring of gas. Without gas storage, gas that is produced from gas reservoirs would be flared and that entails wastage of gas that could have been sent to the end users for industrial or domestic use.

Another environmental and ecological issue here is the combating of greenhouse effect. Continuous flaring of gas aids greenhouse effect. The greenhouse effect is a process by which thermal radiation from a planetary surface is absorbed by atmospheric greenhouse gases, and is re-radiated in all directions. Since part of this re-radiation is back towards the earth's surface, energy is transferred to the surface and the lower atmosphere. As a result, the temperature there is higher than it would be if direct heating by solar radiation were the only warming mechanism. Solar radiation at the high frequencies of visible light passes through the atmosphere to warm the planetary surface, which then emits this energy at the lower frequencies of infrared thermal radiation. Infrared radiation is absorbed by greenhouse gases, which in turn re-radiate much of the energy to the surface and lower atmosphere which results in global warming.

A greenhouse gas is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect. The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane (natural gas), nitrous oxide, and ozone.

7. Saves operator from paying huge penalty of flaring

From the economic standpoint, when gas is flared there is loss of income and even at present, in most countries, companies pay penalty for flaring gas. In Nigeria, the flare penalty is \$3.5/1000 cu.ft, so the operating company would pay a penalty of \$3.5 for every thousand cubic ft of gas flared (Eboh, 2009).

For reservoir Z-16T that has a working gas capacity of 8.8 Bcf, if the company flares about 50% of the gas produced, it would be losing a huge sum of money:

Then, estimated penalty=

$= \$3.5/1000 \times 50/100 \times 8.8 \times 10^9$

= \$15.4 million

8. Use of already existing facilities

Utilizing depleted oil reservoirs for storage of gas is highly economical as the operating company will not install new facilities for underground gas storage, there are already existing facilities in the site. The previous facilities used in the site for oil production could also be used for the injection and withdrawal of gas. This reduces the installation of new flowlines, compression facilities and other conditioning facilities.

Conclusion

At the end of this study it has shown that reservoir Z-16T if reconditioned will be suitable for underground natural gas storage. The injection and withdrawal of gas from the reservoir can produce large portion of the remaining oil which was termed unrecoverable. Storage of gas in reservoir Z-16T serves two purposes: underground natural gas storage and secondary oil recovery practice.

Generally, the use of depleted reservoir for underground gas storage is highly viable.

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NOMENCLATURE

API = American Petroleum Institute

bbl = Barrel

B_o = Oil formation volume factor

B_g = Gas formation volume factor

Bscf = Billion standard cubic foot

B_w = Water formation factor

C = Reservoir flow coefficient

MMSTB = Million stock tank barrel

MMscf = Million standard cubic foot

n = Back-pressure exponent

N = Stock tank oil-in-place

N_p = Cumulative oil production

P_1 = Initial pressure of reservoir

P_2 = Final pressure of reservoir

P_{pc} = Pseudo-critical pressure

P_{pr} = Pseudo-reduced pressure

P_r = Reservoir pressure

psia = Pounds per square inch (atmospheric)

psig = Pounds per square inch (gauge)

P_{wf} = Well flowing pressure

Q = Flow rate

Q_{sc} = Flow rate at standard condition

R_s = Gas solubility

R_p = Gas-oil-ratio

scf = Standard cubic foot

SG = Specific gravity

T_{pc} = Pseudo-critical temperature

T_{pr} = Pseudo-reduced temperature

V_{inj} = Volume of gas injected

V_1 = Initial volume of gas

V_2 = Final volume of gas

Z = Gas compressibility factor

Z_1 = Initial gas compressibility factor

Z_2 = Final gas compressibility factor

^0F = Degree Fahrenheit

^0R = Degree Rankine