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EVALUATION AND PERFORMANCE OF NATURAL GAS STORAGE IN DEPLETED GAS RESERVOIRS

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Abstract

Natural gas can readily be stored in depleted gas reservoirs, but when under storage in the storage horizon, this gas may experience some anomalies that may affect its inventory and performance. Evaluation and performance of the natural gas stored was determined by inventory analysis and by primary depletion performance. This made use pressure-content plots of P/Z versus inventory to determine gas migration into or away from the storage reservoir and its magnitude. The optimal performance of the stored gas was carried out by comparing the various stored volumes, the amount of non effective gas present and how much of it could be recovered. This was done for the storage reservoir when it was not subject to gas gain or loss, when it was subject to gas loss and when it was subject to gas gain. It was shown that gas storage in depleted gas storage reservoir subjected to gas gain is the best form of underground natural gas storage.

Key words: Underground gas storage, evaluation, performance, pressure-content, inventory.

1. Introduction

Natural gas, a colorless, odourless gaseous hydrocarbon, like most other commodities can be stored for an indefinite period of time. There are three major reasons why natural gas is stored; meeting seasonal demand requirements, insurance against unforeseen supply disruptions, or just as a means of conservation.

Natural gas can be stored in the following ways; storage in pipelines, underground storage in depleted oil or gas fields, underground storage in aquifers, storage under high pressure in steel reservoirs, storage by natural gas solution in propane, liquefied natural gas (LNG) storage.

Among these storage options, underground storage either in depleted oil/gas reservoirs or aquifer offers the best option in terms of cost [1,2]. Long term demand variations require large storage of natural gas. These seasonal demand variations can be met in two ways: peak-load plants which can be brought quickly into operation and as swiftly shut down and underground natural gas storage if naturally occurring features exists in the area of interest [1]. For economic reasons gas utilities, gas pipelines, gas producers and large ultimate gas consumers store gaseous fuel underground all over the world.

1.1 Depleted gas reservoir

The most common underground gas storage facilities are those that use deep underground natural gas reservoirs that have been depleted through earlier production. These reservoirs are naturally occurring and their potential as secure containers have been proven over the millennia that the reservoirs held their original deposits of natural gas.

An underground gas storage reservoir is a permeable underground rock formation that is confined by impermeable rock and/or water barriers and is identified by a single natural formation pressure. Depleted gas reservoirs are prime candidates for storage. They are normally pressurized back to their original discovery pressure when they are converted to storage reservoirs.

Gas fields at discovery have average pressures of 3000 psia, in the tune of 0.43 – 0.52 psi per foot f depth. The highest pressure level normally will provide the maximum storage capacity and the wells will have the highest flow capacities. As gas is pumped in, the reservoir pressure rises and as gas flows out, the rate of the gas flow decreases as does the pressure and thus the energy is depleted.

However, if a good cap rock is present, a top storage pressure higher than the discovery pressure (overburden pressure) of up to 0.7 psi per foot of depth or 100- 200 psi above virgin pressure can be considered. A storage top pressure above the discovery pressure should not be selected when the cap rock is thin or when mechanical conditions are questionable [3]. Before developing gas storage in a depleted gas field, it is indispensable to check whether it corresponds to required withdrawal rate and imperviousness of the cap rock.

1.2 Evaluation of inventory

The amount of natural gas in storage in a depleted gas reservoir at any point in time is the inventory. Traditional inventory verification are based on real gas law

$$PV = ZnRT \tag{1}$$

Inventory analysis is a way to keep track of the amount of gas in the storage field. It reconciles the inventory that is actually in the storage horizon with the value carried by gas accounting "book value". Evaluation of inventory is generally approached by two independent concepts: volumetric and depletion. The volumetric formula

$$Q = (Gas\ pore\ volume)\left(\frac{PT_b}{P_bTZ}\right) \tag{2}$$

is sensitive to changes in the variables involved in the equations. Therefore when calculating the amount of gas stored in a depleted gas reservoir, care must be taken to compensate for the disparity in porosity as it occurs throughout the reservoir.

Once the geological information as to the productive area, thickness of the payzone, porosity and water saturation is established, equation 2 above evolves to

$$Q = Ah\phi\left(\frac{PT_b}{P_bTZ}\right)(1 - S_w) \tag{3}$$

1.3 Performance of a depleted gas reservoir

The performance of a depleted storage gas reservoir is evaluated by the depletion concept based on pressure measurement of the natural gas stored. Closed pressure measurements for a period of 3 to 15 days or more are used for all wells, normally when at maximum or minimum storage pressure. The performance of a depleted gas storage reservoir determines the deliverability. The deliverability depends on pressure, a function of volume of the gas in storage. The pressure content plot monitors how the reservoirs act during storage.

2. Review of literature

Historical records show that underground storage of natural gas has been available almost as long as long distance pipelines. In 1915, natural gas was first successfully stored underground in Welland County, Ontario, Canada. Several wells in a partially depleted gas field were reconditioned and gas was injected into the reservoir during the summer and withdrawn the following winter. By 1930, nine storage sites in six different states in the US were in operation with a total capacity of about 18 billion cubic feet (Bcf). Before 1950, essentially all underground gas storage consisted of reused partially or fully depleted gas reservoirs. Early growth of UGS was slow as the gas industry grew at a slow pace, but by the late 1960's there was significant growth and rapid expansion of storage continued to develop into the seventies. By 1975, 376 pools were in use storing a total of 6644 Bcf of gas.

In 1997, there were 580 UGS sites worldwide, of which 448 were in depleted reservoirs. In 2006, of the estimated 606 UGS sites, the number in depleted reservoirs had grown to 495 [4].

According to Knepper [5], a partially depleted oil field has many characteristics of a partially depleted gas field when they are both being used as UGS site. The same procedures of development and operation apply. Depleted oilfields however do create some problems not encountered in gas fields. Bennion et al.[6] pointed out that of all the types of UGS available, depleted gas reservoir are on the average the cheapest, the easiest to develop, operate and maintain.

Tek [7] hinted that the factors that determine whether or not a depleted gas reservoir will make a suitable storage facility are both are both geographic and geologic. Geographically, depleted gas reservoirs must be relatively close to consuming regions. They must also be close to transportation infrastructure including truck, pipelines, and distribution systems. While depleted gas reservoirs may be numerous, they are more abundantly available in producing regions. Geologically, depleted gas formations must have high permeability and porosity. The porosity of the formation determines the amount of natural gas that it may hold, while its permeability determines the rate at which natural gas flows through the formation, which in turn determines the rate of withdrawal and injection of the working gas.

In order to maintain pressure in depleted gas reservoirs, about 50 percent of the natural gas in the formation must be kept as cushion gas. However, depleted gas reservoir having already been filled with natural gas and hydrocarbons, do not require the injection of what will become physically unrecoverable gas; that gas already exists in the formation [8].

Bennion et al. [6] noted that the performance of a storage facility is variable, and depends on factors such as the amount of gas in the reservoir at any particular time, the pressure within the reservoir, compression capability available to the reservoir, the configuration and capabilities of surface facilities associated with the reservoir and other factors. In general, a UGS facility's performance varies directly with the total amount of gas in the reservoir: it is highest when the reservoir is full and declines as working gas is withdrawn.

Katz [9] used material balance as an expression of conservation of mass; the amount of mass leaving a control volume is equal to the amount of mass entering the control volume minus the amount of mass accumulated in the control volume. He used reservoir pressure measured over time to estimate the volume of hydrocarbon remaining.

Wells et al. [10] established that the continuity equation in the storage system at any point in time imposes that:

Rate of mass in – rate of mass out + source or sink rate = rate of accumulation of mass.

Wallbrecht [4] recognized that the pressure/volume performance of a reservoir during storage exhibited attributes of a "leaking tank" when compared to its primary depletion performance. He quantified the suspected leak both in terms of rate/volume, cause and impact on future operations.

Tek [7] provided actual or measured storage performance. It was provided in the form of P/Z versus cumulative gas production G_p plot. In this case, G_p was replaced by stored gas inventory. Initial inspection of this performance revealed a profile which was not to be expected based on previous primary performances.

Aminian and Brannon [11] evaluated a depleted gas-condensate reservoir for gas storage. They used the Peng-Robinson Equation of State (PE-EOS) to predict the liquid yield during storage cycle. They also used the PE-EOS to predict liquid yield for several separator pressures. They considered several cases without complete mixing to study the impact of mixing on liquid yield. The results were then used to design surface facilities.

Bagci and Ozturk [12] carried out a performance analysis of horizontal wells for underground gas storage in depleted gas fields. They examined five scenarios for forecasting of injection and withdrawal performance of the reservoir using five newly drilled horizontal wells with a combination of existing vertical wells. With a predetermined injection rate of 65MMscf/day, they observed that five horizontal injector-five vertical producer wells arrangement was the most successful in handling the gas inventory. The injection and production periods were 5 months and 7 months respectively.

3. Methodology

3.1 Inventory analysis

Inventory represents the total volume of the natural gas in the storage reservoir at any point in time. It represents the sum total of native gas and injected gas. It varies from a minimum value at the conclusion of withdrawal to a maximum value at the conclusion of injection. The total volume of gas in a storage reservoir can be segmented into the following parts:

Working gas (Top gas)

This is the volume of gas that is injected and produced during the storage cycles. It is the regularly injected and withdrawn gas each cycle. The amount of working gas is determined by metering gas in and out of storage reservoir. The injection cycle period for depleted gas reservoirs is about 200 to 250 days, while the withdrawal cycle is about 100 to 150 days.

Cushion gas (Base gas)

This is the permanent volume of gas needed to fill the reservoir to a point where the pressure in the reservoir will provide significant flow of gas when needed. It is that gas that is left behind at all times in the reservoir during storage operations. It is usually 30 to 50 percent of the total inventory.

Physically unrecoverable gas

This is the gas that is trapped by physical forces in the pores of the rock. It cannot be removed regardless of how low the well head pressure is dropped.

3.2 Volumetric estimation of gas stored in a depleted gas reservoir

In deriving the estimate of gas stored in a depleted gas reservoir, the following assumptions were made:

- A constant volume storage reservoir, with no change in gas pore volume due to water influx or compaction
- Residual gas present in the connate water in the storage horizon
- Provision for compensation for disparity in porosity as it occurs throughout the reservoir
- Average reservoir pressure was used
- Base gas is 40 percent of total inventory

Gas content to present gas/water contact

$$G_{gwc} = 43560 A_g h_g \emptyset \left(\frac{P}{Z}\right)\left(\frac{T_b}{P_b T}\right)(1 - S_w) \tag{4}$$

Residual gas content in water

$$G_r = 43560 A_w h_w \emptyset \left(\frac{P}{Z}\right)\left(\frac{T_b}{P_b T}\right) S_g \tag{5}$$

Total gas content in storage

$$G = G_{gwc} + G_r \tag{6}$$

If the measured inventory is not equal to total gas content in storage G in equation 6, it implies the presence of non-effective gas.

3.3 Non-effective gas (NEG)

This is a volume of gas that the books indicate is stored in the reservoir, but has no apparent significant impact on the performance of the storage facility. NEG may be the result of gas that was actually injected (present but not effective during storage or not present as a result of migration away from the reservoir). NEG may also be as a result of gas that was not actually injected.

NEG volumes may be positive or negative, recoverable or non-recoverable. For NEG>0, there is gas loss. Foe NEG<0, there is gas gain. For a storage reservoir subject to loss or gain in inventory, the NEG can be determined from a plot of P/Z versus inventory.

3.4 Determination of non-recoverable gas

The amount of non-recoverable gas is of interest in storage reservoirs since it has to do with the mechanics of storage reservoirs. Abandonment pressure varies for different gas fields. Common abandonment pressure values are in the range of 50 – 100 psi. The non-recoverable gas content of a field is the gas that is left at the abandonment pressure.

In water drive gas reservoirs or aquifer storage projects, water will flush a portion of the reservoir while gas is being removed below the original aquifer pressure. Such invading water will trap the gas at the prevailing pressure.

In abandoning a field, it is assumed that gas will be produced from the wells following a withdrawal period. Water from the aquifer will enter the reservoir, interfering with well operation. At some point, it will become non-economical to continue production and the reservoir will be abandoned. At abandonment, the reservoir is divided into three portions. The first is the low pressure gas space at the crest of the reservoir, from which the last gas is withdrawn. This layer must be thick enough to permit gas production from a group of wells without interference from advancing water. The other two parts of the reservoir are the parts that have been invaded by water which has residual gas saturation and the bypassed reservoir sand below the level of the advancing water front.

The calculation of the non-recoverable gas includes these three portions of the reservoir and the gas that has dissolved in water contacted by gas at any different time during operation.

The non-recoverable gas is given by the expression

$$Q_m = V_{ab}(1 - S_w)\frac{1}{B_g} + (V_{max} - V_{ab})(1 - S_w)(1 - F_{sw})\frac{1}{B_{g,m}} + (V_{max} - V_{ab})F_{sw}S_{gr}\frac{1}{B_{g,m}} + Q_s \quad (7)$$

The first term on the R.H.S. of equation 7 above represents the gas content for the unflooded zone above the gas-water contact at abandonment. The second term on the R.H.S. of equation 7 represents the gas content of the no-swept or bypassed zone below the gas water contact and the third term represents residue gas content for the swept portion.

3.5 Evaluation and performance of gas storage in depleted gas reservoir

The evaluation and performance based on the volumes of gas sections in the storage reservoir was determined on plots of P/Z versus inventory for the storage reservoir when it experienced no loss in inventory and when it experienced gain in inventory. Comparison was done between the ratios of the working gas volume to the total inventory and the ratios of the working gas volumes to injected base to estimate the performance.

4. Data presentation and analysis of results

For a hypothetical gas storage reservoir's recorded historical data, the following results were obtained from plots of P/Z versus inventory on Cartesian coordinates for the following cases:

Case 1 Volumetric (constant volume) storage reservoir subject to no gas loss or gas gain

For a volumetric (constant volume) storage reservoir, pressure-content plot was represented by a straight line. The slope of this line is inversely proportional to the pore volume of gas bubble. The plot of P/Z versus inventory for the volumetric reservoir expressed the amount of inventory that had to be left in or injected into the storage horizon for corresponding P/Z values. In volumetric reservoirs, as the inventory changes, P/Z remains on a straight line.

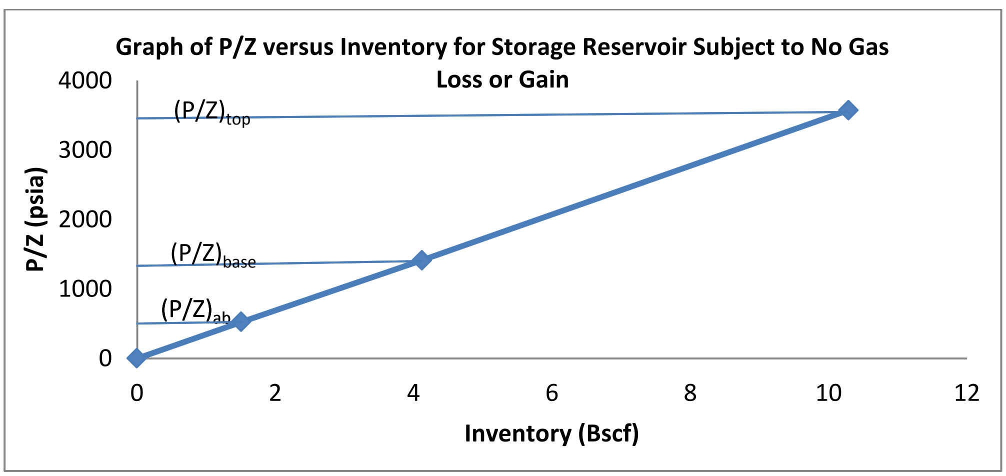

Figure 1 P/Z versus inventory for storage reservoir subject to no gas loss or gain.

Case 2 The gas storage reservoir when subject to loss of inventory

When the storage reservoir was subject to loss of its inventory, the pressure-content line had a lateral parallel shift to the right. The intercept of the line with the inventory axis provided the magnitude of the loss which in this case was 1.05 Bscf. The lost gas may have been as a result of gas being injected and present in the reservoir but not effective during storage, may have migrated away from the reservoir or may have been caused by measurement errors. It is seen from the plot that since the storage horizon was experiencing gas loss, more amount of gas to be left or pumped into the storage reservoir for corresponding P/Z values.

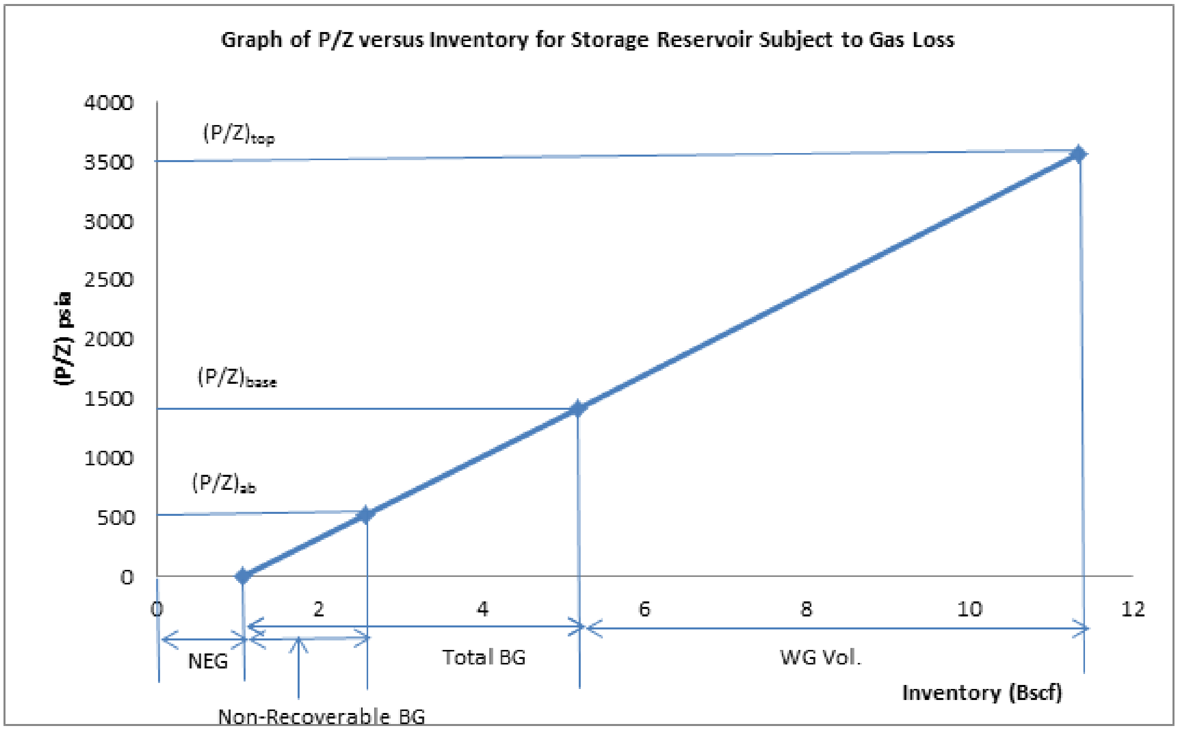

Figure 2 P/Z versus Inventory for storage reservoir subject to gas loss.

Case 3 The gas storage reservoir when subject to inventory gain

When the storage reservoir experienced gas gain, the pressure-content line had a parallel shift to the left. The intercept of the line with the inventory axis provided the magnitude of the gas gain which in this case was 2.95 Bscf. The negative sign indicates the presence of volumes of NEG in the storage horizon. The NEG might have migrated into the storage horizon during storage or might have been present even before the injection took place. For P/Z values above abandonmentP/Z, the negative sign indicates the amount of NEG volume that is recoverable at a correspondingP/Z, while at P/Z values below abandonment, the NEG volume becomes unrecoverable and the negative sign gives the maximum amount of NEG volume that is present, but cannot be recovered.

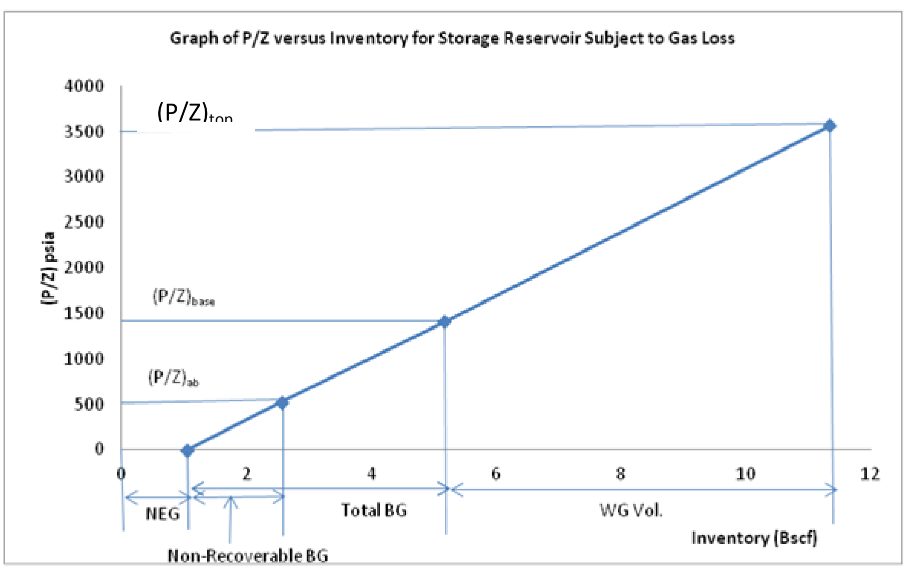

Figure 3 P/Z versus inventory for storage reservoir subject to gas gain.

Table 1 Summary of inventory evaluation results

Measurement condition	P/Z (psia)	Case1 (Bscf)	Case 2 (Bscf)	Case3 (Bscf)
$(P/Z)_0$	0.00	0.00	1.05	-2.95
$(P/Z)_{ab}$	525.76	1.51	2.56	-1.44
$(P/Z)_{base}$	1412.00	4.12	5.17	1.17
$(P/Z)_{top}$	3571.43	10.29	11.34	7.34

Case1: NEG=0 No gas loss or gain; Case 2: NEG>0 Gas loss; Case 3: NEG<0 Gas gain

Table 1 above provides the amount of gas that had to be left in the storage reservoir or injected into it to attain the corresponding (P/Z) values.

Table 2: Summary of results on performance

Case	Injected Base Gas Volume (Bscf)	Working Gas Volume (Bscf)	Total Inventory (Bscf)	Working Gas/Total Inventory	Volume (%)	Working Gas Volume/Injected Base Gas Volume	Percentage change in Volume
Case1	4.12	6.17	10.29	0.5996	59.96	1.50	0.00
Case 2	5.17	6.17	11.34	0.5441	54.41	1.19	-7.42
Case3	1.17	6.17	7.34	0.8406	84.06	5.27	40.19

Case1: NEG=0 No gas loss or gain; Case 2: NEG>0 Gas loss; Case 3: NEG<0 Gas gain

From table 2, it was seen that for case 3, when the reservoir experienced gas gain (NEG<0), 84.06 percent of the total injected inventory was available as working gas as against 59.96 percent for case 1(NEG=0) and 54.41 percent for case 2 (NEG>0). This result shows that case 3 has 40.19 percent more inventory than case 1 and 54.49 percent more inventory than case 2.

The performance result shows that in case 1, for every 1.00 Bscf of base gas injected, it delivers 1.50 Bscf of working gas. In case 2, for every 1.00 Bscf of base gas injected only 1.19 Bscf of working gas can be delivered, while for case 3, 1.00 Bscf of gas delivers as high as 5.27 Bscf working gas.

5. Conclusion

It is concluded from the results obtained that:

At NEG=0, that is, for storage reservoir not subject to gas loss or gain, the inventory indicates the amount of gas that is left in the storage reservoir or that needs to be injected into it for the corresponding P/Z values to be achieved. When NEG=0, the storage reservoir behaves like a true volumetric tank. Indications from primary depletion performance, shows that the storage gas performance is almost optimal at NEG=0.

When NEG>0, that is, the storage reservoir was subject to gas loss as shown in case 2, more volume of gas above the normal quantity is required in the storage as most of it migrates away from the storage horizon. For this case, the reservoir performance is too low and hence not a good gas storage reservoir.

When NEG<0, that is, the storage reservoir was subject to gas gain as in case 3, gas migrates into the reservoir and hence reduces the amount of gas needed to be pumped into or left in the storage horizon to perform optimally and hence makes more gas available for use.

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Nomenclature

P =Reservoir pressure (psia)
V =Volume of gas (cuft)
Z =Real gas deviation factor
n =Number of moles
R =Universal gas constant
T =Reservoir Temperature (^{o}R)

Q =Amount of gas in storage reservoir
P_b =Measurement base pressure (psia)
T_b =Base temperature (^oR)
A =Area (acre)
S_w =Water saturation (fraction)
S_g =Gas saturation
G_{gwc} =Gas content to present gas water contact
G_r =Residual gas content in water
G =Total gas in storage
G_p =Cummulative gas produced (scf)
A_g =Area of reservoir occupied by gas (acre)
A_w =Area of reservoir occupied by water (acre)
h_g =Net effective formation thickness occupied by gas (ft)
h_w =Net effective formation thickness occupied by water (ft)
$\emptyset$ =Porosity (fraction)
Q_m =Volume of non-recoverable gas in standard condition (scf)
V_{ab} =Volume of gas reservoir space not flooded at abandonment (cuft)
B_g =Gas formation volume factor at abandonment (scf/cuft)
$B_{g,m}$ =Gas formation volume factor at the mean reservoir pressure (scf/cuft)
P_{ab} =Abandonment pressure (psia)
V_{max} =Maximum volume of reservoir space ever containing gas at the maximum pressure P_{max} (cuft)
F_{sw} = Sweep factor
S_{gr} =Residual gas saturation
Q_s =Gas dissolved in water

Subscripts

top = top gas (working gas)
base = base gas (cushion gas)
ab = abandonment

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