A COMPARATIVE ASSESSMENT ON THE EFFECT OF WATERINFLUX/PRODUCTION, FORMATION AND RESIDUAL FLUIDCOMPRESSIBILITY, AND GAS SORPTION ON THE VALUE OF ORIGINAL GAS IN PLACE USING THE MATERIAL BALANCE EQUATION

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ABSTRACT-For a volumetric gas reservoir, gas expansion (the most significant source of energy) dominates depletion behavior, and the general gas MBE is a very simple yet powerful tool for interpretation. However, in cases where other source of energy are significant enough to cause deviation from the linear behavior of the P/Z plot, a more sophisticated tool is required. For this, a more advanced form of the MBE has been developed, and the standard P/Z plot is modified to maintain a linear trend with the simplicity of interpretation. Material balance has long been used in reservoir engineering practice as a simple yet powerful tool to determine the Original-Gas-In-Place (G). The conventional format of the gas material balance equation is the simple straight line plot of P/Z versus cumulative gas production (Gp) which can be extrapolated to zero P/Z to obtain G. The graphical simplicity of this method makes it very popular. The method was developed for a "volumetric" gas reservoir. It assumes a constant pore volume of gas and accounts for the energy of gas expansion, but it ignores other sources of energy such as the effects of formation compressibility, residual fluids expansion and aquifer support. It also does not include other sources of gas storage such as connected reservoirs or adsorption in coal/shale. In the past, researchers have introduced modified gas material balance equations to account for these other sources of energy. However, the simplicity of the P/Z straight line is lost in the resulting complexity of these equations. In this research project work, a new format of the gas material balance equation is presented which recaptures the simplicity of the straight line while accounting for all the drive mechanisms. It uses a P/Z** instead of P/Z. The effect of each of the mentioned drive mechanisms appears as an effective compressibility term in the new gas material balance equation. Also, the physical meaning of the effective compressibilities are explained and compared with the concept of drive indices. Furthermore, the gas material balance is used to derive a generalized rigorous total compressibility in the presence of all the above-mentioned drive mechanisms, which is very important in calculating the pseudo-time used in rate transient analysis of production data

Keywords-Reserves, Volumetric gas reservoir, cumulative gas production , Aquifer, original-gas-in-place, advanced material balance Equation

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ISSN 2229-5518

1.0 INTRODUCTION

It has been of great interest to find the original-gas-in-place by using material balance. The conventional gas material balance equation was developed for a "volumetric" gas reservoir. Therefore, the P/Z versus cumulative gas production plot may give misleading results in some situations e.g. when the formation compressibility is of the same order of magnitude as gas compressibility (overpressured reservoirs) or where desorption plays a role (CBM/shale). Figure 1 shows P/Z versus Gp for several scenarios with the same original-gas-in-place (G). It can be seen from this figure that except for the volumetric reservoir, the plot is not a straight line, because gas expansion is not the only drive mechanism. In fact, water encroachment in water-drive reservoirs, formation and residual fluid expansion in overpressured reservoirs and gas desorption in coalbed methane (CBM) or shale reservoirs can have a significant role as a driving force in these cases. In these situations, where the gas expansion is not the dominant driving force, modified material balance equations have been developed by several researchers. Among them, Ramagost and Farshad17 modified the conventional material balance equation to account for pore volume shrinkage due to formation and residual fluid expansion and introduced a new plotting function that keeps the material balance as a straight line. So that the modified material balance equation can be used for overpressured reservoirs. Later, Rahman16 introduced a rigorous form of material balance equation that considers the effect of the formation and residual fluid expansion.

The attempt to find a material balance equation for unconventional gas reservoirs started when these resources become more popular. Jensen and Smith7 proposed a simplified material balance equation for unconventional gas reservoirs by assuming that the stored free gas is negligible and consequently omitting the effect of water saturation completely. However, King8 derived a comprehensive material balance equation for unconventional gas reservoirs that accounts for the free and adsorbed gas, water encroachment/production and water and formation compressibility. Seidel suggested that the water saturation change does not have a significant effect on material balance and substituted constant water saturation in King's8 material balance.

This study presents an advanced, rigorous, gas material balance equation and its plotting function that unifies all the above-mentioned modifications in one equation. The new gas material balance equation has the same format as traditional material balance and can be plotted as a straight line with Pi/Zi as y-intercept and G as x-intercept. A significant advantage of this material balance equation is that it can be used to define the total compressibility of the system so that the pseudo-time calculated with this total compressibility honors material balance in all situations.

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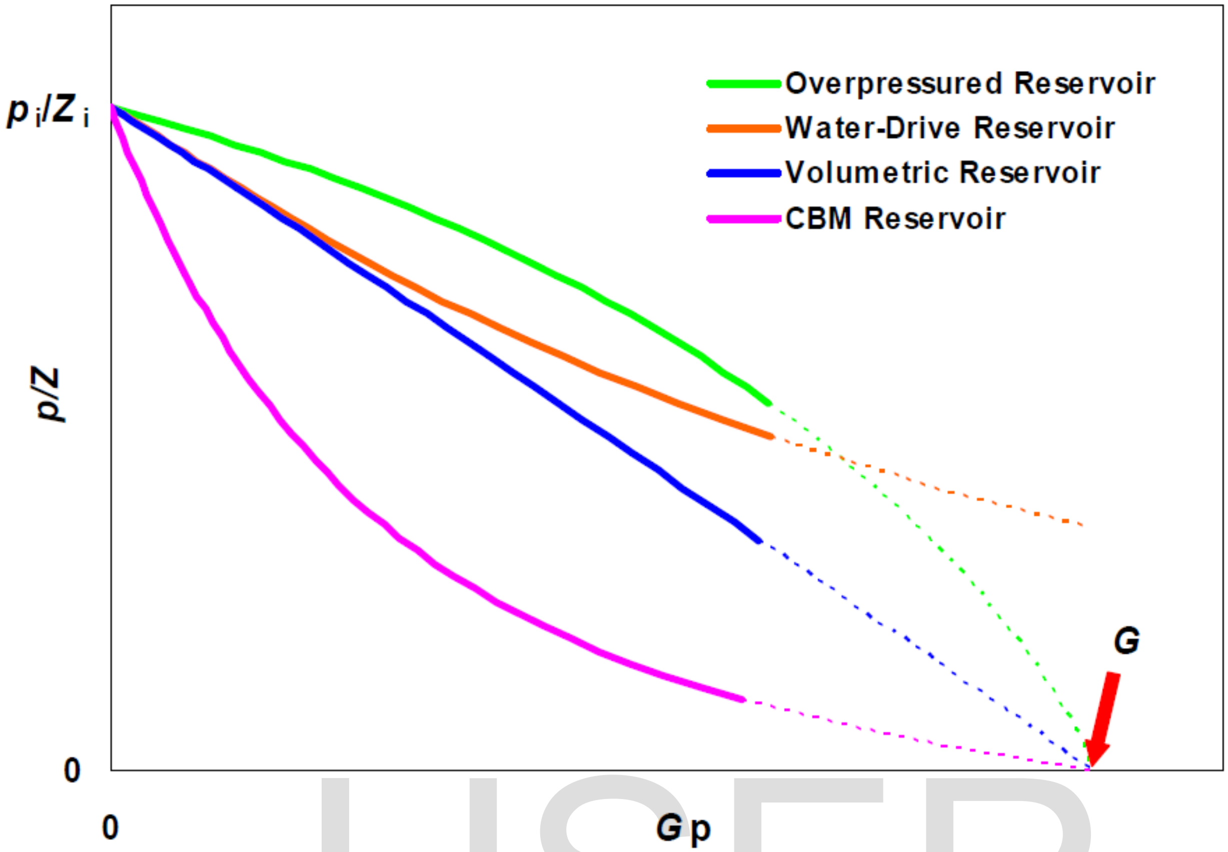

Figure 1 Conventional plot: P/Z versus cumulative gas production.

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1.1 PROBLEM STATEMENT

Determining the original gas in place, OGIP requires the knowledge of conventional gas material balance equation, CMBE. To derive the Advanced Gas Material Balance Equation, one must put into consideration the conventional material balance which overestimates the value of OGIP and define each of the various reservoir properties which were neglected in the conventional material balance. In the Advanced Gas Material Balance Equation, the effect of water influx/production, for an overpressured reservoir formation and residual fluid compressibility effect, and for a CBM reservoir, effect of gas desorption will be incorporated into the equation. One must also have in mind that the AMBE must be in a simple format of an equation of a straight line when compared to the conventional MBE.

1.2 AIM

To show the effect of; water influx/production, formation and residual fluid compressibility, and gas sorption on the value of original gas in place.

1.3 OBJECTIVE

To derive the advanced gas material balance equation.

To Apply the AMBE to a few reservoirs.

To interpret the result and compare the disparity between the AMBE and the conventional MBE.

To show the effects of the aforementioned effects on the value of original gas in place.

$$\frac{P}{Z} = \left(-\frac{P_i}{Z_i} * \frac{1}{G}\right) G_p + \frac{P_i}{Z_i} \qquad 1$$

In his work on CBM, King8 introduced P/Z* to replace P/Z, by modifying Z, parameter to incorporate the effect of adsorbed gas so that the total gas in place is interpreted rather than just the free gas in place; and a straight line analysis technique is still used.This concept has been extended to additional reservoir types with Fekete's10 P/Z** method. The reservoir types considered in the advanced material balance equation are; overpressured reservoirs, water drive reservoirs, and connected reservoirs. The total Z** equation and the modified material balance equation is shown in this work. (Moghadam et al. 2009)10

1.4 LIMITATION

This paper is but limited to analysis of data from conventional gas reservoir, overpressured reservoirs and water drive gas reservoirs. Therefore results are obtained without the use of coal bed methane reservoir parameters.

2.0 METHODOLOGY

The methods used for this study are as follows;

Study and Derive the Advanced Gas Material Balance Equation

Apply the equation to some conventional gas reservoirs

Interpret the results from the plots

Compare the disparity between the AMBE and the Conventional MBE

And make recommendations if possible

2.1. STUDY AND DERIVE THE ADVANCED GAS MATERIAL BALANCE EQUATION

For a volumetric gas reservoir, gas expansion (the most significant source of energy) dominates depletion behavior, and the general gas MBE is a very simple yet powerful tool for interpretation, equation (see equation 1). However, in cases where other sources of energy are significant enough to cause deviation from the linear behavior of the P/Z plot, a more sophisticated tool is required. For this, a more advanced form of the MBE has been developed, and the standard P/Z plot is modified to maintain a linear trend with the simplicity of interpretation.

The Advanced Gas Material Balance Equation (AMBE), to account for water encroachment in water drive reservoirs, expansion of formation and residual liquids in over-pressured reservoirs, and gas desorption in coalbed methane (CBM) and shale gas reservoirs in the same simple format of Equation 1. However, the modification needs to be started from the material balance equation by neglecting all terms leaving behind only the gas terms to derive equation 2.1.

$$G = \frac{G_p B_g}{B_g - B_{gi}}$$

$$GB_{gi} = \left(G - G_p\right) B_g \qquad 2.1$$

Each of the above-mentioned effects can be added to the right-hand side of Equation 2.1 as a volume change term.

$$GB_{gi} = \left(G - G_p\right) B_g + \Delta V_{wip} + \Delta V_{ep} + \Delta V_d \qquad 2.2$$

The explanation of each of the volume change terms is provided in the following sections.

3.1.1 WATER INFLUX AND PRODUCTION

In a water-drive reservoir, the aquifer provides pressure support for the reservoir by encroachment of water into the gas reservoir. The encroached water (We) decreases the pore volume available for the remaining gas. The reservoir volume change due to the net encroached water (ΔV_{wip}) can be calculated from (2.3):

$$\Delta V_{wip} = 5.615\left(W_e - W_p B_w\right) \qquad 2.3$$

Where

We = water encroachment into the gas reservoir

Wp = water produced at surface

Bw = water formation volume factor

(5.615 is a constant used only in oilfield units)

2.1.2 OVERPRESSURED RESERVOIR

Formation and residual fluids compressibilities are usually very small in comparison with the gas compressibility. Therefore, in general, ignoring the formation and the residual fluids expansion does not affect the gas material balance significantly. However, at high pressures the gas compressibility is of the same order of magnitude as that of the formation and residual liquids. Overpressured reservoirs are the most common example of this situation, where ignoring the effect of formation and residual fluids expansion may result in serious overprediction of G. In overpressured reservoirs, the P/Z versus Gp plot yields two distinct slopes. The first slope (shallow) is in the pressure range where formation and residual fluids expansion play a significant role, while the second slope (steep) reflects the region where gas expansion is the dominant production mechanism Ramagost and Farshad17 considered the effect of formation and residual fluid expansion by a volume change equal to;

$$\frac{GB_{gi}\{(S_w C_w + C_f)(P_i - P)\}}{1 - S_w}$$

(Ramagost & Farshad, 1981)17

Later, Rahman et al.16 introduced a rigorous form of this volume change by integrating the compressibility equation for any of the substances in the reservoir. The total effect of formation and the residual fluids compressibility can be added together as:

$$\Delta V_{ep} = \frac{GB_{gi}}{S_{gi}}\left[\left(1 - e^{-\int_P^{P_i} c_f df}\right) + S_{wc}\left(e^{\int_P^{P_i} c_w dp} - 1\right) + S_o\left(e^{\int_P^{P_i} c_o dp} - 1\right)\right] \quad 2.4$$

When matrix shrinkage occurs during coalbed methane production, the (fracture) porosity containing the free gas increases. In that situation, Cf has a negative value and is a complex function of pressure.

If Cf, Cw and Co are constant values, a simplified form of Equation (2.4) can be written as:

$$\Delta V_{ep} = \frac{GB_{gi}}{S_{gi}}\left[\left(1 - e^{-C_f(P_i - P)}\right) + S_{wc}\left(e^{C_w(P_i - P)} - 1\right) + S_o\left(e^{C_o(P_i - P)} - 1\right)\right] \quad 2.5$$

Equation (2.6) is the format used by Ramagost and Farshad17. Because of its simplicity, it is the format that is used in this research project work, but for a more rigorous calculation, the form of Equation (2.4) should be used.

The approximate form of equation (2.5) can be found by considering $e^x \approx 1 + x$ as:

$$\Delta V_{ep} = \frac{G_f B_{gi}}{S_{gi}}(C_f + S_{wc}C_w + S_{oi}C_o)(P_i - P) \quad 2.6$$

(Rahman, Anderson, & Mattar, 2006)16

2.1.3 CBM/SHALE GAS DESORPTION

The gas storage mechanism in a CBM (or shale gas) reservoir is unlike that of a conventional gas reservoir. In a typical gas reservoir, gas is stored in the pores by compression. In a CBM/shale reservoir, in addition to the free gas (Gf) stored in the fracture network, gas is stored within the coal/shale matrix by adsorption. As the reservoir pressure is reduced, gas is desorbed from the surface of the matrix. The amount of gas stored by adsorption can exceed the gas stored by compression. Desorption of gas is commonly described by the Langmuir Isotherm as:

$$\text{specific gas constant} = \frac{V_L P}{P_L + P}$$

Where;

VL = Langmuir Volume

PL = Langmuir Pressure

Specific gas content: the volume of gas per unit mass of coal.

Therefore the adsorbed gas amount, Ga

$$\text{Adsorbed gas} = G_a = \frac{\rho_B V_B (V_L P)}{P_L + P}$$

Where:

ρB and VB are the density and volume of the coal, respectively, and VL is on a "dry, ash-free" basis.

The material balance equation is based on the reservoir volume that the free gas occupies at the initial pressure. For CBM, this is equal to GfBgi. In a conventional gas reservoir, G=Gf , but for a CBM reservoir, the total OGIP (G) includes the free gas (Gf) and the adsorbed gas (Ga). The volume of "desorbed" gas at reservoir pressure p which is added to the "free" gas. The desorbed gas volume which needs to be added to the right-hand-side of Equation 1, can be calculated from (for Sgi>0),

$$\Delta V_d = \frac{\rho_B B_g G_f B_{gi}}{S_{gi}\varphi}\left(\frac{V_L P_i}{P_L + P_i} - \frac{V_L P}{P_L + P}\right) \quad 2.7$$

The advanced material balance equation with consideration to the above stated effects can be derived by substituting equations 2.3, 2.6 and 2.7 in equation 2.2.

$$G_f B_{gi} = (G_f - G_p)B_g + (W_e - W_p B_w) + \frac{G_f B_{gi}}{S_{gi}}(C_f + S_{wc}C_w + S_{oi}C_o)(P_i - P)$$

$$+ \frac{\rho_B B_g G_f B_{gi}}{S_{gi}\varphi}\left(\frac{V_L P_i}{P_L + P_i} - \frac{V_L P}{P_L + P}\right) \quad 2.8$$

Dividing through both sides of equation 2.8 by; $\frac{G_f B_{gi}}{S_{gi}}$; (reservoir pore volume), it can be reduced to;

$$\frac{P}{Z}(S_{gi} - C_{wip} - C_{ep} - C_d) = \frac{P_i}{Z_i}\left(1 - \frac{G_p}{G_f}\right)S_{gi} \quad 2.9$$

Where;

C_{wip}, C_{ep}, and C_d are defined by;

C_{wip} is the change in pore volume due to the water influx/production

$$C_{wip} = \frac{\Delta V_{wip}}{\frac{G_f B_{gi}}{S_{gi}}} = \frac{5.615\left(W_e - W_p B_w\right)}{\frac{G_f B_{gi}}{S_{gi}}}$$

C_{ep} is the change in pore volume due to the formation and residual fluid expansion

$$C_{ep} = \frac{\Delta V_{ep}}{\frac{G_f B_{gi}}{S_{gi}}} = (C_f + C_w S_{wc} + S_o C_O)(P_i - P)$$

C_d is the relative change in pore volume due to gas desorption.

$$C_d = \frac{\Delta V_d}{\frac{G_f B_{gi}}{S_{gi}}} = \frac{\rho_B B_g}{\varphi}\left(\frac{V_L P_i}{P_L + P_i} - \frac{V_L P}{P_L + P}\right)$$

It should be noted that the variables C_{wip}, C_{ep}, and C_d are not compressibility (as implied by their symbols), but they represent the relative change in the pore volume caused by the specific mechanism.

Also, for a non-coalbed methane reservoir (conventional gas reservoir), adsorbed gas Ga=0, this implies that □Vd and Cd are also 0, and G=Gf.

Plotting functions of the advanced material balance equation

Equation (2.9) is an easy formulation for the general material balance equation and can be plotted as $\frac{P}{Z}\left(S_{gi} - C_{wip} - C_{ep} - C_d\right)$ versus Gp to give a straight line. However, it is derived based on the pore volume of the free gas. Therefore, the straight line crosses the abscissa at Gf (free gas volume) not G (total gas in place). This is an inconvenience and is a disadvantage of this plotting format when compared to the conventional material balance where the abscissa is G (total gas in place), it is worth mentioning that G can be found easily if Gf is known.

$G = G_f + \frac{G_f B_{gi}}{S_{gi}} \cdot \frac{\rho_B V_B (V_L P)}{P_L + P}$

It should be noted that equation (2.9) must be solved iteratively in the case of water influx/production because Gf appears in the Cwip term.

In his work on CBM material balance, King8 introduced Z* as:

$$Z^* = \frac{Z}{\left((S_{gi} - (C_f + C_w S_{wi})(P_i - P) - \frac{W_e - W_p B_w}{\frac{G_f B_{gi}}{S_{gi}}} + \frac{\frac{\rho_B B_g}{\varphi}}{\frac{V_L P}{P_L + P}}\right)} \quad 2.10$$

and reformatted Equation 1 as below:

$$\frac{P}{Z^*} = \left(1 - \frac{G_P}{G}\right)\frac{P_i}{Z_i^{\,*}} \quad 2.11$$

This equation has the same format as the conventional gas material balance equation, and can be plotted as a straight line of P/Z* versus Gp which extrapolates to G, This format has a clear advantage over that of Figure 1 in that it extrapolates to the more practical value of total gas-in-place (G) rather than the free gas (Gf). Whereas this format is theoretically applicable to gas reservoirs other than CBM, the fact that the P/Z* values bear little resemblance to the conventional P/Z values detracts from its utility.

In an effort to generalize the gas material balance equation for all reservoirs (conventional, overpressured, CBM/shale), we have developed a Z** variable to replace King's8 Z* and have re-written the gas material balance equation, Equation 2.9, as:

$$\frac{P}{Z^{**}} = \left(1 - \frac{G_P}{G}\right)\frac{P_i}{Z_i^{\,**}} \quad 2.12$$

The advantage of the Z** format is that the P/Z** values are similar in magnitude to the conventional P/Z values. As shown in Figure 5, P/Z** versus Gp is a straight line that starts from the conventional Pi/Zi and extrapolates to G. This formulation and presentation has simplified the applicability of the general material balance equation. The definition of Z** was derived from Equations 2.9 and 2.12 as:

$$Z^{**} = \frac{P}{\left(\frac{1}{S_{gi}}\frac{P}{Z}\left(S_{gi} - C_{wip} - C_{ep} - C_d\right) + \frac{P_i}{Z_i}\left(\frac{G}{G_f} - 1\right)\right)\frac{G_f}{G}} \quad 2.13$$

Also, Z** is related to King's 8Z* by the following relationship:

$$Z^{**} = Z^*\left(\frac{Z_i}{Z_i^{\,*}}\right)$$

Equation 2.12 is the Advanced gas material balance equation for all gas reservoirs (conventional, overpressured, CBM/shale). When plotted as P/Z** versus Gp it yields a straight line, which like the conventional P/Z plot, starts from the conventional Pi/Zi and extrapolates to the total gas-in-place, G. (Moghadam, Jeje, & Mattar, 2009)10

2.1.4 WATER DRIVE GAS RESERVOIR

The presence of an aquifer can be detected by rearranging the Schiltuis material balance equation to contain only the gas and water expansion terms as follows (Pletcher, 2000)11;

$$F = G\left(E_g + E_{fw}\right) + W_e \quad 2.14$$

Where;

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$$F = G_p B_g + W_p B_w$$

Often in gas reservoirs, the formation and residual fluid compressibility term, E_{fw} is negligible compared to E_g and can therefore be ignored. Then, rearranging equation 2.14 ,we have:

$$\frac{G_p B_g}{B_g - B_{gi}} = G + \frac{W_e - W_p B_w}{B_g - B_{gi}} \qquad 2.15$$

The LHS of equation 2.15 can be plotted against the terms on the far RHS of the equation with G, as the intercept representing the gas in place.

2.2 APPLICATION OF THE ADVANCED GAS MBE TO CONVENTIONAL GAS RESERVOIRS

The advanced gas material balance equation can be applied to the following reservoir A, B, and C as shown in the results (See Tables 2.1-2.6)

But for an over pressured reservoir, formation and residual fluid compressibility term, E_{fw} is not negligible, in which case E_{fw} cannot be ignored and equation 2.15 should be written as;

$$\frac{F}{E_t} = G + \frac{W_e}{E_t} \qquad 2.16$$

Where; E_t is the total compressibility = $E_g + E_{fw}$

If Equation 2.16 is plotted, the gas in place can be obtained from the graph of F/Et against We/Et as G.

2.2.1 CASE I: AN OVER PRESSURED RESERVOIR WITH RELATIVELY MODERATE WATER INFLUX/PRODUCTION

3.1 RESULTS AND DISCUSSION OF RESULTS

RESULTS

Analysis of the reservoirs A, B and C are shown in appendix B and the resulting plots are interpreted below;

DISCUSSION OF RESULTS

Reservoir A: An Overpressured Reservoir With Moderate Water Influx

From the plot, figure 3, the value of G (OGIP) obtained from the conventional P/Z plot was 107.87Bscf for the reservoir A. While that for the advanced P/Z plot for reservoir A shows a value of G at 85.92 which is less than that obtained from the conventional P/Z plot, and when this values are compared to that of the water drive plot, figure 4, it shows that the value of G from the plot is almost equal to that of the advanced P/Z plot indicating that the conventional P/Z plot was overestimating the OGIP while neglecting the effects of water influx/production and for an overpressured, reservoir and residual fluid compressibility.

Reservoir B: An Overpressured Reservoir With Strong Water Influx/Production.

From the plot, figure 5, the value of G (OGIP) obtained from the conventional P/Z plot was 107.8Bscf for the reservoir B. While that for the advanced P/Z plot for reservoir B shows a value of G at 89.5Bscf which is less than that obtained from the conventional P/Z plot, and when this values are compared to that of the water drive introduced, so that the material balance equation can be plotted as a straight line with Pi/Zi as y-intercept, and G as x-intercept.

The similarity of the recommended plotting procedure, Pi/Z** versus Gp, to the more commonly used P/Z format is a great practical advantage. It allows the use of a rigorous material balance formulation for complex and unconventional gas reservoirs, while retaining the simplicity and familiarity of the commonly used P/Z format.

plot, figure 6, it shows that the value of G from the plot is equal to that of the advanced P/Z plot indicating that the conventional P/Z plot was overestimating the OGIP while neglecting the effects of water influx/production and for an overpressured, reservoir and residual fluid compressibility.

Reservoir C: An Overpressured Reservoir With Negligible Water Influx/Production.

From the plot, figure 7 the value of G (OGIP) obtained from the conventional P/Z plot was 107.759Bscf for the reservoir C. While that for the advanced P/Z plot for reservoir C shows a value of G at 104.821Bscf which is less than that obtained from the conventional P/Z plot, though quite close and this is due to the effect of reservoir and residual fluid compressibility, indicating that the conventional P/Z plot was overestimating the OGIP while neglecting the effect.

This trend in the plots indicates that the conventional P/Z plots neglect water influx/production and the effect of reservoir and residual fluid compressibility, and therefore was overestimating the value of OGIP. This shows the disparity between the two equations.

4.1 CONCLUSION

An advanced gas material balance equation has been presented, and the corresponding plotting function

The advanced gas material balance equation is used to derive a rigorous definition for total compressibility that can be used for analyzing fluid flow in unconventional gas reservoirs, or when gas is not the only mobile phase.

The water plots for each of the reservoirs A through C shows similar or close to equal value of G for the advanced gas material balance equation P/Z plot indicating that the conventional material balance equation was overestimating the OGIP while neglecting the effect of water influx/production and for an overpressured reservoir, the effect of formation and residual fluid compressibility.

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ISSN 2229-5518

4.2 RECOMMENDATIONS

From the results obtained and after comparative analysis, it can be deduced that the conventional material balance equation overestimates the value of OGIP due it's to neglecting the effect of water influx/production and formation and residual fluid compressibility. This can also be put simply as, the conventional material balance equation is solely applicable to volumetric gas reservoirs. In contrast to this, the advanced gas material balance equation which incorporates the effect of water influx/production, for an over-pressured reservoir, the effect of formation and residual fluid compressibility and for a CBM reservoir, the effect of gas desorption makes the advanced gas Material balance equation an important tool for calculating the OGIP for all gas reservoirs. Hence the advanced gas material balance equation is recommended for use in the industry as it gives the exact or close to the actual value of OGIP. Another significant advantage of this material balance equation is that it can be used to define the total compressibility of the system so that the pseudo-time calculated with this total compressibility honors material balance in all situations.

TABLES

Table 2.1 and 2.2, shows the production and pressure data for a period of ten (10) years for Reservoir A respectively.

TABLE 2.1 PROPERTIES OF A TWO CELL GAS SIMULATION MODEL	
Node area	640 Acres
Node thickness = net pay thickness	200ft
Porosity	15%
Gas reservoir pore volume	74.5×106 res bbl
Aquifer original water in place	74.5×106 res bbl
Sw	15%
OGIP	100.8Bscf
Permeability	200mD
Cf	6×10-6 psi -1
Cw	3×10-6 psi -1
Reservoir Temperature	239°F

TABLE 2.2-PERFORMANCE HISTORY OF TWO-CELL GAS-SIMULATION MODEL

year	P (psi)	Z	Bg (RB/SCF)	Bw (RB/STB)	Wp (STB)	We (STB)	Gp (SCF)
0	6411	1.1192	6.28E+05	1.0452	0	0	0
1	5947	1.089	6.59E+05	1.0467	378	273294	5.48E+09
2	5509	1.0618	6.93E+05	1.048	1434	552946	1.10E+10
3	5093	1.0374	7.33E+05	1.0493	3056	817481	1.64E+10
4	4697	1.0156	7.78E+05	1.0506	5284	1068632	2.19E+10
5	4319	0.9966	8.30E+05	1.0517	8183	1307702	2.74E+10
6	3957	0.9801	8.91E+05	1.0529	11864	1535212	3.29E+10
7	3610	0.9663	9.63E+05	1.054	16425	1752942	3.83E+10
8	3276	0.9551	1.05E+06	1.0551	22019	1962268	4.38E+10
9	2953	0.9467	1.15E+06	1.056	28860	2163712	4.93E+10
10	2638	0.9409	1.28E+06	1.0571	37256	2359460	5.48E+10

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2.2.2 CASE II: AN OVER PRESSURED RESERVOIR WITH CONSIDERABLE WATER INFLUX/PRODUCTION

Table 2.3 and 2.4 shows the PVT data for Reservoir B on a quarterly basis, for four (4) years production interval.

TABLE 2.3 PROPERTIES OF THE RESERVOIR

Node area	720 Acres
Node thickness = net pay thickness	220ft
Porosity	20%
Gas reservoir pore volume	74.5×106 res bbl
Aquifer original water in place	74.5×106 res bbl
Sw	12%
Permeability	250md
Cf	8×10-6 psi -1
Cw	3×10-6 psi -1
Reservoir Temperature	239°F

TABLE 2.4: PRODUCTION AND PRESSURE DATA FOR FOUR (4) YEARS PRODUCTION INTERVAL

Year (Quaterly)	P (psi)	Z	Bg (RB/Mscf)	Bw (RB/STB)	Wp (STB)	We (STB)	Gp (Bscf)
0	6411	1.1192	6.28E-01	1.0452	0	0	0
1	5947	1.089	6.59E-01	1.0467	378	273294	5.48E+00
2	5509	1.0618	6.93E-01	1.048	1434	552946	1.10E+01
3	5093	1.0374	7.33E-01	1.0493	3056	817481	1.64E+01
4	4697	1.0156	7.78E-01	1.0506	5284	1068632	2.19E+01
5	4319	0.9966	8.30E-01	1.0517	8183	1307702	2.74E+01
6	3957	0.9801	8.91E-01	1.0529	11864	1535212	3.29E+01
7	3610	0.9663	9.63E-01	1.054	16425	1752942	3.83E+01
8	3276	0.9551	1.05E+00	1.0551	22019	1962268	4.38E+01
9	2953	0.9467	1.15E+00	1.056	28860	2163712	4.93E+01
10	2638	0.9409	1.28E+00	1.0571	37256	2359460	5.48E+01
11	2560	0.921678	1.31E+00	1.057306	38823.3	2408141	5.61E+01
12	2492	0.91842	1.34E+00	1.057561	40768.14	2450343	5.73E+01
13	2400	0.916055	1.37E+00	1.057836	42862.49	2507661	5.89E+01
14	2285	0.912404	1.41E+00	1.058223	45813.55	2579171	6.09E+01
15	2101	0.905654	1.48E+00	1.058807	50264.39	2693698	6.41E+01

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ISSN 2229-5518

2.2.3 CASE III: AN OVER PRESSURED VOLUMETRIC RESERVOIR WITH NEGLIGIBLE WATER INFLUX/PRODUCTION

Table 2.5 and 2.6 shows a production and pressure that for reservoir C, for a production period of 15 years.

TABLE 2.5 PROPERTIES OF THE RESERVOIR

Node area	680 Acres
Node thickness = net pay thickness	200ft
Porosity	15%
Gas reservoir pore volume	74.5×106 res bbl
Sw	8%
Permeability	250md
Cf	8×10-6 psi -1
Cw	2.5×10-6 psi -1
Reservoir Temperature	239°F

TABLE 2.6 PRESSURE AND PRODUCTION DATA

Year	P (psi)	Z	Bg	Bw	Wp	We	Gp
			(RB/Mscf)	(RB/STB)	(STB)	(STB)	(Bscf)
0	6411	1.1192	6.28E+05	1.0452	0	0	0
1	5947	1.089	6.59E+05	1.0467	0	0	5.48E+09
2	5509	1.0618	6.93E+05	1.048	0	0	1.10E+10
3	5093	1.0374	7.33E+05	1.0493	0	0	1.64E+10
4	4697	1.0156	7.78E+05	1.0506	0	0	2.19E+10
5	4319	0.9966	8.30E+05	1.0517	0	0	2.74E+10
6	3957	0.9801	8.91E+05	1.0529	0	0	3.29E+10
7	3610	0.9663	9.63E+05	1.054	0	0	3.83E+10
8	3276	0.9551	1.05E+06	1.0551	0	0	4.38E+10
9	2953	0.9467	1.15E+06	1.056	0	85	4.93E+10
10	2638	0.9409	1.28E+06	1.0571	0	125	5.48E+10
11	2560	0.921678	1.31E+06	1.057306	0	190	5.61E+10
12	2492	0.91842	1.34E+06	1.057561	6.628	240	5.73E+10
13	2400	0.916055	1.37E+06	1.057836	12	347	5.89E+10
14	2285	0.912404	1.41E+06	1.058223	20.9457	456.3334	6.09E+10
15	2101	0.905654	1.48E+06	1.058807	33.4450	651.1204	6.41E+10

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PLOTS OF THE RESULT

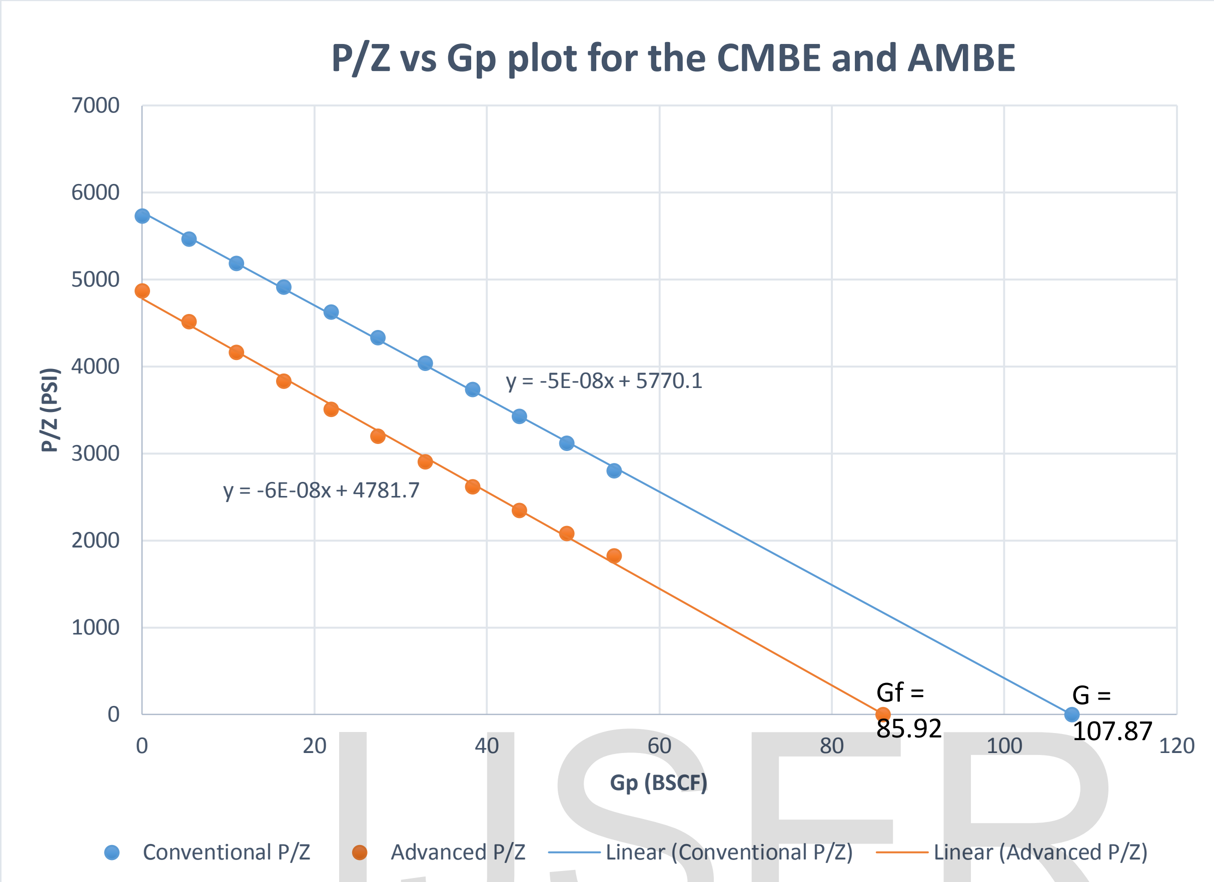

Figure 2 comparative P/Z plot for reservoir A

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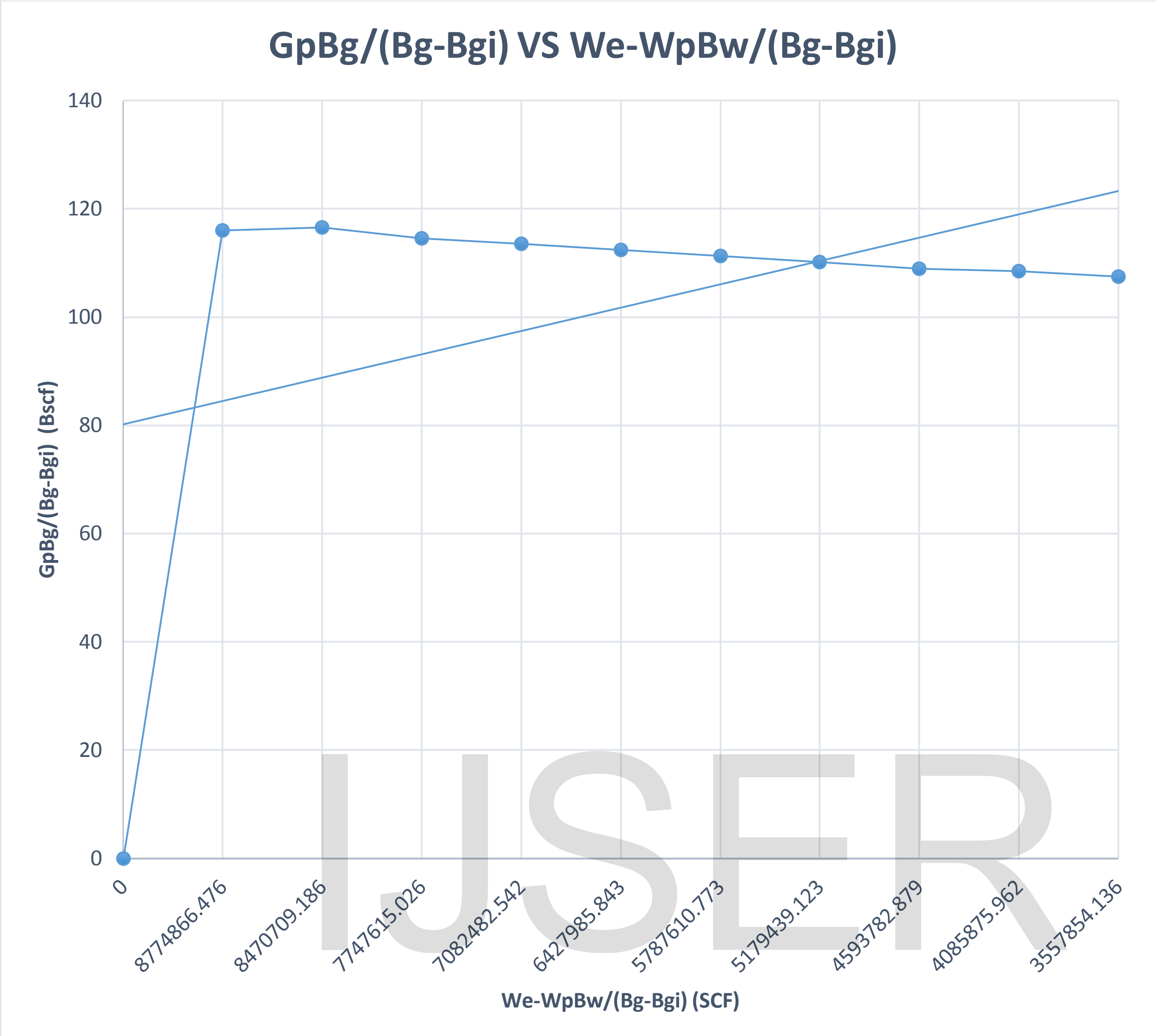

Figure 3 Water plot for reservoir A

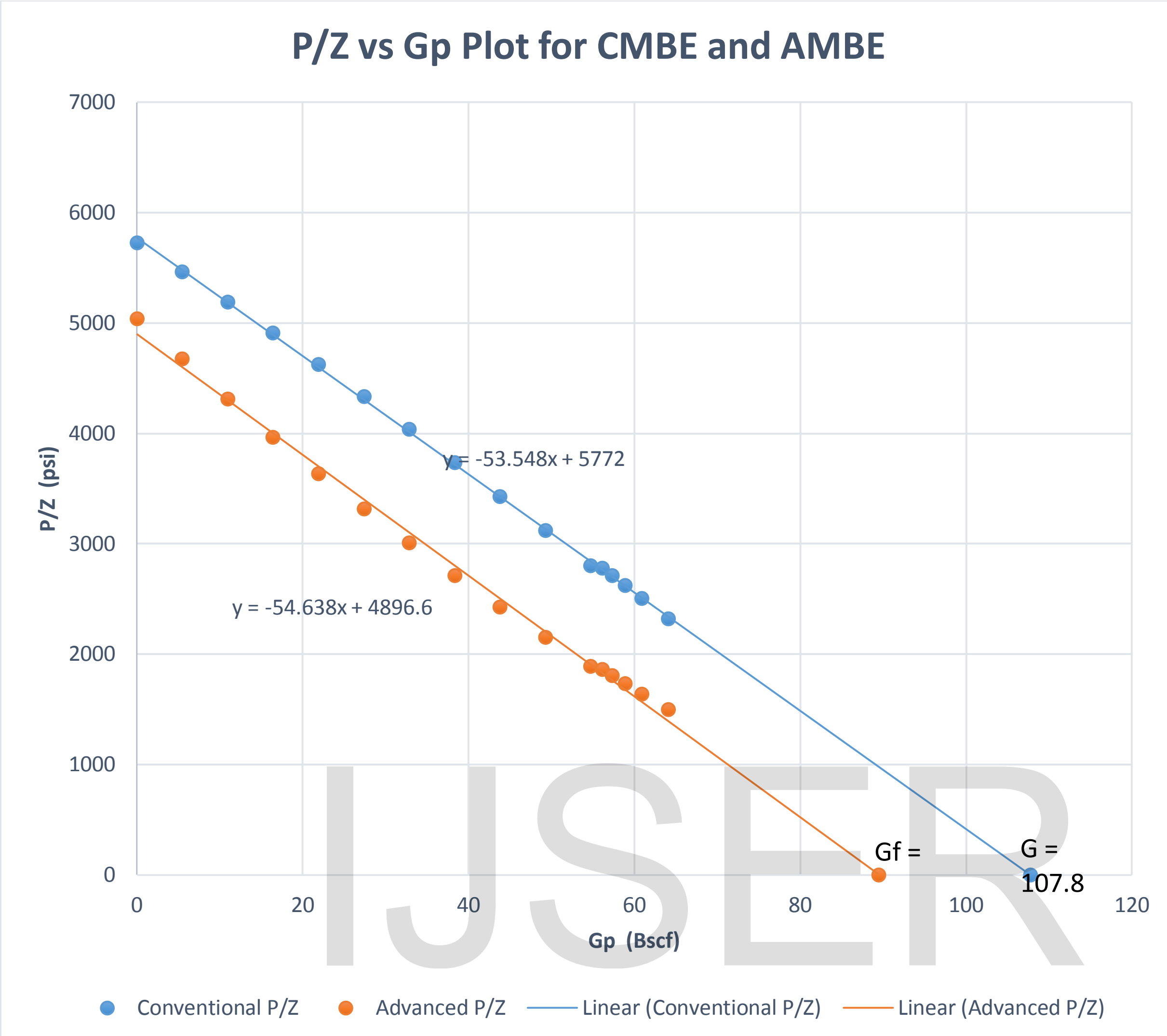

Figure 4 Comparative P/Z plot for reservoir B

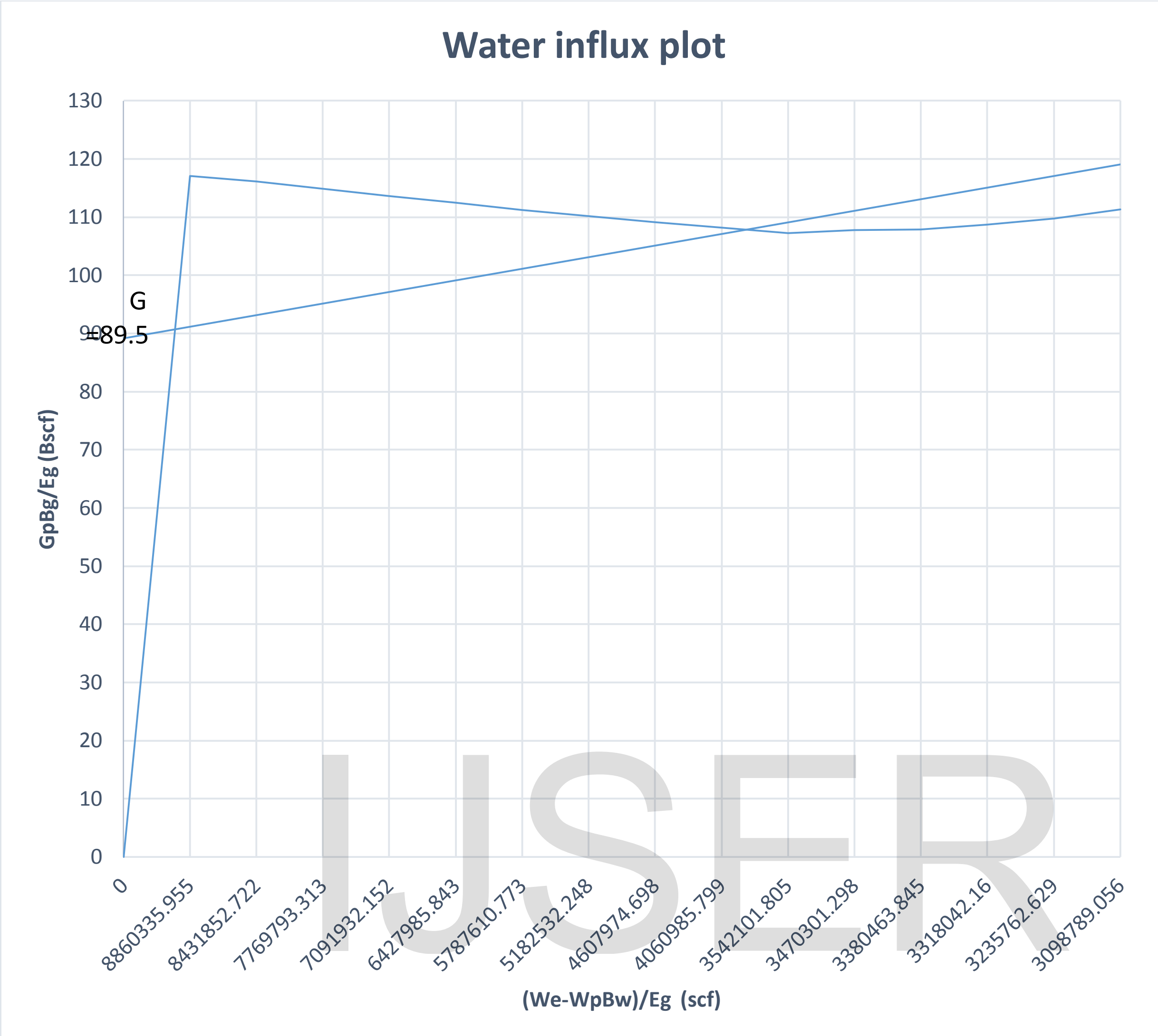

Figure 5 Water influx plot for reservoir B

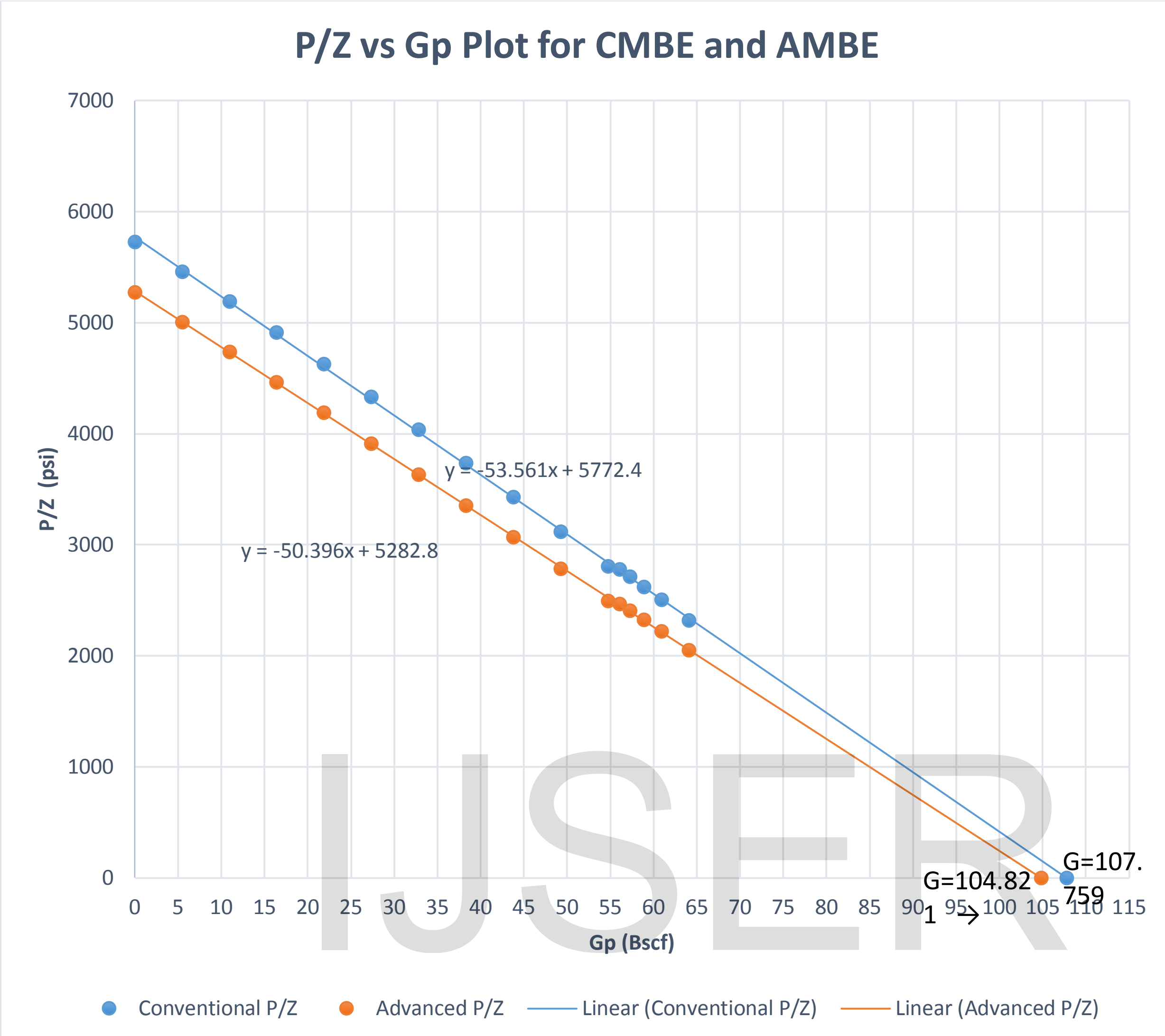

Figure6 Comparative P/Z Plot for Reservoir

ISSN 2229-5518

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ISSN 2229-5518

APPENDIX
NOMENCLATURE

Bg	gas formation volume factor at time t	ft3/scf, m3/m3
Bgi	initial gas formation volume factor	ft3/scf, m3/m3
Bw	water formation volume factor	bbl/stb, m3/m3
C	compressibility	1/psia, 1/Pa
c	The summation of cwip, cep and cd	
Cd	relative volume change due to CBM gas desorption, $\frac{\Delta V_d}{\frac{G_f B_{gi}}{S_{gi}}}$	
Cep	relative volume change due to residual fluid and formation, $\frac{\Delta V_{ep}}{\frac{G_f B_{gi}}{S_{gi}}}$	
Cf	formation compressibility	1/psia, 1/Pa
Cg	gas compressibility	1/psia, 1/Pa
Co	oil compressibility	1/psia, 1/Pa
Ct	total compressibility	1/psia, 1/Pa
Cw	water compressibility	1/psia, 1/Pa
Cwip	relative volume change due to water influx and production, $\frac{\Delta V_{wip}}{\frac{G_f B_{gi}}{S_{gi}}}$	
G	original-gas-in-place	Bscf, m3
Ga	adsorbed-gas-in-place	Bscf, m3
Gf	free-gas-in-place	Bscf, m3
Gp	cumulative gas produced to time t	Bscf, m3
k	permeability	md, m2
kr	permeability relative to water	md, m2
p	pressure	psia, Pa
PL	Langmuir pressure	psia, Pa
Psc	standard conditions reservoir pressure	psia, Pa
q	flow rate	MMscfd, m3/s
Sg	gas saturation	%
Sgi	initial gas saturation	%
So	oil saturation	%
Soi	initial oil saturation	%
Sw	water saturation	%
Swi	initial water saturation	%
T	reservoir temperature	oF, K
t	time	hours, s
ta	pseudo-time	hours, s
Tsc	standard conditions temperature	oF, K
VB	bulk volume	ft3, m3
Vi	initial volume	ft3, m3
VL	Langmuir volume	scf/ton, m3/kg
We	Water encroachment into formation	bbl, m3
Wp	cumulative water produced	Bbl, m3
Z	Gas compressibility factor	no units
Zi	initial gas compressibility factor	no units
5.615	Conversion constant in oilfield units	ft3/bbl 3

Greek Symbols

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φ	porosity	%
ψ	pseudo-pressure	psia2/cp, Pa/s
μ	viscosity	cp, Pa.s
ρB	bulk density	lb/ ft3, kg/m3
ΔV	change in volume	scf, m3
ΔVd	change in volume due to CBM gas desorption	ft3, m3

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