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Material Balance Calculations in Tight Gas Reservoirs: The Pitfalls of P/z Plots and a More Accurate Technique

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Abstract

Through the use of theoretical and field .examples, the potentially large errors associated with using straight line P/z decline (tank) analysis to assess gas in place and reserves in tight gas reservoirs are illustrated. The basic tank assumption that reservoir pressure gradients are small can be violated, even with long shut-in times. It is also demonstrated that a reasonably straight line P/z decline does not necessarily indicate that the reservoir behaves as a tank. The Communicating Reservoir (CR) model is presented as a simple, yet much more accurate, method of performing material balance calculations in tight reservoirs. The results of the application of the CR model to the Waterton Gas Field are used to illustrate the success and large impact that can be obtained by examining the pressure behavior more closely than simply plotting P/z.

Introduction

The use of pressure decline versus gas production (Gp) material balance plots (P/z plots) to estimate gas initially in place (GIIP) is a very common technique within gas reservoir engineering[1]. The technique is very simple to apply, since it is not dependent on production rates, well details or reservoir properties. Essentially, the method consists of using the rate of pressure decline to estimate the size of a reservoir. If the reservoir is behaving in a tank-like manner, then pressure, corrected for non-ideal gas behavior, will decline linearly with production. Extrapolation of this line to abandonment pressure and zero pressure estimates ultimate recovery and GIIP respectively.

The simplicity of the technique and success within relatively permeable gas reservoirs have resulted in its almost universal application. Acquisition and divestment evaluations, particularly for smaller assets that don't justify simulation, are often based solely on the method. The use of P/z plots has become so entrenched as an industry standard that the fundamental assumptions behind the method are often forgotten or ignored.

The key assumption involved in the straight line P/z plot material balance technique is that the reservoir behaves as a tank. That is, there is little or no pressure variation within the reservoir and there is no additional pressure support to the system. The lack of pressure variations within the reservoir is required to ensure that pressure measurements taken at well locations represent true average reservoir pressures, and that the entire reservoir can be described with one pressure value. In high permeability reservoirs, a generally low gas viscosity ensures small pressure gradients exist away from the wellbore and the average reservoir pressure estimates can be readily made using short-term build-ups or static pressure surveys.

In many cases, however, reservoir characteristics can cause the P/z plot to be non-linear. For example, condensation below the dew point will cause the overall compressibility of the system to change. In such cases the use of a "two-phase z", based on constant volume depletion experiments, will correct the curvature. In other cases, curvature caused by an aquifer, an oil leg, or rock compressibility may require more complex algorithms to "straighten" the P/z decline.

This paper demonstrates that the concept of the straight line P/z plot material balance also fails in tight, lower permeability reservoirs. In these cases, the tank assumption does not apply by definition - tight reservoirs lead to substantial pressure gradients. These gradients manifest themselves in terms of scattered, generally curved, and rate dependent P/z plot behavior. This behavior is readily illustrated through the use of both reservoir simulation and field examples, which shows that the P/z plot methodology can incur greater than 100% error in estimating GIIP and reserves. Unlike other sources of non-linear P/z plot behavior, no simple corrections are available to alleviate the problem.

One obvious solution to the material balance problem in tight reservoirs is to use reservoir simulation. However, time and expense for simulation often cannot be justified, leaving P/z plots as the only alternative. A different material balance methodology, the Communicating Reservoir or CR model, is presented here that can much more accurately determine reservoir size. This model can be implemented using a simple stand-alone or spreadsheet program. The accuracy and utility of the CR model is demonstrated by application to the same field and simulation examples where the P/z plot method is shown to fail. Even in cases where simulation is justified, the CR model has shown to give a head start in understanding the reservoir.

Deviation from Tank-Like Behavior

The essence of the errors associated with the use of P/z plots in tight gas reservoirs is that substantial pressure gradients exist within the formation, resulting in a violation of the basic tank assumptions. Shut-in times of months or even years can be required to establish the reservoir pressure surrounding the well[2]. Even if moderately long shut-in or build-up times could economically be performed, heterogeneities can cause the determination of an average reservoir pressure to be practically impossible. (To add further to the problem, PVT non-linearities create additional error since an "average" pressure generally does not apply when pressures vary far from the average value.)

To illustrate these effects, a series of reservoir simulations have been performed on a simple 2-D 25x25x1 grid, representing a 10.5 E9m3 gas pool of 100m thickness. Table 1 contains the pertinent information regarding the set up of the simulation. In this example, a single, centrally located, vertical well is used to deplete the reservoir. The results are presented in terms of reservoir pressure (well grid block pressure) versus Gp. Since the gas was input as having ideal properties, pressure is equivalent to P/z and there are no condensate effects.

Fig. 1 shows the pressure decline, measured once per year, with production for the cases of a $k{\bullet}h$ = 10,000 md•m (high k) reservoir, and a $k{\bullet}h$ = 100 md•m (low k) reservoir. In all other aspects, the simulation input were identical. The higher permeability pool pressure decline points almost directly at the true GIIP of 10.5 E9m3. Simulation results showed little areal pressure variation throughout the grid and that the reservoir performance is tank-like.

In contrast, the pressure decline is not linear (i.e. not tank-like) for the low k case. Initially, the gridblock pressure declines very rapidly as the area surrounding the well cannot be recharged as fast as it is depleted by the well. This early, rapid pressure decline is seen often in tight gas reservoirs, and is an indication that the use of P/z plot analysis may be inappropriate. It is clearly apparent that the use of these early points would dramatically underestimate reservoir size.

After a time, the low k case pressure decline follows a straight line at roughly the same slope as the high k case. An extrapolation of this line would indicate a GIIP of roughly 9 E9m3 (>10% error). Such an extrapolation could easily be made if the initial pressure was not accurately known, or if the linearity of subsequent points would cause one to doubt the initial pressure measurement. Confidence in the initial pressure would result in a more poorly fit decline and an even larger error in GIIP calculation - as low as 7 E9m3 (>35% error). Late in time, the slope again changes, pointing to a higher GIIP value. This fairly abrupt change occurs when the gas rate falls off of its plateau level, illustrating that P/z plots become very rate dependent in tight gas reservoirs.

The use of the P/z plot to estimate remaining gas in place is particularly risky since the data only point to the true GIIP after most of the gas has been produced. This is well beyond the development planning time frame in most cases. For the current example, it is easy to imagine the remaining gas in place being estimated at 2 E9m3 after production of 5 E9m3, when in reality the reservoir still contains more than 5 E9m3 of remaining gas!

It can be argued that the reason for the difference in simulation results is due to the lack of sufficient build-up time prior to pressure measurements. While this does add to the problem, long shut-in times prior to static pressure measurement may only partially correct the problem. **Fig. 1** also shows the pressure decline for the same low permeability reservoir with a 36 day shut-in period prior to each pressure measurement. In terms of lost revenue, it would be difficult to justify such long shut-in periods and in many cases, full build-up information would be required to estimate the true reservoir pressure. For this simple, homogeneous example, the use of extended shut-in times does indeed partly alleviate the problem. However, extended shut-in times are not nearly as effective in alleviating the problem in heterogeneous reservoirs, as will be demonstrated later.

Rate dependence of the slope can create further misleading "straight-line" behavior in the P/z plot. **Fig. 2** shows the early pressure decline for the tight reservoir case where the early production is increased (ramped up) over time. Often, early production ramps up due to facilities coming on stream or as a more mature gas source declines leaving facilities capacity increasingly available. In this case, the sudden, early pressure drop noted in previous examples, is spread out over a number of years and almost appears linear with production. This apparent linearity can be misleading since it could be interpreted as indicating tank-like behavior while it is only a result of the P/z plot rate dependence.

The erroneous extrapolation of the early points curve in **Fig. 2** would lead to an estimated GIIP of only 6 E9m3 - an error of more that 40%! A more correct GIIP estimate could only be made later in the reservoir life. Note that this case also includes the 36-day shut-in period prior to pressure measurements.

Heterogeneity Effects

The problems in using P/z plots to perform a material balance become much greater if the reservoir permeability is heterogeneous. As an illustration, heterogeneous permeability fields were input into the previous simulation model. Roughly 27% of the gridblocks (representing 2.8 E9m3 GIIP) were assigned a relatively high permeability (1000 md.m) while the remainder (representing 7.7 E9m3 GIIP) were assigned low permeability (10 md.m). A series of five cases were run with the heterogeneity assigned to the gridblocks according to the patterns shown in **Fig. 3**. Heterogeneous Case #5 consisted of a random placement of high *k* and low *k* gridblocks. The results of the simulations, in terms of P/z versus Gp are shown in **Fig. 4**.

It is clear than the true GIIP of 10.5 E9m3 could not be established in any of the heterogeneous, tight gas reservoirs by using P/z plots. It is remarkable that in all but Case #5, fairly long straight line decline periods can be seen, all pointing to incorrect GIIP values. P/z plots are virtually useless for GIIP determination in every case presented. Worse, the plots can be extremely misleading. The P/z plots would suggest GIIPs ranging from 6.5 E9m3 (38% error) for Case #3 to 9 E9m3 (14% error) for Case #1. Only very late in the production life does the pressure decline point anywhere near to the true GIIP. Consequently the errors, in terms of remaining gas in place, can be huge. Once again, a 36-day shut-in period was assumed for all cases.

Unlike the homogeneous case, pressure build-ups would not be of help in determining true average reservoir pressure, unless extended for impractically long periods of time. Simulation results show that substantial pressure gradients exist within the tight reservoir that would require months, if not years, of shut-in time to stabilize to the point where an average pressure could be determined.

Scatter in Pressure Data

Pressure gradients mean that wells located in different parts of the reservoir will record differing pressures under reasonable shut-in times. The pressure at these wells can also be influenced by their previous rate of production, surrounding permeability distribution, and the amount of shut-in time. These variations will manifest as scatter within the P/z plot that remain after correction for gauge errors.

Unlike curvature, which can also be caused by complex gas phase behavior or additional pressure support sources, scatter in the P/z plot is diagnostic of substantial reservoir pressure gradients. Hence, if substantial scatter is seen in a P/z plot, the tank assumption is being violated and the P/z plot should not be used to determine the GIIP and reserves.

Real-life examples of the P/z scatter taken from multi-well gas pools in the Waterton Gas Field are shown in **Figs. 5 to 7**. Although straight-lines are shown drawn through these points, the "tank" assumption is clearly violated. The question is, can these material balances be believed? Clearly a different method of material balance calculation is required.

Communicating Reservoir Model

A different technique that has proven successful in performing material balances in tight gas reservoirs is the Communicating Reservoir (CR) Model. Rather than using a single tank, the technique consists of subdividing the reservoir into a number of tanks that are allowed to communicate. Such tanks can either be depleted directly by wells, or indirectly via other tanks.

Flow rates between tanks is set proportionally to either the difference in the square of tank pressures or the difference in pseudo-pressures. In terms of pressure squared, the flow between two tanks *x* and *y* is determined as:

$$q_{xy} = C_{xy} \cdot (P_x^2 - P_y^2) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where C_{xy} is termed the communication factor and q_{xy} is the rate of flow between the two tanks. Individual tank pressures are determined by assuming straight line P/z versus G behavior where G includes both Gp (gas produced by wells in the tank) and Ge (gas efflux to or influx from connected tanks).

A CR model input consists of defining the amount of gas contained within each tank (tank sizes), the inter-tank communication factors, the initial pressure of the tanks, and the production rate profiles from the individual tanks. For simplicity, CR model simulations are performed fully explicit in time. At each time step, the pressures in the various tanks are calculated, yielding a pressure profile that can be matched to the actual pressure decline.

Rather than plotting P/z versus Gp, the pressure decline is compared with actual pressures as a function of time. Such pressure versus time plots reveal information about reservoir performance that is lost in a typical P/z plot. Performing a material balance history match consists of varying the number of tanks required, the size of the tanks, and the communication factors until an acceptable match of the pressure decline is obtained.

While the CR model was originally built to handle gas reservoirs containing partially sealing faults, it has also proven to considerably improve material balance accuracy over conventional P/z plots in tight pools. *The improved accuracy stems from its ability, albeit crudely, to incorporate reservoir pressure gradients, which are completely neglected in the single tank, conventional P/z plot method.*

Although the use of the CR model requires a computer, the algorithm can easily be input into a spreadsheet program. The CR model results presented in this paper were all generated using a simple spreadsheet program that can handle up to 10 tanks in a single reservoir. If a spreadsheet program is not available, only rudimentary programming skills are required to generate a stand-alone CR model solver. A third option is to make use of a reservoir simulator, using gridblocks to represent tanks.

Application of the CR Model

To illustrate its ability to match actual pressure declines, the communicating reservoir model has been applied to the heterogeneous tight reservoir example cases described previously. The history match to the heterogeneous Case #3 is shown in **Fig. 8**. The match is clearly superior to either the tank model associated with the initial P/z decline analysis (7 E9m3) or the tank model containing the true 10.5 E9m3 GIIP. A graphical representation of the best fit CR model is shown in **Fig. 9**. The representation contains a small tank of some 3.2 E9m3 that is directly depleted by the well and a larger tank of 7.5 E9m3 that feeds the smaller one. In contrast to the P/z Plot results, the total GIIP of 10.7 E9m3 very closely agrees with the true GIIP of 10.5 E9m3 and closely matches the actual pressure decline.

In such theoretical cases, the CR model can be rather imprecise in the GIIP determination. For example, there is some latitude to make the indirectly depleted tank somewhat larger (or smaller) and the communication factor smaller (or larger), resulting in some total GIIP uncertainty. For the case described above, the match only severely deteriorates outside of the 10.0 to 11.5 E9m3 GIIP range. Although somewhat imprecise, the result is still far more accurate than that achieved using the conventional P/z plot method. The imprecision, as demonstrated later, is a result of the lack of rate variation employed in the reservoir simulation input, and virtually disappears when real data is used. In practice, reservoir rates often fluctuate substantially over time, providing a more difficult profile to match and increasingly constrains the CR model results.

A common first reaction to exposure to the CR model is that a better match of the pressure decline is obtained solely due to an increase in the number of degrees of freedom over the P/z plot. However, the problem of too many degrees of freedom can be avoided by employing Occam's razor[3], i.e. using a simple to complex methodology of applying the CR model. Initial attempts at matching the pressure decline should only incorporate as many tanks as required to duplicate the significant pressure scatter between wells. That is, the reservoir should be divided into as few tanks as possible that contain wells that are proximate and that measure consistent reservoir pressures. Only if the model is still incapable of matching the observed pressure decline should additional tanks be added. Additional tanks can be added by either subdividing the previously defined tanks or by adding tanks that contain no drainage points.

The simple to complex methodology ensures that the model does not contain unnecessary degrees of freedom. Using the current example, only one tank is necessary to represent the region depleted by production, since there is only one well in the reservoir. However, as the P/z plot indicated, a single tank cannot adequately match the actual pressure decline. This required the incorporation of a second tank, which allowed a satisfactory match of the entire pressure profile.

Material Balance Calculations in the Waterton Field

The spreadsheet CR model application described previously has been applied to the tight gas pools within the Waterton Gas Field to aid in reserves evaluation and determine the size of potential remaining gas targets. Most of the results of the CR model have been recently supported by full field simulation, and have led to both reserves revisions and development projects to increase gas recovery. Three examples are shown in this paper to illustrate the pitfalls of using P/z plots in tight gas reservoirs and to illustrate the success obtained with the CR model.

The Waterton gas field is located along the edge of the Rocky Mountain Front Range in southwestern Alberta (**Fig. 10**). Intense folding and thrust faulting has resulted in a complex of over-thrust Mississippian and Devonian carbonates at depths of approximately 3500 m in which sour, wet gas has been trapped. Production from the structures depends primarily on permeability enhancement due to natural fractures. Well productivity is found to vary considerably both between and within individual reservoirs, depending on the degree of fracturing.

Sheet III. The largest reservoir within the Waterton Field is the Sheet III pool. The pool was discovered in 1957, and since 1961 has produced 72 E9m3 of gas. The reservoir production profile is shown in **Fig. 11**. Since the pool is towards the end of its producing life, small errors in GIIP calculations can dramatically effect the estimated remaining reserves and hence, alter both the value of the reservoir and its anticipated producing life. Due to the complexity of the structure and pore system, volumetric gas estimates for the pool contain very large uncertainties causing both GIIP and reserves estimates to be highly reliant on material balance results.

Historically, the GIIP within Sheet III has been estimated using the classical P/z analysis as shown in **Fig. 5**. The most recent assessment of GIIP using this technique is some 82 E9m3 and at abandonment, gas recovery is expected to be 76 E9m3. However, the tank model does a poor job of matching historical pressure, even when a two-phase z factor is applied to the decline. A straight line consistently overestimates pressure in the middle of the field life and fails to duplicate the decline in slope at late times. This is further illustrated in **Fig. 12**, where the actual pressure decline over time is compared with tank models representing 75, 80 and 85 E9m3 GIIP. The tank models can match either the middle period or the late period reasonably well, but not both.

Use of the communicating reservoir model dramatically increased the quality of the pressure decline match. In the application of the model, separate tanks were used for the production from each of the seven canyons where wells were drilled to the pool. An eighth tank was used to represent areas of the reservoir that were not directly depleted (i.e. the flanks of the structure). The matches of pressure decline for two of the canyons are shown in **Figs. 13, 14**. The matches for the remaining canyons are of similar quality.

Not only does the CR model match the pressure for all times, but many subtle changes in pressure behavior due to variations in canyon production rates are duplicated. These subtle changes are a result of the variations in production rates associated with the depletion of a real reservoir, as seen in **Fig. 11**. The process of matching these subtle variations in reservoir pressure allows the CR model to be tuned to greater precision than was evident from the theoretical example discussed previously. The pressure decline in the eighth, indirectly depleted tank is shown in **Fig. 15**. The final pressure in this tank is somewhat (approx. 3 MPa) higher than those drained directly by wells, suggesting that areas of the reservoir that are less effectively depleted.

The CR model that produced the pressure decline match is represented in **Fig. 16**. The model determined that the GIIP is approximately 98 E9m3, and forecasted ultimate recovery to be some 82 E9m3. This means that the remaining developed reserves are actually 10 E9m3, or 2.5 times the 4 E9m3 suggested by the P/z Plot analysis! In addition, the CR model indicated that additional reserves potential exists in the field if the higher pressure areas of the field could be located and drilled.

Since the CR work was performed, detailed, full field simulations have been used to confirm the higher GIIP value. The simulations identified that the flanks and northern area of the gas pool likely contain higher pressure gas than the southern crest of the reservoir where all of the wells are located. It has been concluded that the indirectly depleted, higher pressure tank used in the CR model likely represents these flank/northern areas.

The business impacts associated with correctly assessing the reservoir GIIP and reserves are substantial. Remaining reserves from the pool have been more than doubled; simply by a better understanding of the depletion process. In addition, a northern well producing from a deeper reservoir was sidetracked into the Sheet III pool and confirmed higher pressure in the north. This well is expected to add 1 E9m3 reserves to the pool. Additional wells and sidetracks are currently being drilled, to access the more poorly drained areas of the reservoir.

Sheet IVc. Volumetric analysis of the Sheet IVc pool indicates that some 12.5 E9m3 of GIIP is contained within two non-communicating zones - the upper Mississippian Mounthead (Mmh) and Mississippian Livingstone (Mlv) formations. The P/z plot for Sheet IVc is shown in **Fig. 6**. Although there is an extreme amount of scatter due to differing zonal and areal pressures, the GIIP indicated from any straight line plotted through the data falls well short of the 12.5 E9m3 volumetric estimate.

To reduce the amount of scatter, an attempt was made at subdividing the reservoir into two areas (North and South) and into two zones (Mmh and Mlv), i.e. a simple four-tank representation. Due to a difference in fluid composition, total production and (to a lesser degree of confidence) pressure could be allocated between the two zones. Individual P/z plot material balances were performed on the areas/zones as shown in **Fig. 17**. While the use of four zonal/area P/z plots reduced the scatter somewhat, the total GIIP estimate of 6.9 E9m3 remained considerably smaller than the volumetric estimate.

The area/zonal P/z plot methodology proved a failure when the actual pressure profile was simulated using a four non-communicating tank model. The resulting pressure profiles, shown in **Fig. 18** had two of the areas/zones completely depleted. In fact, production from these zones/areas continues today, indicating that the zones/areas do communicate.

This inconsistency disappears when the material balance analysis is performed with the CR model, shown in **Fig. 19**. In addition, the model, illustrated in **Fig. 20**, results in a GIIP estimate (11.5 bcm) that is in approximate agreement with volumetrics.

Sheet IV. The Sheet IV pool P/z plot, shown in **Fig. 7**, is an excellent example of how pressure decline information can be lost when only plotted against gas production. As with Sheet IVc, the Sheet IV P/z plot shows considerable scatter and suggests a GIIP much smaller than the 28 E9m3 estimated from volumetrics. What is lost in the P/z plot is the fact that this pool was shut-in for several years midway through its life (**Fig. 21**). When the pool is subdivided into five areas to account for areal pressure variation and the pressure for each area plotted against time, the build up of reservoir pressure during the long shut-in period becomes apparent (**Fig. 22**). This build-up of pressure cannot be duplicated by using either a single or multi non-communicating tank model, since an external source of pressure energy is needed to recharge the area surrounding the producing wells..

The combination of extended production and shut-in periods for the pool results in a good variation in rate behavior to calibrate the CR model. Unlike a tank model, the CR model was able to duplicate both the pressure decline and build-up, as shown for Area #1 in **Fig. 23**. As with Sheet IVc, the CR model GIIP of 28.5 E9m3 is in approximate agreement with volumetrics and later confirmed using reservoir simulation. The CR model is illustrated in **Fig. 24**.

Summary. In all three of the pools described, the use of the CR models has resulted in increases in the dynamic GIIP estimates that are much closer to the volumetric estimates. In addition, reservoir simulation has been able to confirm the validity of the increases in both GIIP and reserves that the CR models have indicated. The value of the Waterton Gas Field has been substantially impacted by this work and further field developments are planned to exploit the poorly drained areas of the reservoirs. Clearly, the use of P/z plots to estimate GIIP in these tight reservoir can be very misleading.

In addition to the reservoirs shown, the CR model has been successfully applied to other tight gas pools within Waterton, Canada, Europe and Asia - all leading to substantially better reservoir characterization and forecasts.

Conclusions

1. The use of linear P/z decline analysis and tank modelling is misleading in determining (generally underestimates) GIIP in tight gas reservoirs. In such reservoirs, substantial pressure gradients can exist within the reservoir even after considerable shut-in periods.
2. Apparent straight line P/z decline cannot be used to conclude that a gas reservoir behaves as a tank. Such a straight line may or may not point to the true GIIP.
3. Scatter in the pressure decline (after accounting for measurement errors) is caused by pressure gradients in tight gas reservoirs and should not be arbitrarily dismissed. Scatter and curvature contain valuable information that can and should be exploited much more than simply plotting P/z versus Gp. Essential information, lost in the P/z plot, can be gained by viewing the pressure decline versus time, along with a rate plot.
4. The Communicating Reservoir (CR) model is illustrated as a simple method of performing material balance analysis in tight gas reservoirs. The model is able to more accurately estimate reservoir size than the conventional P/z plot method.
5. The application of both tank and CR Modelling is illustrated for three pools in the Waterton Gas Field. In all three cases the CR model has been able to precisely follow the actual pressure decline and is in close agreement with volumetrics and reservoir simulation. In all three cases, the tank models (P/z plots) indicated substantially lower GIIP and reserves.
6. The use of the CR model can lead to development opportunities that would be missed if less accurate material balance methods are applied. It has the ability to quickly and accurately assess the reserves, future potential, and value of a gas reservoir more reliably than is done using the current industry standard technique.

Nomenclature

C = communication factor, E3m3/(d•kPa^2)
GIIP = gas initially in place, E9m3
Gp = cumulative gas production, E9m3
Ge = cumulative gas efflux, E9m3
P = reservoir pressure at datum, kPa
q = gas flowrate, [E3m3/d]
z = non-ideal gas factor

Acknowledgments

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References

1) Dake,L.P.:Fundamentals of Reservoir Engineering, Elsevier Science Publishers B.V., Amsterdam (1978)
2) Meehan,D.N., Verma,S.K.; "Improved Reservoir Characterization in Low Permeability Reservoirs With Geostatistical Models", SPERE, August 1995.
3) William of Occam; "*pluritas non est ponenda sine necessitate*" or nature likes things as simple as possible, 14th C.

Tables

Table 1 - Reservoir Simulation Model Parameters

Grid:	25 (88m) x 25 (88m) x 1 (100 m)
Gas PVT :	Ideal gas behavior
Gas Viscosity :	0.013 cp @ 1.0 MPa
	0.030 cp @ 35.0 MPa
Sw:	10%
Porosity:	8%
Initial Pressure	30 MPa
Production Plateau:	200 E6m3/yr
Well Skin	-0.5
Well Radius	0.1 m
Minimum FBHP	1 Mpa

Figures

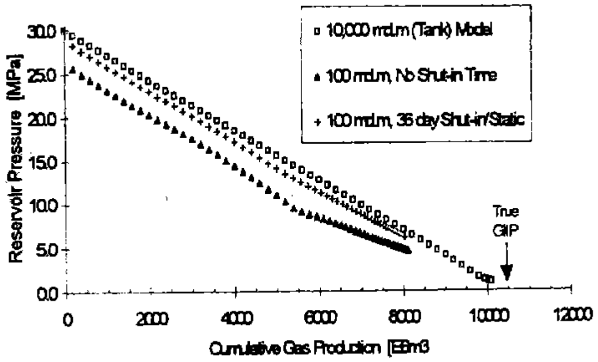

Figure 1: P/z plot from simulation for high and low homogeneous permeability gas reservoirs. Only late in the depletion, when production rates have declined considerably does the low permeability P/z plot point to the true GIIP.

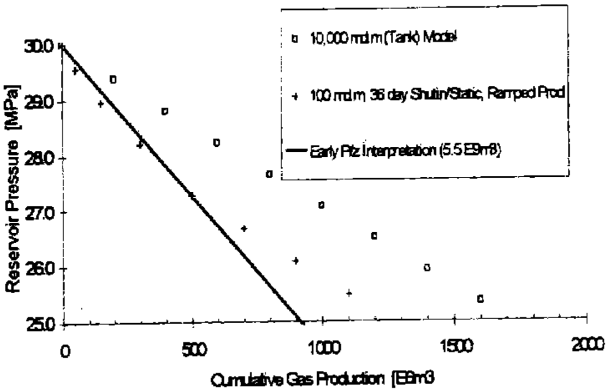

Figure 2: Early P/z plot Behavior for high and low permeability gas reservoirs with increasing early production rate. Note the almost "linear" behavior of the first four points in the tight reservoir case that would extrapolate to only 1/2 of the true GIIP.

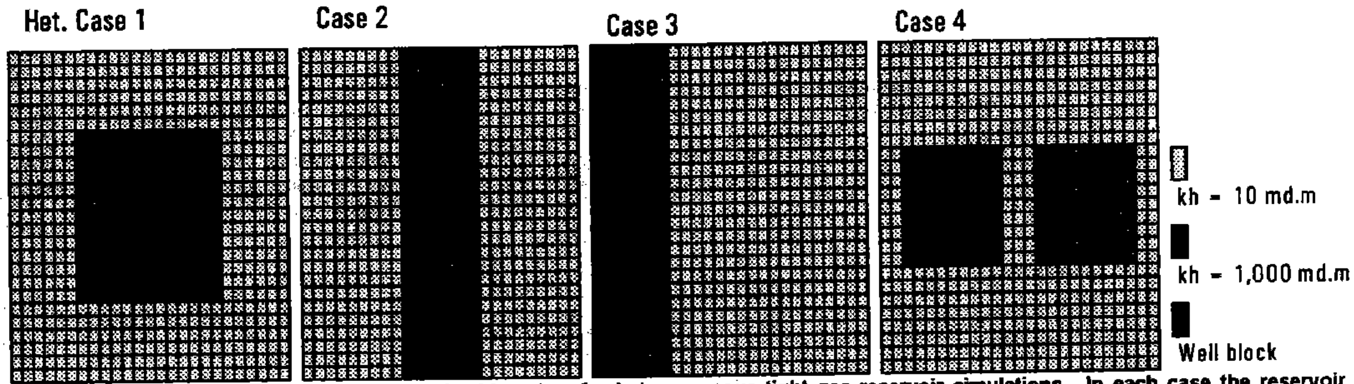

Figure 3: Areal permeability distribution and grid system for heterogeneous tight gas reservoir simulations. In each case the reservoir is depleted by a single well in a higher permeability area. Case 5 consists of a random distribution of high and low permeability gridblocks.

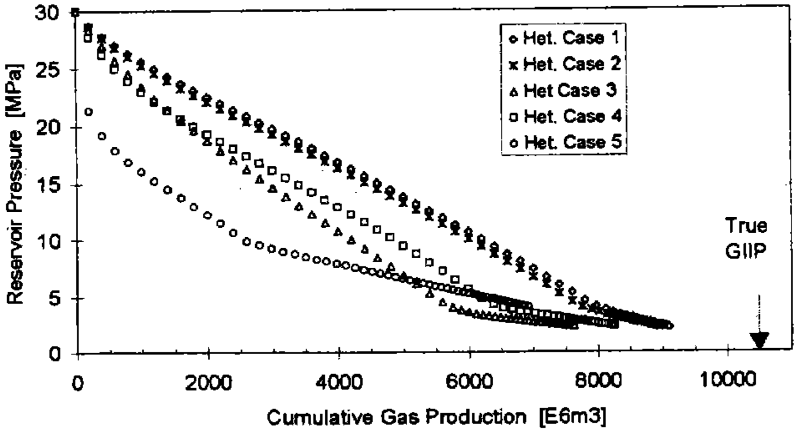

Figure 4. P/z plots from simulation for heterogeneous low permeability gas reservoirs. None of the pressure declines point to the true GIIP for the simulation. Most cases also contain reasonably "linear" behavior that might erroneously lead to the conclusion that the reservoirs are behaving tank-like. All cases include a 36-day shut-in prior to pressure measurement.

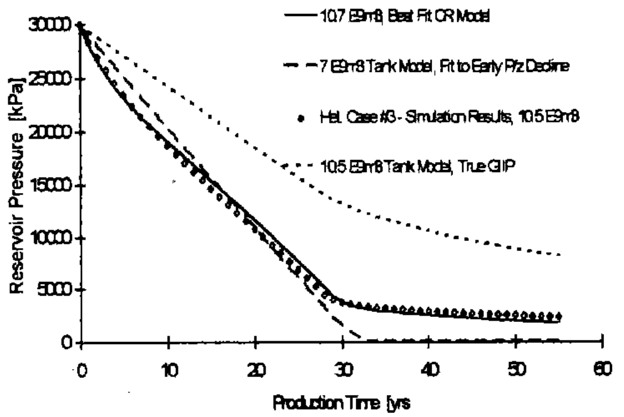

Figure 8. Match of the pressure decline vs. time of the simulation results from heterogeneous reservoir Case 3 by the Communicating Reservoir (CR) Model. The CR Model GIIP is in approximate agreement with the true GIIP. Note that the Tank Model derived from the early P/z Plot decline does not match the late period. Also, the Tank Model sized to the true GIIP does not match the pressure decline at all.

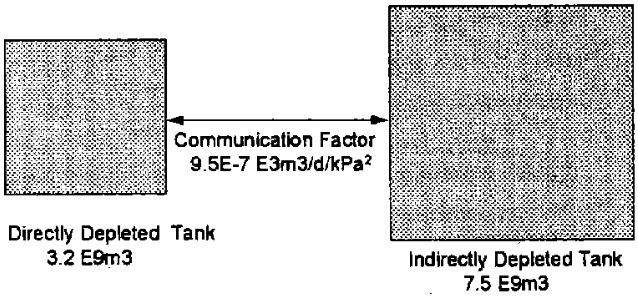

Figure 9. Diagrammatic representation of the CR model used to match the heterogeneous Case 3 simulation results. The model consists of a 3.2 E9m3 tank containing the production well, in communication with a second 7.5 E9m3 tank.

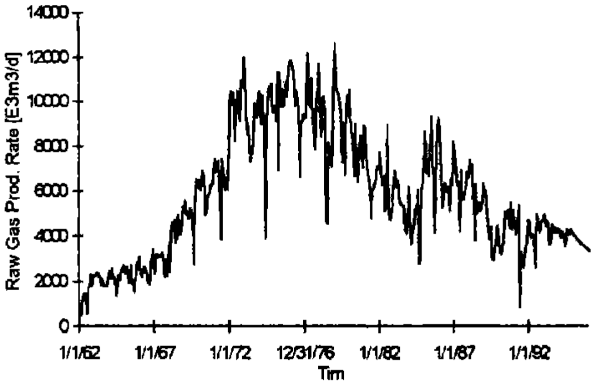

Figure 11. Production history of the Waterton Sheet III reservoir. The irregularity of production allows the CR model to match pressure profile subtleties, resulting in a precise estimate of the reservoir GIIP

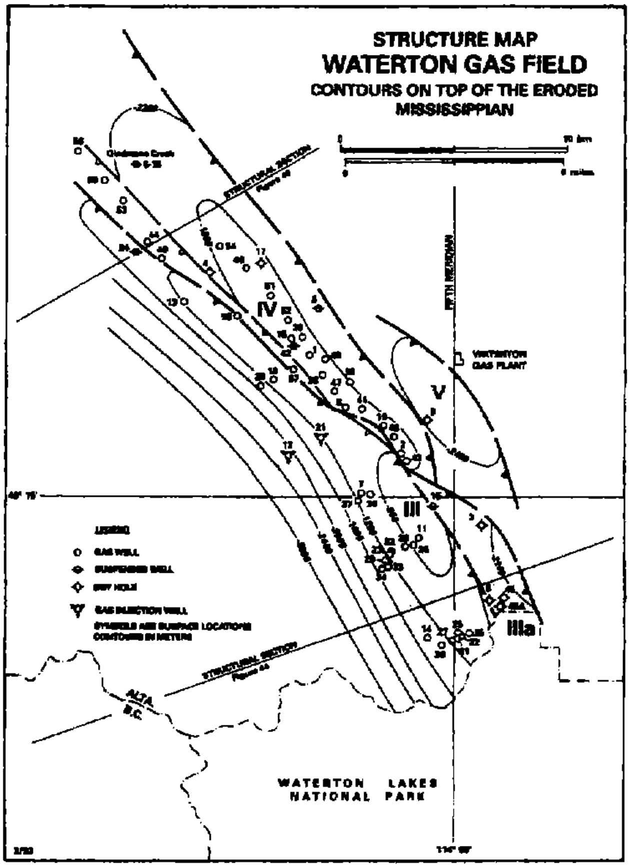

Figure 10. Areal Map of the main producing reservoirs in the Waterton Gas Field showing both Sheet III and Sheet IV. Sheet IVc lies below Sheet III and is located between Sheet III and Sheet IV on the map.

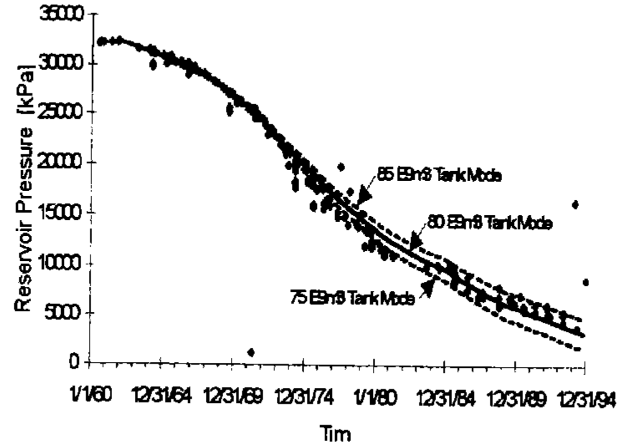

Figure 12. Comparison of actual Waterton Sheet III pressure decline with Tank Model results. The Tank Model cannot match both the mid-time pressure and late-time pressures at the same time, regardless of the tank size used.

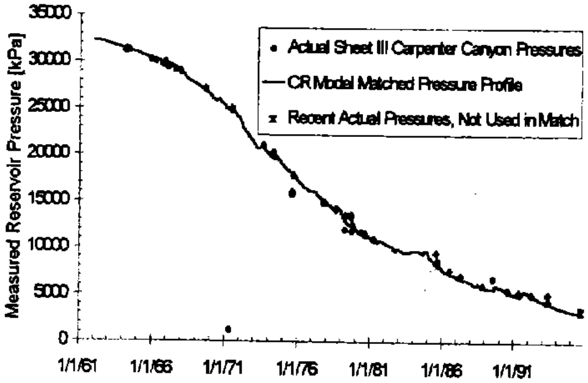

Figure 13. CR Model match of Waterton Sheet III Pressure Decline in Carpenter Canyon. Unlike the tank model, the CR model can match the whole pressure profile, including changes in the decline slope caused by variable production rates.

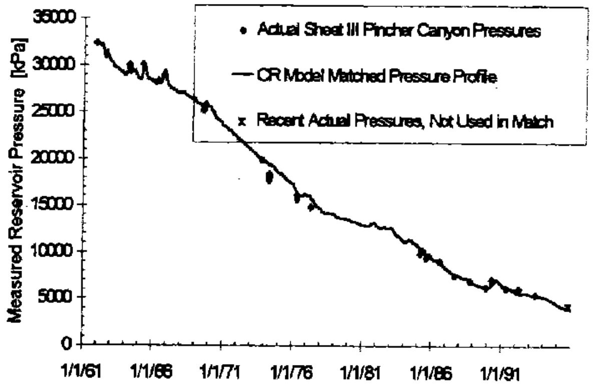

Figure 14. CR Model match of Waterton Sheet III Pressure Decline in Pincher Canyon. As in Figure 13, the CR model can match the whole pressure profile. The CR model has also been able to able to forecast recent pressure measurements made in both canyons.

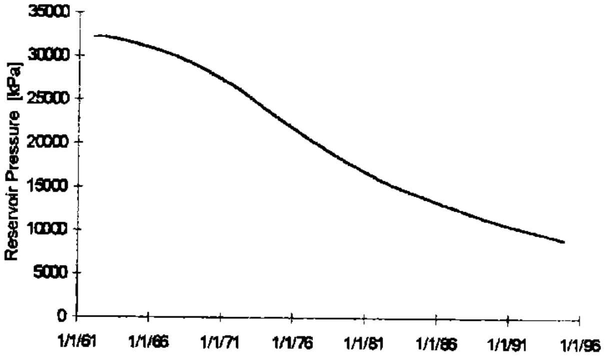

Figure 15. Pressure profile of indirectly depleted tank as forecast by the Waterton Sheet III CR model. The substantially higher pressure of this tank suggests that there are regions or zones within Sheet III that are more poorly depleted, indicating potential development opportunities in the reservoir.

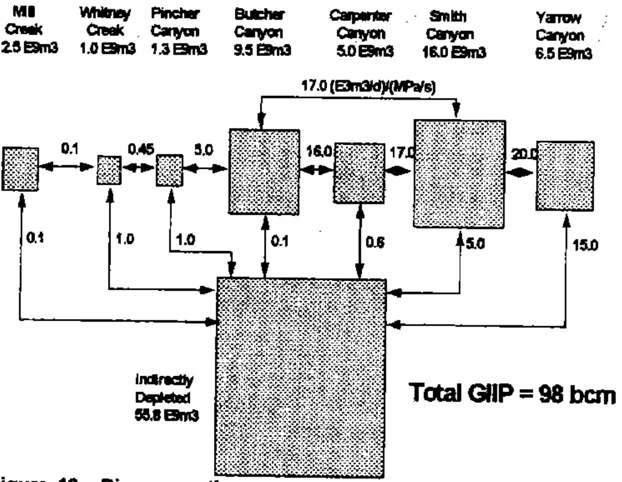

Figure 16. Diagrammatic representation of the Waterton Sheet III CR model. The total GIIP of 98 E6m3 substantially exceeds the 82 E6m3 generated by the convention P/z Plot method.

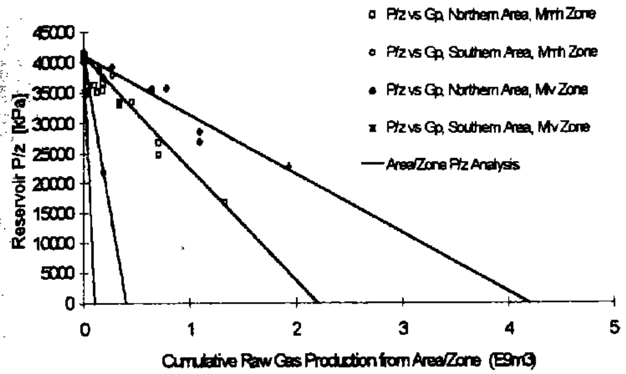

Figure 17. P/z Plot analysis performed on Waterton Sheet IVc by zone and area, assuming independent declines. While this method can reduce the scatter from the P/z plot, the resulting total GIIP determination of 6.9 E9m3 remains considerably lower than the volumetric estimate of 12.5 E9m3.

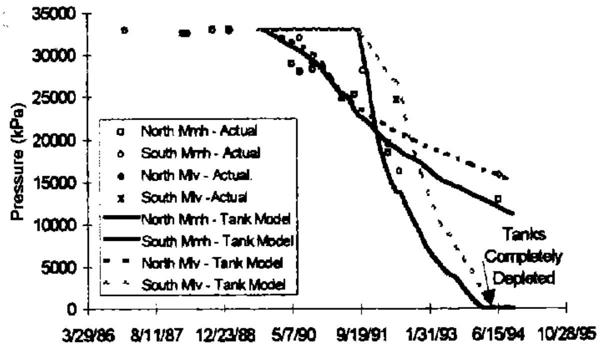

Figure 18. Comparison of Tank Model results with actual pressure decline for Waterton Sheet IVc, using the tank GIIP estimates from the analysis in Figure 17. The Tank model predicts that both zones in the Southern area of the reservoir should be completely depleted, yet production from this area continues.

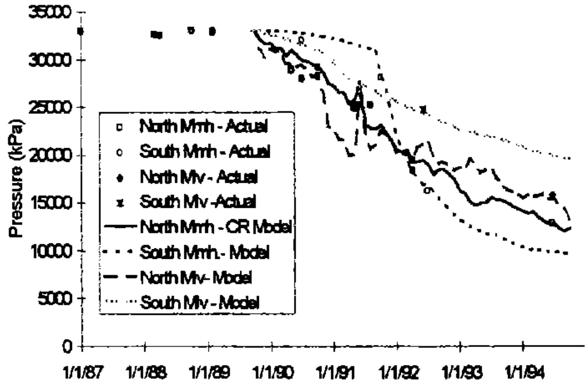

Figure 19. Comparison of CR model results with actual pressure decline for Waterton Sheet IVc. The model matches actual data more closely than the multiple tank model shown in Figure 18. In addition, the CR problem is physically consistent - none of the areas/zones show complete depletion.

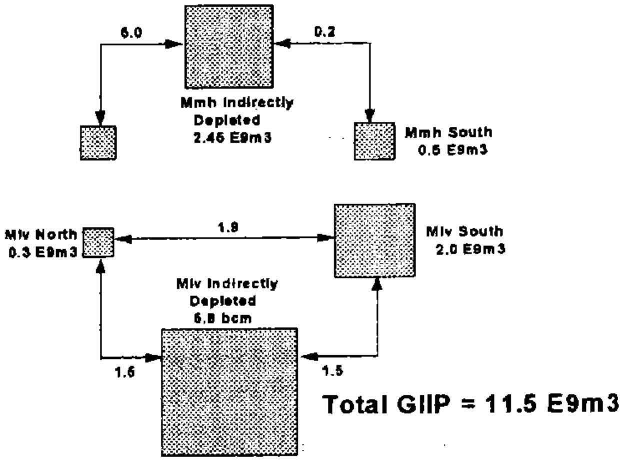

Figure 20. Diagrammatic representation of the matched CR model for Waterton Sheet IVc that produced the results shown in Figure 19. Note that unlike the multiple tank model derived from P/z Plots, the total GIIP of 11.5 E9m3 is in rough agreement with volumetrics.

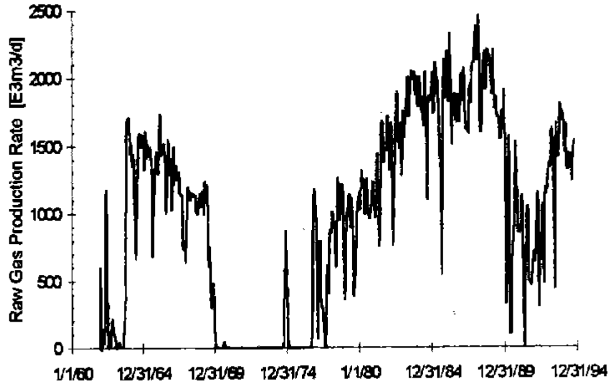

Figure 21. Waterton Sheet IV production history profile. Fluctuations in rate, including an 8 year shut-in period beginning in 1970 influences the pressure decline profile. This information is lost in the P/z Plot shown in Figure 7.

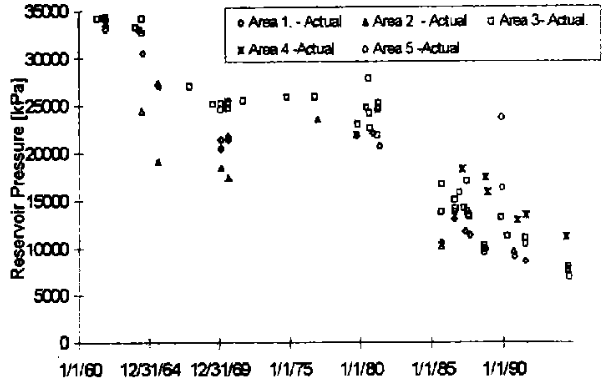

Figure 22. The pressure decline versus time reveals character in the data lost in the P/z plot shown in Figure 7. When viewed along with Figure 21, a buildup in pressures is seen between 1969 and 1977, corresponding to the long shut-in period.

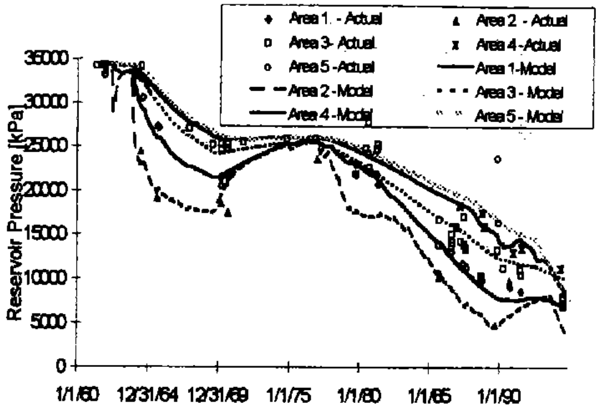

Figure 23. Comparison of the history matched CR model results with actual pressure decline for Waterton Sheet IV. The CR model is able to duplicate the reservoir build-up during the extended shut-in period. According to the tank-like assumption fundamental to the use of P/z plots for material balance, such build-ups cannot occur.

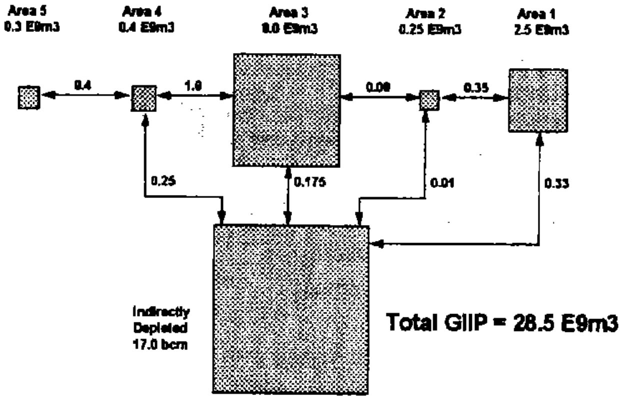

Figure 24. Diagrammatic representation of the matched CR model for Waterton Sheet IV that produced the results shown in Figure 23. The model GIIP is in rough agreement with both volumetrics and reservoir simulation.