# DETERMINATION OF GAS IN-PLACE FROM ANALYTICAL ANALYSIS OF SHUT-IN OR FLOWING PRESSURE SURVEY DATA

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## INTRODUCTION

There is evidence that the current need for natural gas reserves has made certain low permeability reservoirs, heretofore considered marginal or uneconomical, candidates for development. Accurate estimates of the gas in-place in these reservoirs will not only be important for pipeline contracting purposes, but will become fundamental requirements for establishing the most economic well spacing and the best facilities and operations design.

Considerable effort has been directed to the problem of estimating the gas initially in-place and in predicting future performance of natural gas wells. Basically, the techniques described in various reviews of the methods used fall into the volumetric or the performance categories.[1,2,3] The volumetric technique, based on geological considerations, is useful in the very early stages of a reservoir's life. The pressure production methods, based on data recorded during the producing life of a well, are generally considered more accurate and can side-step the error in volumetric estimates caused by unknown reservoir properties.

Most theories for estimating the gas in-place have been based on one or more idealizations. Most performance calculations assume semisteady-state flow, small and constant compressibility, gas viscosity calculated at an average pressure, radial flow and all other ideal reservoir considerations.[4,5] Most calculation methods require that the pressures on which the solution is based be weighted average representations of reservoir pressure.

With the acceptance of real gas potential,[6] and the development of equations defining the average pressure in bounded reservoirs of different configurations,[7] it becomes feasible to develop a process for estimating the initial gas in-place from shut-in or flowing pressure data that is not stabilized. The method can take into consideration the geometry of the drainage area and the fact that the gas compressibility may vary widely because of large pressure drops in a low permeability system.

The equations expressing the semisteady-state pressure drawdown or build-up in terms of the real gas potential at the wellbore are presented as Eqs. (2) and (3) below. In order to prove the validity of the concept, three separate executions of a numerical simulation model were performed to develop pressure-production data suitable to check out the new procedure. Two different geometries and two different well flowing conditions were imposed on the numeric models so as to develop data under a range of assumptions. In all instances, a known amount of gas was assigned to the models and a pressure history corresponding to the assigned withdrawal schedule was developed. This pressure history, if correctly evaluated by the proposed procedure, should generate the known gas in-place to a high degree of resolution.

## DERIVATION OF THE ANALYTICAL MODEL

The material balance equation for a finite gas reservoir with no water drive is:

$$G = \frac{G_p}{1 - \frac{z_i}{p_i}\frac{\bar{p}}{\bar{z}}} \qquad (1)$$

where:

$G$ = Gas initially in-place, MMSCF
$G_p$ = Gas produced at the time of test, MMSCF
$p_i$ = Initial reservoir pressure, psia

$z_i$ = Super compressibility factor at initial conditions
$\bar{p}$ = Average stabilized pressure of the reservoir at the time of test, psia
$\bar{z}$ = Average super compressibility factor corresponding to $\bar{p}$, pressure

When the well has been produced for a time such that semisteady-state flow conditions prevail, the following equation describes the flow from the reservoir into the wellbore:

$$\left\{ m(\bar{p}) - m(p_{wf}) \right\} / q = C_1 \qquad (2)$$

where:

$m(\bar{p})$= Pseudogas potential corresponding to a pressure, p

$$= 2 \int_{p_b}^{p} \frac{p dp}{\mu_{(p)} \, z_{(p)}}$$

$p_{wf}$ = Flowing bottomhole wellbore pressure at the time of test, psia

$$C_1 = \frac{48.379 \; p_{sc} T}{kh} \left( \ln \frac{4A}{\gamma C_A \; r_w{}^2} + 2s \right)$$

q = Gas flow rate at the time of test, MSCFD

Equation (2) assumes either there is no turbulent flow in the reservoir or that there is no significant change in the gas flow rate from one test period to another such that the turbulent effect is approximately constant.

Generally, most gas wells are tested periodically. The testing procedure is comprised of measuring the flowing pressure, then shutting the well for a period and measuring the shut-in wellhead pressure.

Proper superposition of semisteady-state flow and unsteady-state shut-in transients, results in the following equation describing shut-in pressure behavior of the wellbore.

$$\frac{m(\bar{p}) - m(p_{ws})}{q} = \frac{48.379 \; p_{sc} T}{kh} \left[ \ln \frac{4A}{\gamma \; C_A \; r_w{}^2} + 2s - p_D \, (\Delta t_{Dw}) \right] \qquad (3)$$

where:

$p_{ws}$= Shut-in bottomhole wellbore pressure, psia
$\Delta t_{Dw}$= Dimensionless shut-in time =

$$\frac{0.000264 \; k \Delta t}{\phi \mu c \; r_w{}^2}$$

$p_D$ = Dimensionless pressure function

If the shut-in time is the same for each test, then $p_D \; (\Delta \, t_{Dw})$ becomes constant and Eq. (3) may be written as:

$$\frac{m(\bar{p}) - m(p_{ws})}{q} = C_2 \qquad (4)$$

where:

$$C_2 = \frac{48.379 \; p_{sc} \; T}{kh} \left[ \ln \frac{4A}{\gamma C_A r_w{}^2} + 2s - p_D \, (\Delta t_{Dw}) \right]$$

DATA REQUIRED FOR THE CALCULATION

The data required for this solution technique is that data normally available from gas well tests. Either the flowing or the shut-in data may be applied to the calculation. If shut-in data are used, the flow rate prior to shut-in and the shut-in bottomhole or wellhead pressure at a recorded time, along with the cumulative production from the well to that point in time, are required. If flowing data are applied to the calculation, the rate of production along with the recorded flowing wellhead and/or bottomhole pressure and the cumulative production data are substituted for the above. Normal data describing the gas properties are also necessary. The proposed procedure can provide the obvious advantage of reserve estimates without shutting-in a subject well. The data required are the practical data recorded and available for most existing fields. New and exotic data are not required.

## SOLUTION TECHNIQUE

The sequence for using Eqs. (1) through (4) in determining the gas in-place and the parameters required to predict the future performance of a well are as follows:

1. A volume of gas is assumed for the drainage pattern and a trial $\bar{p}$ divided by $\bar{z}$ at each test date is determined from Eq. (1) based on the cumulative production.
2. The trial $\bar{p}$ is converted to the corresponding $m(\bar{p})$.
3. Equations (2) and (4) are used to compute the values of $C_1$ and $C_2$ at each test point.
4. An arithmetic average value of $C_1$ and $C_2$ are computed and a standard deviation between the average $C_1$ and $C_2$ values and the computed $C_1$ and $C_2$ values for each test point are obtained as follows:

$$Sy_1 = \left[ \sum_{i=1}^{n} \left\{ (C_1)_i - (C_1)_{avg} \right\}^2 / n \right]^{0.5} \quad (5)$$

and

$$Sy_2 = \left[ \sum_{i=1}^{n} \left\{ (C_2)_i - (C_2)_{avg} \right\}^2 / n \right]^{0.5} \quad (6)$$

The value of assumed gas in-place is varied systematically and steps 1 through 4 are repeated until minimum deviations $M_1 = \min(Sy_1)$ and $M_2 = \min(Sy_2)$ are obtained. The best estimate of gas in-place corresponds to the minimum of $M_1$ and $M_2$.

## DATA VALIDITY CHECK

A validity check of the data can be usually made by reviewing plots of the minimum deviation curve (Figs. 1, 3, and 4) and a plot of the change in the terms $[m(p_i) - m(p_{ws})]/q$ for shut-in data and $[m(p_i) - m(p_{wf})]/q$ for flowing data plotted versus Horner time where Horner time is defined as cumulative production divided by test rate (Figs. 2a, 2b, 2c).

If the standard deviation curve has a symmetrical appearance, this indicates the data to have random scatter and the solution should be valid. If, however, the standard deviation curve is asymmetrical in appearance it is an indication of skewed data and the confidence in the solution is reduced. The second plot (Fig. 2) is used to confirm that the pressure points applied to the solution are actually valid and the result of semisteady-state withdrawals. Valid points will approximate a straight line on this plot. Any points widely varying from a straight line should be discarded from the solution.

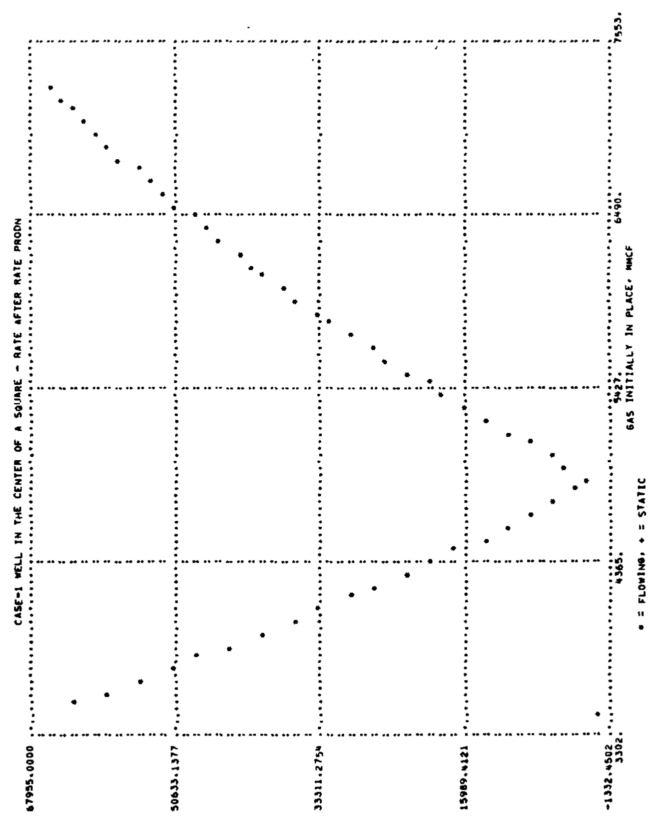


FIG. 1—CASE 1 - WELL IN THE CENTER OF A SQUARE—
. RATE AFTER RATE PRODN

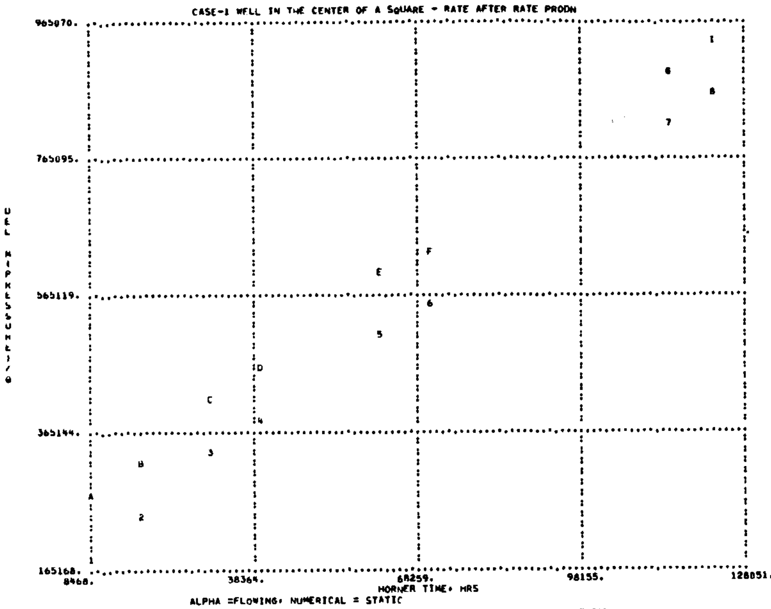


FIG. 2A—CASE 1 - WELL IN THE CENTER OF A SQUARE—RATE AFTER RATE PRODN

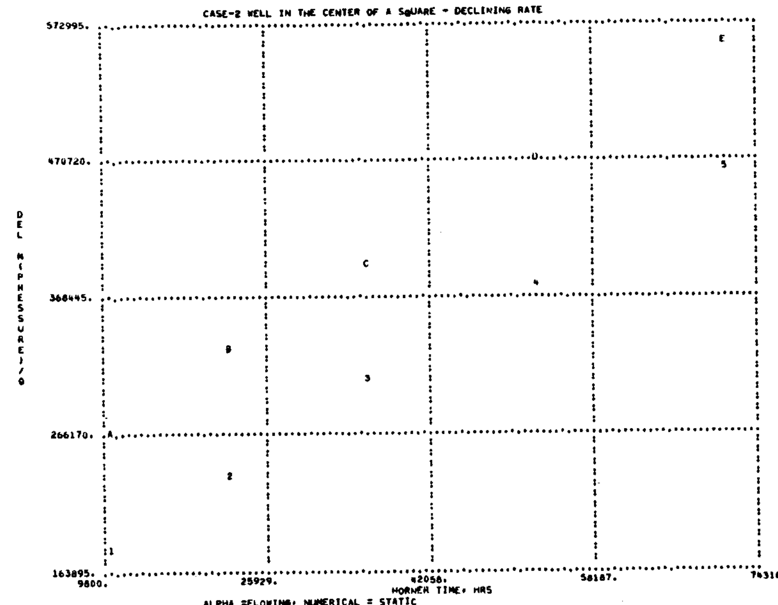


FIG. 2B—CASE 2 - WELL IN THE CENTER OF A SQUARE—DECLINING RATE



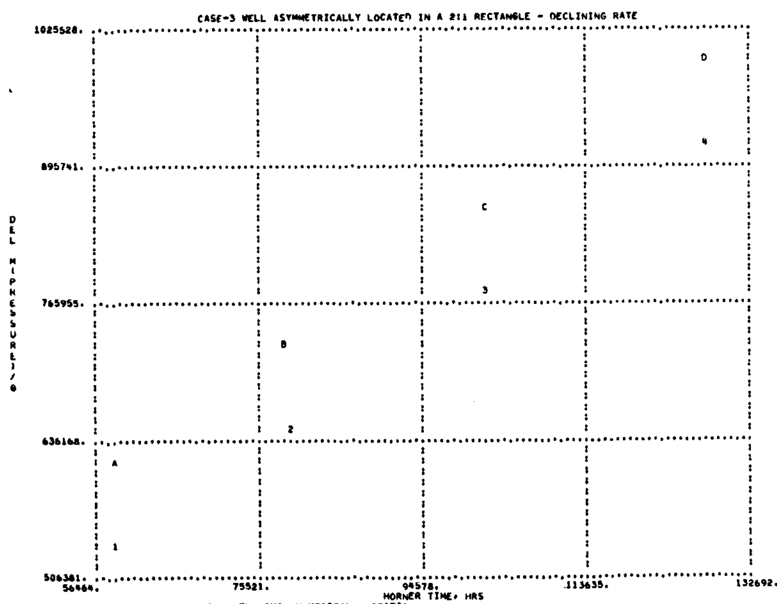


FIG. 2C—CASE 3 - WELL ASYMMETRICALLY LOCATED IN A 2:1 RECTANGLE—DECLINING RATE

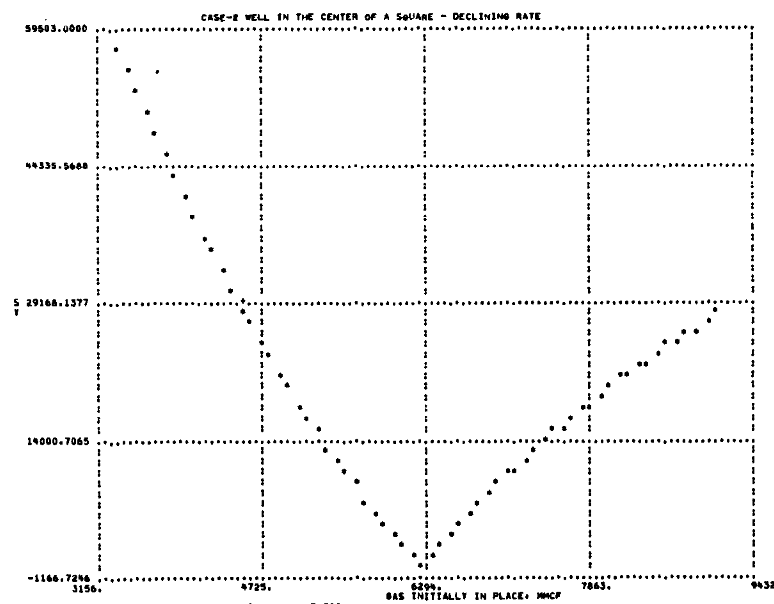


FIG. 3—CASE 2 - WELL IN THE CENTER OF A SQUARE—DECLINING RATE

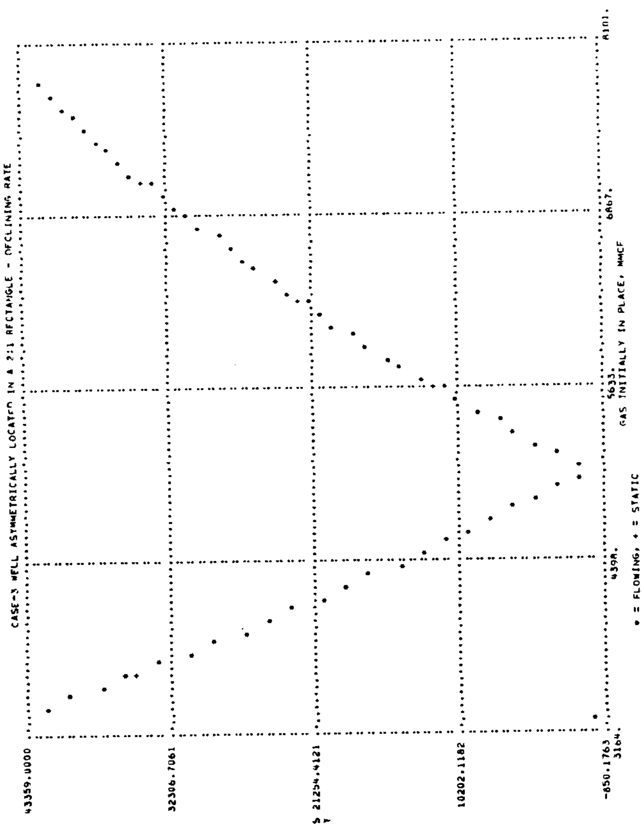

FIG. 4— CASE 3 - WELL ASYMMETRICALLY LOCATED IN A 2:1 RECTANGLE—DECLINING RATE

## RESULTS AND DISCUSSIONS

The validity of the technique was checked against the performance of a well calculated by a single-phase, two-dimensional numeric model under certain operating conditions. The performance history was then used as input data to the new calculation to determine the gas initially in-place. The values of the parameters which were constant in all reservoir model runs are listed in Table 1.

TABLE 1—THE VALUES OF PARAMETERS USED IN THE RESERVOIR MODEL STUDY

| | | |
|---|---|---|
| X-direction reservoir permeability | = | 0.3 md |
| Y-direction reservoir permeability | = | 0.3 md |
| Reservoir thickness, h | = | 80 ft |
| Reservoir hydrocarbon porosity, fraction of pore volume | = | 0.075 |
| Reservoir temperature | = | 636° R |
| Initial reservoir pressure | = | 2500 psia |

Three cases were selected for studying the effects that operating conditions, well location and shape of the drainage area have on the original gas in-place calculations.

*Case 1—Well In The Center of A Square System; Rate After Rate Production*

A well was placed in the center of a square-shaped reservoir of 2200 ft by 2200 ft dimension. This reservoir had 4.8548 billion SCF of gas initially in-place. The well was produced with the following schedule:

| Q, MCFD | Period, Years |
|---|---|
| 1000 | 2 |
| 800 | 2 |
| 600 | 2 |
| 400 | 2 |

Flowing wellbore pressures at the end of each year were computed by the reservoir model. The well block pressure, after each year of production, was assumed to be the shut-in bottomhole pressure. When the performance history obtained from the reservoir model (and presented in Table 2) was used as known data for the calculation of gas in-place by the technique presented in this paper, a value of 4.871 billion SCF of gas initially in-place was calculated from the shut-in and flowing pressure survey data. The error in the calculated value is 0.33% of the actual assigned volume. Figure 1 shows the plot of standard deviations as defined by Eqs. (5) and (6) plotted as a function of gas initially in-place.

*Case 2—Well Located In The Center of a Square Drainage Area; Declining Rate Production Schedule*

A well was placed in the center of a square-shaped reservoir, having 6.2691 billion SCF of gas in-place. The square measured 2750 ft per side. The well was allowed to produce against a constant wellhead pressure of 800 psi absolute. Rock properties in Case 2 were the same as applied to Case 1. Table 3 presents the performance calculated from the numeric model which was used as input data for Case 2. The results of the calculation presented in Fig. 3 indicated there to be 6.259 billion SCF in the reservoir. This results in an error of 0.16%. This agreement, when compared to Case 1, suggests that the calculation procedure is insensitive to gas withdrawal procedures.

## TABLE 2—PRESSURE SURVEY ANALYSIS
By H.J. Gruy and Assoc.

CASE-1 WELL IN THE CENTER OF A SQUARE - RATE AFTER RATE PRODN

INPUT DATA TO PROGRAM

| | | | |
|---|---|---|---|
| SPECIFIC GRAVITY OF NET GAS | .70 | MOLE FRAC OF N2 CONTENT | .0000 |
| BOTTOMHOLE TEMP, DEGREE F | 176. | MOLE FRAC OF CO2 CONTENT | .0000 |
| WELL HEAD TEMP, DEGREE F | 60. | MOLE FRAC OF H2S CONTENT | .0000 |
| DEPTH TO MID-PERF, FEET | 6250. | FLOW PERIOD DURING FLOW TEST, HRS | 0. |
| FRICTION FACTOR (FR) | .01777 | SHUTIN TIME AFTER FLOW, HRS | 168. |
| POROSITY (PORE-FRACTION) | .100 | INITIAL PR (MAX OBS S.I. PR) | 2500.0 |
| WATER SATURATION | .250 | AVERAGE PERMEABILITY, MD | .300 |

SUMMARY OF ANNUAL DELIVERABILITY TESTS

| DATE | M S I | M F L | AVG RATE MCFPD | CUM GAS MCF | TEST RATE MCFPD | PC PSIA | PW PSIA | BHP PSIA | BHFP PSIA | M(PWS) PSISQ/CP | M(PWF) PSISQ/CP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 01/01/73 | | | 1000. | 365000. | 1000. | 1579. | 1333. | 1900. | 1604. | .2899511+09 | .2108135+09 |
| 01/01/74 | | | 1000. | 730000. | 1000. | 1411. | 1134. | 1691. | 1361. | .2330145+09 | .1538302+09 |
| 01/01/75 | | | 800. | 1022000. | 800. | 1354. | 1130. | 1621. | 1352. | .2150706+09 | .1518693+09 |
| 01/01/76 | | | 800. | 1314000. | 800. | 1220. | 966. | 1455. | 1153. | .1749496+09 | .1116343+09 |
| 01/01/77 | | | 600. | 1533000. | 600. | 1207. | 1021. | 1439. | 1216. | .1712853+09 | .1237541+09 |
| 01/01/78 | | | 600. | 1752000. | 600. | 1107. | 902. | 1316. | 1071. | .1441626+09 | .9672427+08 |
| 01/01/79 | | | 400. | 1898000. | 400. | 1135. | 1008. | 1351. | 1197. | .1516514+09 | .1200376+09 |
| 01/01/80 | | | 400. | 2044000. | 400. | 1070. | 934. | 1271. | 1107. | .1347948+09 | .1031534+09 |

| | |
|---|---|
| INITIAL WELL-HEAD SHUT IN PR | 2068. |
| INITIAL BOTTOMHOLE SHUT IN PR | 2500. |
| INITIAL PSEUDO GAS POTENTIAL | .4767289+09 |

## TABLE 3—PRESSURE SURVEY ANALYSIS
By H.J. Gruy and Assoc.

CASE-2 WELL IN THE CENTER OF A SQUARE - DECLINING RATE

INPUT DATA TO PROGRAM

| | | | |
|---|---|---|---|
| SPECIFIC GRAVITY OF NET GAS | .70 | MOLE FRAC OF N2 CONTENT | .0000 |
| BOTTOMHOLE TEMP, DEGREE F | 176. | MOLE FRAC OF CO2 CONTENT | .0000 |
| WELL HEAD TEMP, DEGREE F | 60. | MOLE FRAC OF H2S CONTENT | .0000 |
| DEPTH TO MID-PERF, FEET | 6250. | FLOW PERIOD DURING FLOW TEST, HRS | 0. |
| FRICTION FACTOR (FR) | .01777 | SHUTIN TIME AFTER FLOW, HRS | 168. |
| POROSITY (PORE-FRACTION) | .100 | INITIAL PR (MAX OBS S.I. PR) | 2500.0 |
| WATER SATURATION | .250 | AVERAGE PERMEABILITY, MD | .300 |

SUMMARY OF ANNUAL DELIVERABILITY TESTS

| DATE | M S I | M F L | AVG RATE MCFPD | CUM GAS MCF | TEST RATE MCFPD | PC PSIA | PW PSIA | BHP PSIA | BHFP PSIA | M(PWS) PSISQ/CP | M(PWF) PSISQ/CP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 01/01/73 | | | 1481. | 625640. | 1481. | 1349. | 799. | 1615. | 977. | .2135681+09 | .8083813+08 |
| 01/01/74 | | | 1215. | 1113390. | 1215. | 1264. | 799. | 1510. | 966. | .1878535+09 | .7907218+08 |
| 01/01/75 | | | 1012. | 1516790. | 1012. | 1197. | 800. | 1427. | 959. | .1685500+09 | .7795312+08 |
| 01/01/76 | | | 851. | 1854460. | 851. | 1142. | 799. | 1359. | 954. | .1533944+09 | .7715380+08 |
| 01/01/77 | | | 722. | 2139710. | 722. | 1095. | 799. | 1302. | 950. | .1412111+09 | .7651434+08 |

| | |
|---|---|
| INITIAL WELL-HEAD SHUT IN PR | 2068. |
| INITIAL BOTTOMHOLE SHUT IN PR | 2500. |
| INITIAL PSEUDO GAS POTENTIAL | .4767289+09 |

*Case 3—Well Asymmetrically Located In A Two-to-One Rectangle; Declining Production Rate*

A well was placed in a rectangle having dimensions of 3600 ft by 1680 ft. The well was situated equidistant from the long boundaries and 750 ft from one end. The reservoir was calculated to have 5.0976 billion SCF of gas in-place. The calculated numeric model performance, used as input data for Case 3, is shown as Table 4. Results of the gas in-place calculation are shown as Fig. 4 and indicate an initial gas in-place of 5.0208 billion SCF. This amounts to an error of 1.5% and suggests that the solution is within engineering accuracy even if the drainage area configuration is asymmetrical.

## CONCLUSIONS

The above calculations suggest that the procedure, while still subject to improvement, is within engineering accuracy even when flow rate and drainage areas vary. Although a more accurate method might be developed based on exotic data, this procedure is believed to be practical because it uses data normally recorded in the field. The procedure presented in this paper represents only a status report of a calculation technique under continuous development.

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TABLE 4—PRESSURE SURVEY ANALYSIS
By H.J. Gruy and Assoc.

CASE-3 WELL ASYMMETRICALLY LOCATED IN A 2:1 RECTANGLE - DECLINING RATE

INPUT DATA TO PROGRAM

| | | | |
|---|---|---|---|
| SPECIFIC GRAVITY OF NET GAS | .70 | MOLE FRAC OF N2 CONTENT | .0000 |
| BOTTOMHOLE TEMP, DEGREE F | 176. | MOLE FRAC OF CO2 CONTENT | .0000 |
| WELL HEAD TEMP, DEGREE F | 60. | MOLE FRAC OF H2S CONTENT | .0000 |
| DEPTH TO MID-PERF, FEET | 6250. | FLOW PERIOD DURING FLOW TEST, HRS | 0. |
| FRICTION FACTOR (FR) | .01777 | SHUTIN TIME AFTER FLOW, HRS | 168. |
| POROSITY (PORE-FRACTION) | .100 | INITIAL PR (MAX OBS S.I. PR) | 2500.0 |
| WATER SATURATION | .250 | AVERAGE PERMEABILITY, MD | .300 |

SUMMARY OF ANNUAL DELIVERABILITY TESTS

| DATE | MSI | MFL | AVG RATE MCFPD | CUM GAS MCF | TEST RATE MCFPD | PC PSIA | PW PSIA | BHP PSIA | BHFP PSIA | M(PWS) PSISQ/CP | M(PWF) PSISQ/CP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 01/01/76 | | | 651. | 1585620. | 651. | 1045. | 799. | 1241. | 949. | .1287192+09 | .7635822+08 |
| 01/01/77 | | | 550. | 1803460. | 550. | 1010. | 799. | 1198. | 947. | .1202304+09 | .7604598+08 |
| 01/01/78 | | | 470. | 1988500. | 470. | 981. | 799. | 1163. | 945. | .1135261+09 | .7573374+08 |
| 01/01/79 | | | 404. | 2147090. | 404. | 958. | 799. | 1134. | 945. | .1080980+09 | .7573374+08 |

| | |
|---|---|
| INITIAL WELL-HEAD SHUT IN PR | 2068. |
| INITIAL BOTTOMHOLE SHUT IN PR | 2500. |
| INITIAL PSEUDO GAS POTENTIAL | .4767289+09 |