

MATERIAL BALANCE

In

OIL & GAS RESERVOIRS

A

PRACTICAL APPLICATION

For

PRODUCTION FORECASTS

And

RECOVERY FACTOR ESTIMATES

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May 2000

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PREFACE

The equations and documentation presented here are brief and serve to point out some of the basic relationships in the concept of reservoir management from the application of material balance. In this case, material balance is used as both a history matching tool and a forecasting tool. A forecast of the reservoir's production can be generated given only test data, basic reservoir parameters and PVT analysis. Additionally, an estimate of the reservoir's recovery factor under that drive mechanism can be ascertained.

The subject matter regarding material balance for oil and gas reservoirs is more exhaustive than presented herein and the reader is referred to other literature on the subject matter. The equations and relationships involve can all be referenced in the literature, however, the FORTRAN program MATBAL.EXE and its application is the exclusive work of the author.

MATERIAL BALANCE IN OIL AND GAS RESERVOIRS

Introduction

This document present some basic relationships and an application of Material Balance as applied in forecasting and/or history matching the production of petroleum oil and gas reservoirs. ¹ The author has written a FORTRAN program, MATBAL.EXE, which is applied in a sandstone reservoir as the working example in this document. The production profiles generated can be used as a predictive tool for production profiles for use in reservoir development, business decisions and economics and development planning.

Material Balance Equations

The fundamental production of an oil reservoir with solution gas cap (expansion) drive and an aquifer influx may be express as follow: [APPENDIX ONE - equation symbol definitions]

$$\text{Oil Expansion} + \text{Gas Expansion} + \text{Water \& Matrix Expansion} + \text{Water Influx} = \\ \text{Hydrocarbon Production} + \text{Water Production}$$

$$N(B_t - B_{ti}) + \frac{NmB_{ti}}{B_{gi}}(B_g - B_{gi}) + (1+m)NB_{ti} \left[\frac{c_w S_{wi} + c_f}{1 - S_{wi}} \right] \Delta p + W_e = N_p [B_t + (R_p - R_{si})B_g] + B_w W_p$$

Equation (0)

General Material Balance (MB) Equation

Neglecting compressibility, the general material balance equation can be written for various reservoir types as follows:

Solution Gas Reservoir - Gas Cap Drive - Water Drive

$$N = \frac{N_p [B_t + (R_p - R_{si})B_g] - (W_e - B_w W_p)}{(B_t - B_{ti}) + \left(\frac{m * B_{ti}}{B_{gi}} \right) (B_g - B_{gi})}$$

Equation (1)

MB Oil Reservoir w/ Solution Gas, Gas Cap and Water Drives

Solution Gas Reservoir - Gas Cap Drive - No Water Drive

$$N = \frac{N_p [B_t + (R_p - R_{si})B_g] + B_w W_p}{(B_t - B_{ti}) + \left(\frac{m * B_{ti}}{B_{gi}} \right) (B_g - B_{gi})}$$

¹ Some of the equations have been taken from Craft & Hawkins
Applied Petroleum Engineering Second Edition, 1991 Prentice Hall

Equation (2) *MB Oil Reservoir w/ Solution Gas, Gas Cap Drive and No Water Drive*

Solution Gas Reservoir - No Gas Cap - Water Drive

$$N = \frac{N_p [B_t + (R_p - R_{si})B_g] - (W_e - B_w W_p)}{(B_t - B_{ti})}$$

Equation (3) *MB Oil Reservoir w/Solution Gas, No Gas Cap Drive and No Water Drive*

Solution Gas Reservoir - No Gas Cap - No Water Drive

$$N = \frac{N_p [B_t + (R_p - R_{si})B_g]}{(B_t - B_{ti})}$$

Equation (4) *MB Oil Reservoir w/ Solution Gas Drive, No Gas Cap Drive and No Water Drive*

Where:

$$B_t = B_o + (R_{si} - R_s) \cdot B_g \quad \text{and} \quad B_{oi} = B_{ti}$$

Equation (5) *Two Phase Formation Volume Factor*

$$m = \frac{G \cdot B_{gi}}{N \cdot B_{oi}}$$

Equation (6) *(Initial Reservoir Free Gas Volume) / (Initial Reservoir Oil Volume)*

Under-saturated Oil Reservoir - No Gas Cap - With Water Drive

$$N = \frac{\left[N_p (1 + \Delta p \cdot c_o) - \frac{W_e - W_p}{B_{oi}} \right] (1 - S_w)}{\Delta p [c_o + c_f - S_w (c_o - c_w)]}$$

Equation (7) *MB Under-saturated Oil Reservoir, Above Pb, No Gas Cap and With Water Drive*

$$N = \frac{N_p [B_t + B_g (R_p - R_{si})] - (W_e - W_p)}{B_t - B_{oi}}$$

Equation (8) *MB Under-saturated Oil Reservoir, Below Pb, No Gas Cap and With Water Drive*

Under-saturated Oil Reservoir - No Gas Cap - No Water Drive

$$N = \frac{\left[N_p (1 + \Delta p \cdot c_o) + \frac{W_p}{B_{oi}} \right] (1 - S_w)}{\Delta p [c_o + c_f - S_w (c_o - c_w)]}$$

Equation (9) MB Under-saturated Oil Reservoir, Above Pb, No Gas Cap and No Water Drive

$$N = \frac{N_p [B_t + B_g (R_p - R_{si})] + W_p}{B_t - B_{oi}}$$

Equation (10) MB Under-saturated Oil Reservoir, Below Pb, No Gas Cap and No Water Drive

General MB Equation – Natural Reservoir Energy - Except Pore Volume

Neglecting compressibility, the general material balance equation that includes all natural reservoir energy except changes in pore volume is:

$$N = \frac{N_p B_o + B_g (G_p - N_p R_s) - G (B_g - B_{gi}) - (W_e - B_w W_p)}{B_o - B_{oi} + (R_{si} - R_s) B_g}$$

Equation (11)

General Material Balance Equation

DDI & GDI & WDI

Pirson rearranged the MB Equation to obtain a depletion drive index (DDI), a segregation index, i.e. gas cap index (GDI) and a water drive index (WDI) whose sum is one:

$$DDI = \frac{N (B_t - B_{ti})}{N_p [B_t + (R_p - R_{si}) B_g]}$$

Equation (12)

Depletion (Solution Gas) Drive Index

$$GDI = \frac{\frac{N \cdot m \cdot B_{ti}}{B_{gi}} (B_g - B_{gi})}{N_p [B_t + (R_p - R_{si}) B_g]}$$

Equation (13)

Segregation (Gas Cap) Drive Index

$$WDI = \frac{(W_e - B_w W_p)}{N_p [B_t + (R_p - R_{si}) B_g]}$$

Equation (14)

Water Drive Index

Where:

$$DDI + GDI + WDI = 1.0$$

Figure 7 - A shows the dimensionless water influx for the constant terminal pressure case for radial flow used to derive W_e . Table 3-A shows the relevant relationships that are required to apply Figure 7 - A to determine the water influx.

Gas Reservoir – Volumetric Depletion with Water Influx

The fundamental production of a gas reservoir with an aquifer influx expressed as material balance neglecting compressibility is as follow: (B_{gi} in FT³ / SCF)

Gas Production = Gas Expansion + Water Influx - Water Production

$$G_p B_{gf} = G (B_{gf} + B_{gi}) + W_e - B_w W_p$$

Equation (15)

Gas Material Balance Equation – Water Drive

This is also written as: (B_{gi} in (reservoir barrels, rb) rb / scf)

$$\frac{p}{Z} = \frac{p_i}{Z_i} \left(1 - \frac{G_p}{G} \right) \left/ \left(1 - \frac{W_e}{B_{gi} G} \right) \right.$$

Equation (16)

Gas Material Balance Equation (p/Z) – Water Drive

Should compressibility be determined to be significant in the particular reservoir then the gas material balance equation becomes: (B_{gi} in rb / scf)

$$\frac{p}{Z} \left[1 - \frac{\Delta P (S_{wi} c_w + c_f)}{1 - S_{wi}} \right] = \frac{p_i}{Z_i} \left(1 - \frac{G_p}{G} \right) \left/ \left(1 - \frac{W_e}{B_{gi} G} \right) \right.$$

Equation (17)

Gas Material Balance Equation with Compressibility (p/Z) – Water Drive

Gas Reservoir – Volumetric Depletion with out Water Influx

The fundamental production of a gas reservoir with out an aquifer influx and with no interstitial water production may be expressed as follow:

Gas Production = Gas Expansion

$$G_p B_{gf} = G (B_{gf} + B_{gi})$$

Equation (18)

Gas Material Balance Equation – Depletion Drive

This is also written as:

$$\frac{p}{Z} = \frac{p_i}{Z_i} \left(1 - \frac{G_p}{G} \right)$$

Equation (19)

Gas Material Balance Equation (p/Z) – Depletion Drive

The gas flow rate (MSCF/D) into the well bore in a radial flow system is:

$$Q_g = \frac{0.703 \cdot k_g \cdot h}{\mu_g \cdot Z \cdot T_R} \left[\frac{(P_r^2 - P_{wf}^2)}{(\ln(r_e/r_w) - 0.5 + S)} \right]$$

Equation (20)

Gas Flow Rate Equation- Radial Flow

The gas flow rate (MSCF/D) into the well bore in a hemispherical flow system is:

$$Q_g = \frac{0.703 \cdot k_g \cdot h}{\mu_g \cdot Z \cdot T_R} \left[\frac{(P_r^2 - P_{wf}^2)}{((1/r_e - 1/r_w) - 0.5 + S)} \right]$$

Equation (21)

Gas Flow Rate Equation- Hemispherical Flow

Volumetric gas in place (SCF) is:

$$G = 43560.248 \cdot A \cdot h \cdot \phi \cdot (1 - S_w) \cdot (1/B_{gi})$$

Equation (22)

Volumetric Gas In Place

Gas formation volume factor in FT³/SCF is:

$$B_g = \frac{P_{sc} \cdot Z \cdot T_F}{T_{sc} \cdot P}$$

Equation (23)

Gas Formation Volume Factor

Solution Gas Reservoir - Gas Cap Drive - No Water Drive – Gas Injection

The incremental oil production for a solution gas reservoir with a gas cap drive, no water drive and gas injection during a pressure interval, p_n to $p_{(n-1)}$ as derived from the material balance equation is (B_g in rb/scf):

$$\Delta N_p = \frac{\left[(B_t - B_{oi})/B_g \right] + m_i \cdot B_{oi} \left[(1/B_{gi}) - (1/B_g) \right] + G_{i_{n-1}} - N_{p_{n-1}} \left[(B_t/B_g) - R_{si} \right] - G_{p_{n-1}}}{(B_t/B_g) + R_{si} + (1 - I) \cdot R_{av}}$$

Equation (24)

MB Oil Reservoir with Solution Gas, Gas Cap Drive with Gas Injection

Depletion Drive and Gas Cap Drive Indices at p_n are:

$$DDI = \frac{(B_t - B_{oi} / B_g)}{N_{p_n} [B_t / B_g - R_{si}] + G_{p_n}}$$

Equation (25) *Depletion (Solution Gas) Drive Index – Gas Injection*

$$GDI = \frac{m_i \cdot B_{oi} \cdot (1/B_{gi} - 1/B_g) + G_{i_n}}{N_{p_n} [(B_t / B_g) - R_{si}] + G_{p_n}}$$

Equation (26) *Segregation (Gas Cap) Drive Index – Gas Injection*

Where:

$$DDI + SDI = 1.0$$

And:

$$N_{p_n} = \frac{N_p}{N}$$

i.e. the cumulative oil production to P_n as a fraction of N .

Writing this material balance relationship in conventional terms (B_g in rb / scf):

$$N = \frac{N_{p_n} [(B_t / B_g) + R_{si} + (1 - I) \cdot R_{av}] - N_{p_{n-1}} [(1 - I) \cdot R_{av}]}{(B_t - B_{oi} / B_g) + m_i \cdot B_{oi} [(1/B_{gi}) - (1/B_g)] + G_{i_{n-1}} - G_{p_{n-1}}}$$

Equation (27) *MB Oil Reservoir with Solution Gas, Gas Cap Drive with Gas Injection*

To apply this material balance equation, it is assumed that the gas oil contact remains stationary and that the gas from the gas injection and gas cap expansion diffuses throughout the oil column.

Equations and/or Relationships - Schlithuis

The following relationships are solved in the FORTRAN program MATBAL.EXE which applies the Schlithuis method of solving the material balance. The total (two-phase) formation volume factor:

$$B_t = B_o + (R_s - R_{si}) \cdot B_g$$

Equation (28) *Two-Phase Formation Volume Factor*

The instantaneous solution gas oil ratio:

$$R_R = R_s + \frac{\kappa_g \cdot \mu_o \cdot B_o}{\kappa_o \cdot \mu_g \cdot B_g}$$

Equation (29)

Instantaneous Solution Gas Oil Ratio

The total liquid saturation within the reservoir rock:

$$S_L = S_w + S_o$$

$$S_L = S_w + (1 - S_w) \cdot \left[1 - \frac{N_p}{N} \right] \cdot \left(\frac{B_o}{B_{oi}} \right)$$

Equation (30)

Total Liquid Saturation

$$S_g = \left\{ 1 - \left[1 - \frac{N_p}{N} \right] \cdot \left(\frac{B_o}{B_{oi}} \right) \right\} \cdot (1 - S_w)$$

Equation (31)

Gas Saturation

The critical gas saturation, S_{gc} , (at which free gas flows) can be used to estimate the pressure at which the gas oil ratio will begin to increase significantly. This assumes that the reservoir is allowed to produce without pressure maintenance.

$$S_{gc} = (1 - S_w) \frac{B_t - B_o}{B_t}$$

Equation (32)

Critical Gas Saturation

The Schlithuis method of material balance solves the following relationship for Material Balance Equation 4 is:

$$\frac{N_p}{N} \frac{[B_t + (R_p - R_{si}) \cdot B_g]}{(B_t - B_{ti})} - 1 = 0$$

Equation (33) *MB Oil Reservoir w/ Solution Gas Drive, No Gas Cap Drive and No Water Drive*

Similar and/or equivalent equations are used for the other reservoir drive types as indicated in Material Balance Equations 1 thru 3. Noting that the geologist, geophysicist, petrophysicist and

test engineer, all superb guys, have completed their duties, then a volumetric estimate of the original oil in place (Bbls) is:

$$N = 7758.358 \cdot A \cdot h \cdot \phi \cdot (1 - S_w) / B_{oi}$$

Equation (34)

Volumetric (Stock Tank) Oil In Place

Given that the well has reached a pseudo-steady-state, the oil flow rate (Bbls/d) into the well bore is:

$$Q_o = \frac{0.00708 \cdot k_o \cdot h}{\mu_o \cdot B_o} \left[\frac{(P_r - P_{wf})}{(\ln(r_e / r_w) - 0.75)} \right]$$

Equation (35)

Oil Flow Rate Into Well-Bore –Radial Flow

The oil flow rate equation also assumes radial flow geometry and an incompressible fluid. For hemispherical flow, the oil flow rate equation is:

$$Q_o = \frac{0.00708 \cdot k_o \cdot h}{\mu_o \cdot B_o} \left[\frac{(P_r - P_{wf})}{((1/r_w - 1/r_e) - 0.75)} \right]$$

Equation (36)

Oil Flow Rate Into Well-Bore -Hemispherical Flow

The time required to produced an increment of oil for a given pressure drop can be found by dividing the incremental oil produced that occurred for the corresponding pressure drop by the oil flow rate as computed from Equation (35) :

$$\Delta T = \frac{\Delta N_p}{Q_o}$$

Equation (37)

Time as a Function of Pressure and Flow Rate

For reference and comparison several other relationships for solving the material balance equation are referenced herein.

Equations and/or Relationships - Muskat

The Muskat form of solving the material balance equation for a solution gas drive reservoir with no gas cap or water encroachment is as follows:

$$\frac{\Delta S_o}{\Delta P} = \frac{S_o \cdot \lambda(P) + S_o \left(K_g / K_o \right) \cdot \eta(P) + (1 - S_o - S_w) \cdot \varepsilon(P)}{1 + (\mu_o / \mu_g) \cdot (K_g / K_o)}$$

Equation (38)

Material Balance Equation - Muskat

Where:

$$\lambda(P) = \frac{B_g}{B_o} \cdot \frac{\Delta R_s}{\Delta P}$$

$$\eta(P) = \frac{1}{B_g} \cdot \frac{\mu_o}{\mu_g} \cdot \frac{\Delta B_o}{\Delta P}$$

$$\varepsilon(P) = B_g \frac{\Delta(1/B_g)}{\Delta P}$$

Equations and/or Relationships - Tracy

The Tracy method for solving the material balance for a solution gas drive reservoir with no gas cap and no water drive is:

$$1 = N_{pn} \cdot \omega_{on} + G_{pn} \cdot \omega_{gn}$$

Equation (39)

Material Balance Equation - Tracy

$$R_R = R_s + \frac{\kappa_g \cdot \mu_o \cdot B_o}{\kappa_o \cdot \mu_g \cdot B_g}$$

$$S_L = S_w + (1 - S_w) \cdot \left[1 - \frac{N_p}{N} \right] \cdot \left(\frac{B_o}{B_{oi}} \right)$$

Where:

$$\Delta N_p = \frac{1 - N_{p(n-1)} \cdot \omega_o - G_{p(n-1)} \cdot \omega_g}{\omega_o + \omega_g [R_R + R_{R(n-1)}]} / 2.0$$

$$\omega_o = \frac{[(B_o / B_g) - R_s]}{\left\{ [(B_o / B_g) - R_s] - [(B_{oi} / B_g) - R_{si}] \right\}}$$

$$\omega_g = \frac{1}{\left\{ [(B_o / B_g) - R_s] - [(B_{oi} / B_g) - R_{si}] \right\}}$$

Application - Solution Gas Reservoir - No Gas Cap - No Water Drive

Description of Reservoir

The reservoir to be analyzed is sandstone which produces from two zones separated by a shale section approximately two feet thick. The reservoir drive mechanism is a volumetric, internal solution gas drive. The producing zones have an area of approximately 40 acres. The initial reservoir pressure is estimated at 1350 psi and the average porosity of 31.5% for each productive zone. The thicknesses of the two intervals are 17 and 14 Feet with absolute permeability of 71 md and 41 md respectively. These and other reservoir attributes are also depicted in the user defined input file in *APPENDIX SIX* and in *Table 1-D*. For comparison of drive efficiencies an aquifer and a gas cap are conceptually added to the reservoir model as indicated in *Figure 6 - A* and the appropriate material balance equations are solved along with a gas re-injection scenario.

Description of FORTRAN Program - MATBAL.EXE

The program requires several ASCII input files that are shown in *APPENDIX SIX*. The fixed names of the ASCII files are:

SG_KGKO.TXT
 SG_KO.TXT
 SG_KG.TXT
 PSI_RS.TXT
 PSI_VO.TXT
 PSI_VOB.TXT
 PSI_VG.TXT
 PSI_BO.TXT
 PSI_BOB.TXT
 PSI_BG.TXT
 SW_KRO.TXT
 SW_KRW.TXT

MATBAL.EXE reads the input files and creates an n^{th} degree polynomial equation which is the best fit for each of the physical reservoir properties to be used in the material balance computations. Additional curve fit options are also available.

There only two output files, the first is LSQOUT.TXT and the second is the user defined analysis output file containing the output data from the material balance calculations. LSQOUT.TXT as shown in *APPENDIX SIX* shows the regression coefficients along with the form of equation applied. The analysis output file is then imported into a spreadsheet program for additional analysis and display.

Input Files and Polynomial Correlations

Table 1-A is the MS Excel version of the ASCII input files of K_g/K_o and the relative permabilities of the oil and gas phases as a function of gas saturation, S_g .

Figure 1 - A shows a plot of the relative permeability oil to gas (K_g/K_o) and the relative permeability of the oil and gas phases as a function of gas saturation (S_g) and the polynomial equations that have been fitted as a result of running the FORTRAN program.

The ASCII files for the relative permeability of oil to gas (K_g/K_o) and the relative permeability of the oil and gas phases as a function of gas saturation (S_g) are shown in APPENDIX SIX.

Input Data (ASCII file is input to FORTRAN program)			
S_g (v/v)	K_g/K_o	$K_{ro}\{S_g\}$	$K_{rg}\{S_g\}$
0.34	95.0000	0.0080	0.7600
0.32	65.0000	0.0100	0.6500
0.30	40.2985	0.0134	0.5400
0.28	20.6814	0.0209	0.4322
0.26	11.7696	0.0284	0.3343
0.24	6.6979	0.0360	0.2411
0.22	3.8117	0.0435	0.1658
0.20	2.1692	0.0555	0.1204
0.18	1.2345	0.0721	0.0890
0.16	0.7025	0.0887	0.0623
0.14	0.3998	0.1156	0.0462
0.12	0.2275	0.1503	0.0342
0.10	0.1170	0.1880	0.0220
0.08	0.0520	0.2590	0.0135
0.06	0.0119	0.3532	0.0042
0.04	0.0024	0.5220	0.0013
0.02	0.0002	0.7600	0.0001
0.00	0.0000	1.0000	0.0000
S_g (v/v)	K_g/K_o	$K_{ro}\{S_g\}$	$K_{rg}\{S_g\}$

Table 1-A – S_g K_g/K_o K_{ro} & K_{rg}

Table 1-B is the MS Excel version of the ASCII input files of pressure verses oil and gas viscosity, solution gas oil ratio, oil formation volume and gas formation volume factors. Table 1-C is the MS Excel version of the ASCII file of connate water saturation (S_w) versus relative permeability of oil, (K_{ro}), and relative permeability of water, (K_{rw}).

Figure 1 - B shows a plot of the pressure versus oil and gas viscosities. Figure 1 - C shows a plot of the pressure versus solution gas oil ratio, oil formation volume and gas formation volume factors. Figure 1 - D shows a plot of water saturation versus oil and gas relative permeability.

The ASCII files for the pressure versus oil and gas viscosities, solution gas oil ratio, oil and gas formation volume factors; water saturation versus oil and gas relative permeability are shown in APPENDIX SIX.

APPENDIX FIVE depicts some empirical relative permeability relationships that can be applied in the absence of core data. Applications of these relationships are very dependent on expert petrophysical analysis.

Input Data (ASCII file is input to FORTRAN program)					
P(psi)	Vo(cp)	Vg(cp)	Rs(scf/bbl)	Bo(rb/stb)	1/Bg(scf/ft³)
850.0	1.390	0.0125	247.67	1.141	348.31
800.0	1.447	0.0124	237.03	1.136	326.45
750.0	1.504	0.0122	226.28	1.131	304.81
700.0	1.560	0.0120	215.42	1.127	283.40
650.0	1.617	0.0119	204.47	1.122	262.22
600.0	1.674	0.0117	193.40	1.118	241.26
550.0	1.730	0.0115	182.23	1.113	220.53
500.0	1.787	0.0113	170.96	1.108	200.03
450.0	1.844	0.0112	159.58	1.104	179.75
400.0	1.900	0.0110	148.09	1.099	159.70
350.0	1.957	0.0108	136.51	1.094	139.87
300.0	2.014	0.0107	124.81	1.090	120.27
250.0	2.071	0.0105	113.01	1.085	100.90
200.0	2.127	0.0103	101.11	1.081	81.76
150.0	2.198	0.0101	88.51	1.074	64.01
100.0	2.308	0.0095	70.66	1.064	45.63
50.0	2.465	0.0087	46.82	1.050	27.25
P(psi)	Vo(cp)	Vg(cp)	Rs(scf/bbl)	Bo(rb/stb)	1/Bg(scf/ft ³)

Table 1-B – P vs. Vo(cp) Vg(cp) Rs(scf/bbl) Bo(v/v) 1/Bg(v/v)

Input Data (ASCII file input to FORTRAN program)		
Sw (v.v)	Kro = Ko/K	Krw = Kw/K
0.05	1.025	0.006
0.10	0.999	0.007
0.15	0.96	0.008
0.20	0.885	0.009
0.25	0.775	0.011
0.30	0.650	0.022
0.35	0.525	0.033
0.40	0.430	0.055
0.45	0.320	0.088
0.50	0.220	0.122
0.55	0.150	0.188
0.60	0.100	0.222
0.65	0.065	0.288
0.70	0.050	0.355
0.75	0.040	0.444
0.80	0.035	0.511
0.85	0.025	0.600
0.90	0.015	0.722
0.95	0.005	0.855
Sw (v/v)	Kro = Ko/K	Krw = Kw/K

Table 1-C – Sw vs. Kro & Krw

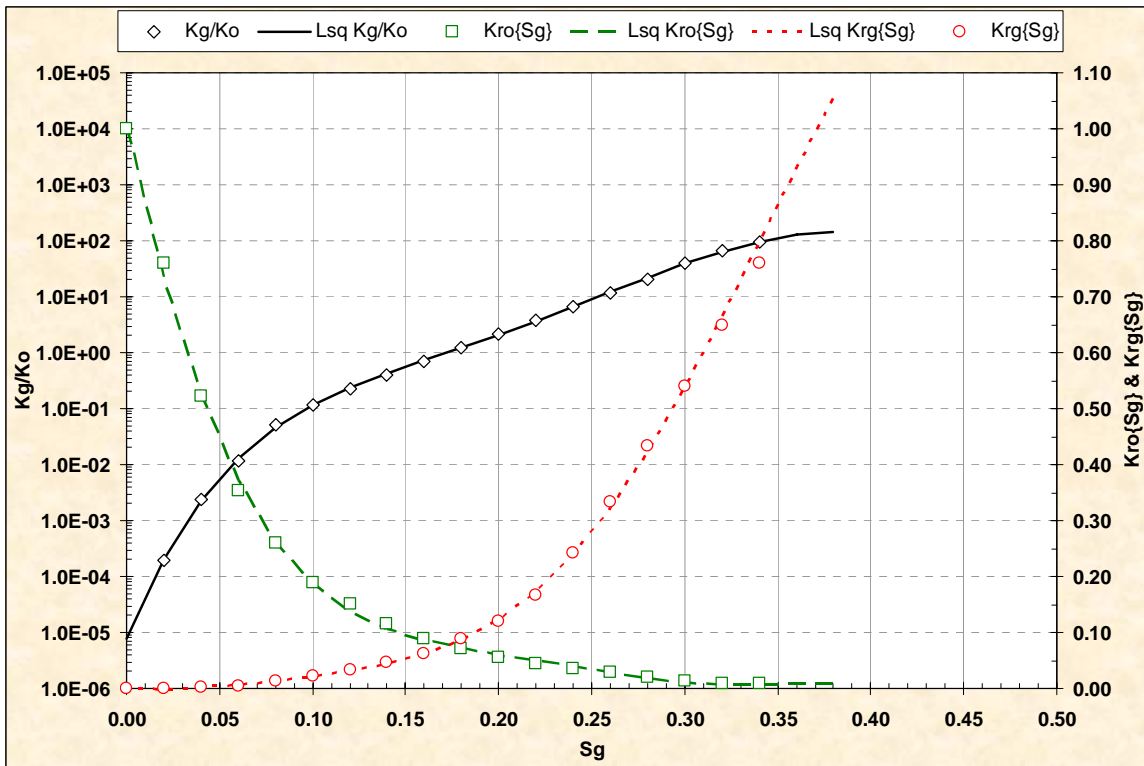


Figure 1 - A – Sg vs. Kg/Ko Kro & Krg Polynomial Fits

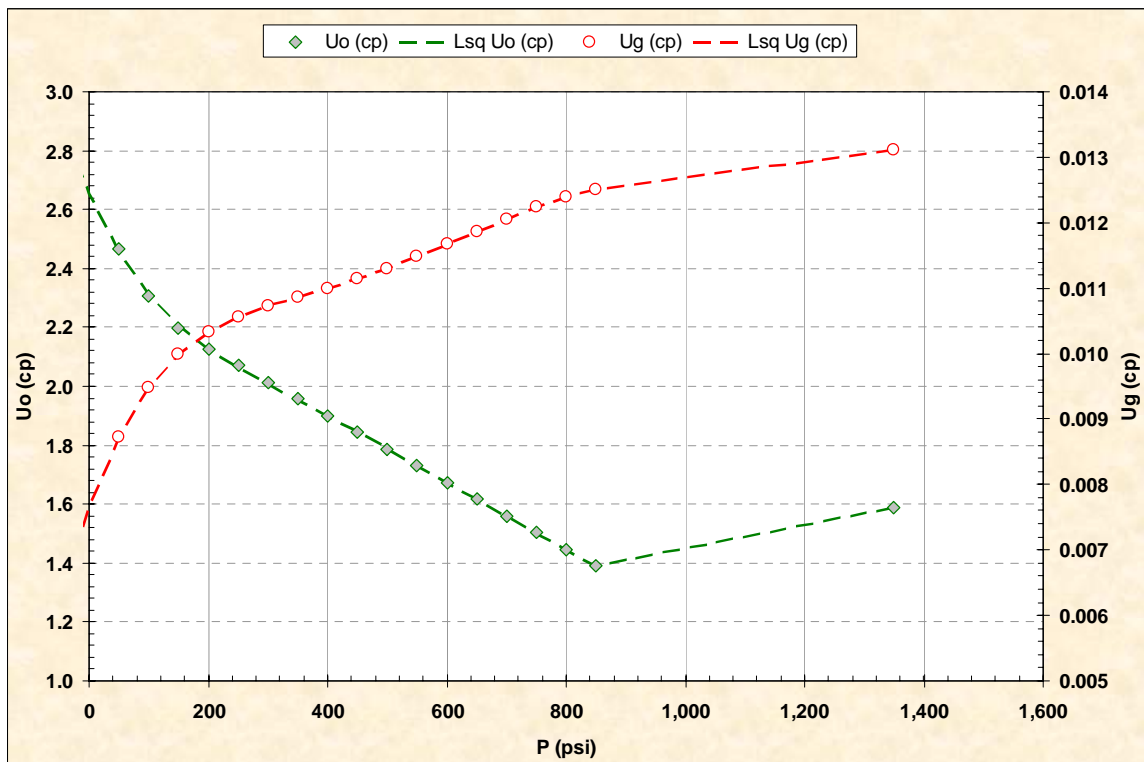


Figure 1 - B – P(psi) vs. Vo(cp) & Vg(cp) Polynomial Fits

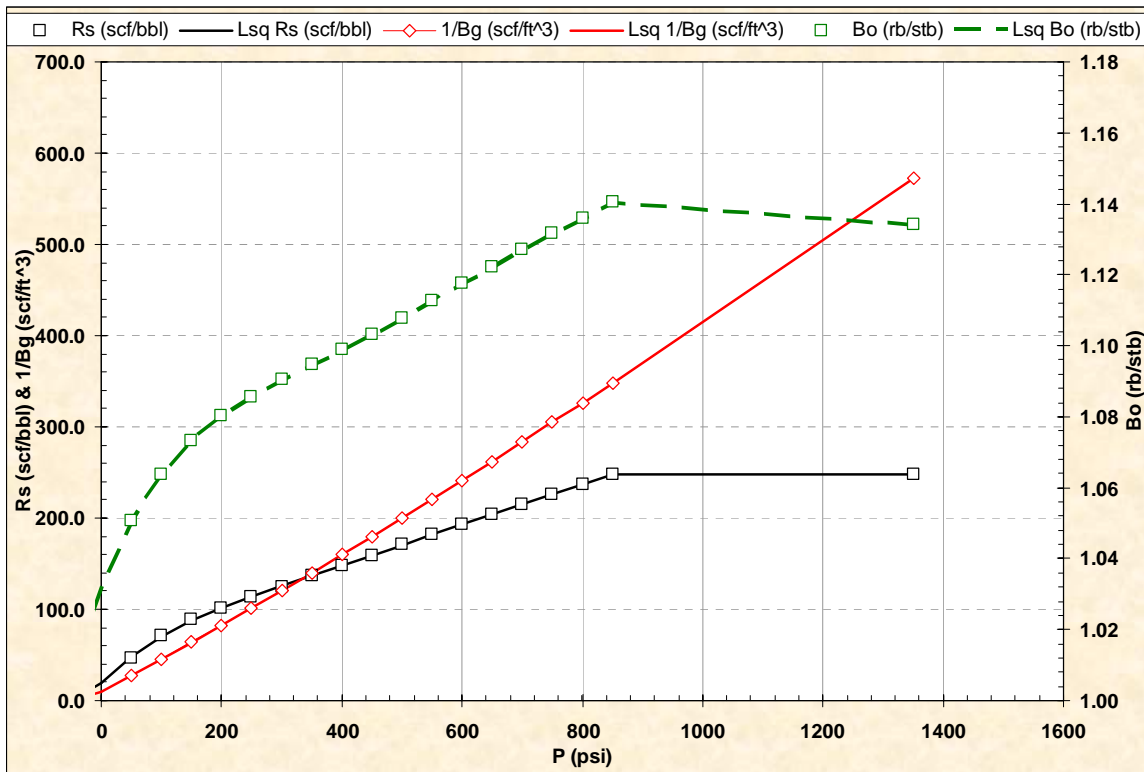


Figure 1 - C – P (psi) vs. R_s (scf/bbl) $1/B_g$ (v/v) & B_o (v/v) Polynomial Fits

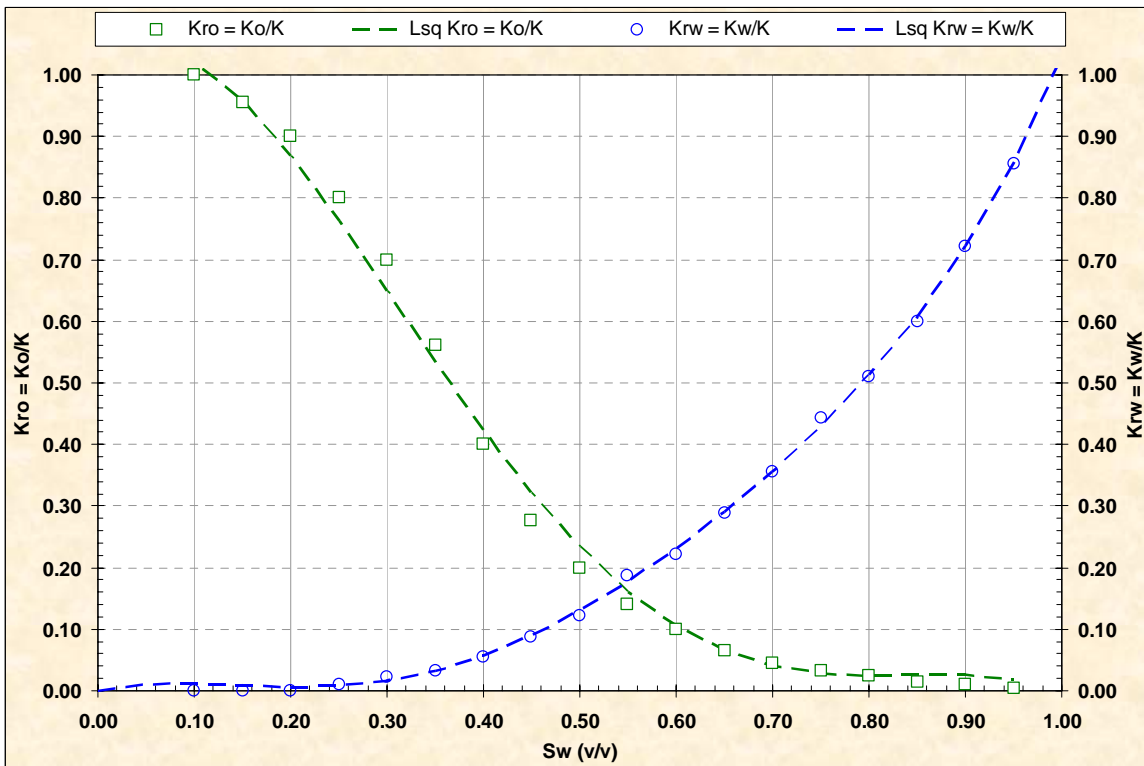


Figure 1 - D – S_w vs. K_{ro} & K_{rw} Polynomial Fits

Table 1-D depicts the reservoir input parameters for up to seven zones; two for this example

Input Data (ASCII file input to FORTRAN program)								
Variable	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Units
PI	1350.0							psia
PBP	850.0							psia
DP	20.0							psia
RW	0.25							Ft.
RE	660.0							Ft.
PW	25.0							psia
THTA	360.0							Degrees
RDSR	744.7							Ft.
RDSA	2234.2							Ft.
MBEQ	4.0							#
GCAP	1.0							v/v
PHI(I)	0.315	0.315						v/v
SW(I)	0.200	0.200						v/v
H(I)	17.0	14.0						Ft.
K(I)	71.0	41.0						md.
ACRE(I)	40.0	40.0						acre
RW75(I)	0.100	0.100						ohm-m
RTEM(I)	199.9	199.9						DegF
Variable	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Units
Calculated Data								
OPIP(I)	1712.0	965.2	0.0	0.0	0.0	0.0	0.0	2137.2MbbI

Table 1-D – Reservoir Input Parameters

Table 2-A presents the physical parameters and the form of the polynomial equations used in Figure 1 - A through Figure 1 - D . The subscript “ob” refers to above bubble point pressure.

Table 2-A – Physical Parameter and Regression Equations	
	Form of Regression Equation
Kg/Ko	$A(0)*EXP[A(1)*S_g+A(2)*S_g^2+A(3)*S_g^3+A(4)*S_g^4+A(5)*S_g^5+A(6)*S_g^6+A(7)*S_g^7]$
Ko	$A(0)+A(1)*S_g+A(2)*S_g^2+A(3)*S_g^3+A(4)*S_g^4+A(5)*S_g^5+A(6)*S_g^6+A(7)*S_g^7$
Kg	$A(0)+A(1)*S_g+A(2)*S_g^2+A(3)*S_g^3+A(4)*S_g^4+A(5)*S_g^5+A(6)*S_g^6+A(7)*S_g^7$
Vo	$A(0)+A(1)*P+A(2)*P^2+A(3)*P^3+A(4)*P^4+A(5)*P^5+A(6)*P^6+A(7)*P^7$
Vob	$A(0)+A(1)*P+A(2)*P^2+A(3)*P^3+A(4)*P^4+A(5)*P^5+A(6)*P^6+A(7)*P^7$
Bo	$A(0)+A(1)*P+A(2)*P^2+A(3)*P^3+A(4)*P^4+A(5)*P^5+A(6)*P^6+A(7)*P^7$
Bob	$A(0)+A(1)*P+A(2)*P^2+A(3)*P^3+A(4)*P^4+A(5)*P^5+A(6)*P^6+A(7)*P^7$
Krg	$A(0)+A(1)*S_g+A(2)*S_g^2+A(3)*S_g^3+A(4)*S_g^4+A(5)*S_g^5+A(6)*S_g^6$
Vg	$A(0)+A(1)*P+A(2)*P^2+A(3)*P^3+A(4)*P^4+A(5)*P^5+A(6)*P^6+A(7)*P^7$
1/Bg	$A(0)+A(1)*P+A(2)*P^2+A(3)*P^3+A(4)*P^4+A(5)*P^5+A(6)*P^6+A(7)*P^7$
Rs	$A(0)+A(1)*P+A(2)*P^2+A(3)*P^3+A(4)*P^4+A(5)*P^5+A(6)*P^6+A(7)*P^7$
Kro	$A(0)+A(1)*S_w+A(2)*S_w^2+A(3)*S_w^3+A(4)*S_w^4+A(5)*S_w^5+A(6)*S_w^6+A(7)*S_w^7$
Krw	$A(0)+A(1)*S_w+A(2)*S_w^2+A(3)*S_w^3+A(4)*S_w^4+A(5)*S_w^5+A(6)*S_w^6+A(7)*S_w^7$

Table 2-A is specific to the example in this document; MATBAL.EXE has the facility to curve fit any of the input curves with one of nine different correlations as shown in Table 2-B.

Table 2-B – MATBAL.EXE Regression Equations				
NTYPE				
1	Y vs X	$Y = A+B*X+C*X**2+ \dots$		
2	LN(Y) vs X	$Y = A*EXP(B*X+C*X**2+ \dots)$	(Y > 0)	
3	LN(Y) vs LN(X)	$LN(Y) = A+B*LN(X)+C*LN(X)**2+ \dots$	(X & Y>0)	
4	Y vs LN(X)	$Y = A+B*LN(X)+C*LN(X)**2+ \dots$	(X > 0)	
5	Y vs X	$Y = A+B*X$		v1
6	LN(Y) vs X	$Y = A*EXP(B*X)$	(Y > 0)	v1
7	LN(Y) vs LN(X)	$LN(Y) = A+B*LN(X)$	(X & Y>0)	v1
8	Y vs LN(X)	$Y = A+B*LN(X)$	(X > 0)	v1
9	Y vs X	$Y = A+B*X$		v2
10	LN(Y) vs X	$Y = A*EXP(B*X)$	(Y > 0)	v2
11	LN(Y) vs LN(X)	$LN(Y) = A+B*LN(X)$	(X & Y>0)	v2
12	Y vs LN(X)	$Y = A+B*LN(X)$	(X > 0)	v2

Regression equations 9 through 10 are analogous to regression equations 5 through 8 which are in turn analogous to regression equations 1 through 4. The difference is internal to MATBAL.EXE but the flexibility has been added to compensate for the data inputs which do not always yield a regression fit. For example if you determine that your equation is polynomial and chose to fit your input data with equation 1 and it fails to make a fit, then try equation 5; if that should fail to fit then choose regression equation 9.

Material Balance Results – Forecasts

The oil production profile as a function of pressure drop is shown in *Figure 2 - A* and was generated from importing the output ASCII file from MATBAL.EXE into a MS Excel spreadsheet. The material balance program solved for the production profile above and below the bubble point pressure and decline curve analysis was used to forecast the profile to lower pressures and hence later time. Fundamental relationships for Exponential, Hyperbolic and Harmonic Decline cures are given in *APPENDIX THREE* for reference. Variations in decline analysis can be applied to create numerous production profiles for sensitivity analysis etc.

Figure 2 - B shows the oil production profile with the pressure axis converted to time. *Figure 2 - C* clearly depicts the reservoir's primary recovery factor, which is approximately 20%. The solution gas production profile is shown in *Figure 3 - A* along with the solution gas oil ratios. *Figure 3 - B* shows the gas production profile as a function of time. *Figure 4 - A* shows the water production profile as a function of pressure and *Figure 4 - B* as a function of time.

Should production data from the reservoir be known and/or available then the relative input parameters could be adjusted to match the production and hence predict the future production with additional confidence.

Figure 2-A Qo Np & Np/N vs. Pressure

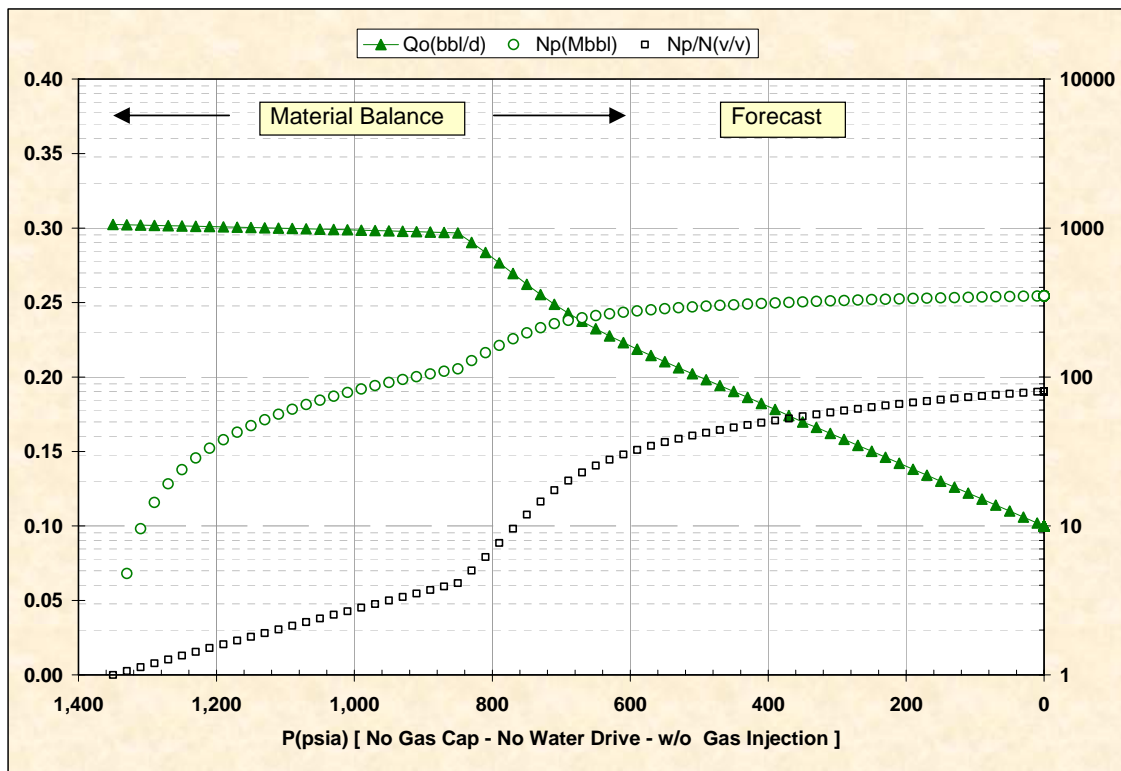


Figure 2 - A – Qo Np & Np/N vs. Pressure

Figure 2-B Qo Np & Np/N vs. Time

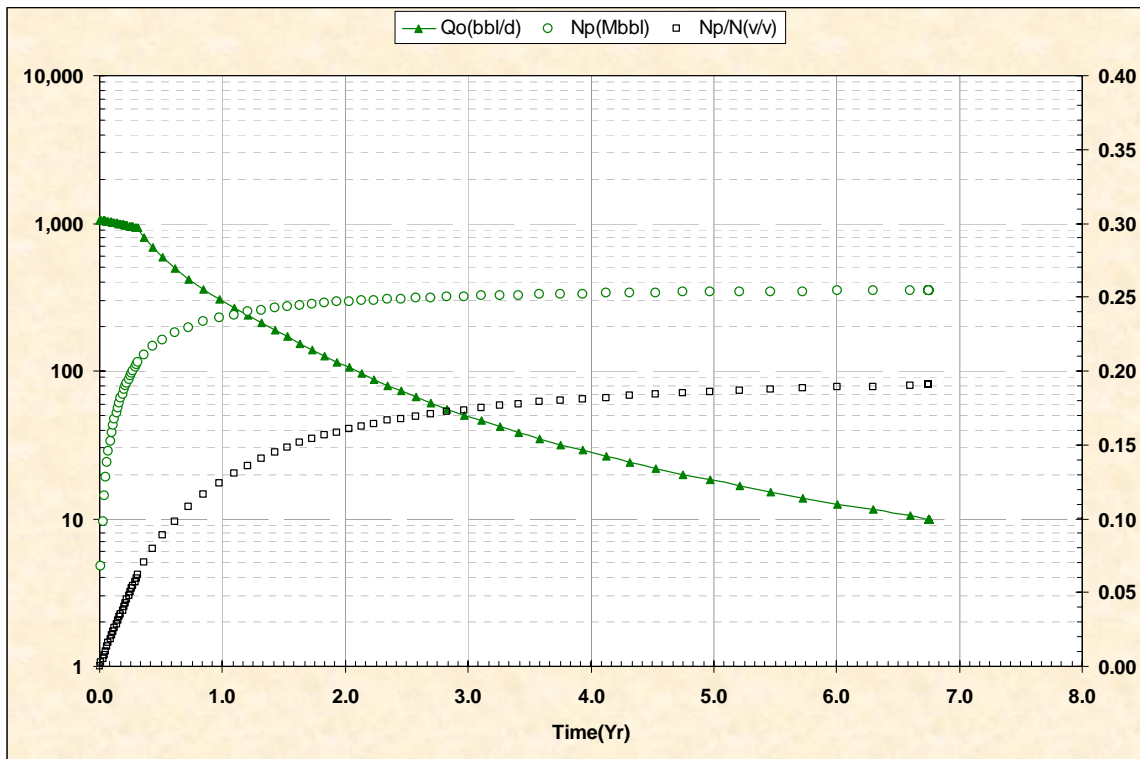


Figure 2 - B – Qo Np & Np/N vs. Time

Figure 2-C P Rp Rs vs. Np/N

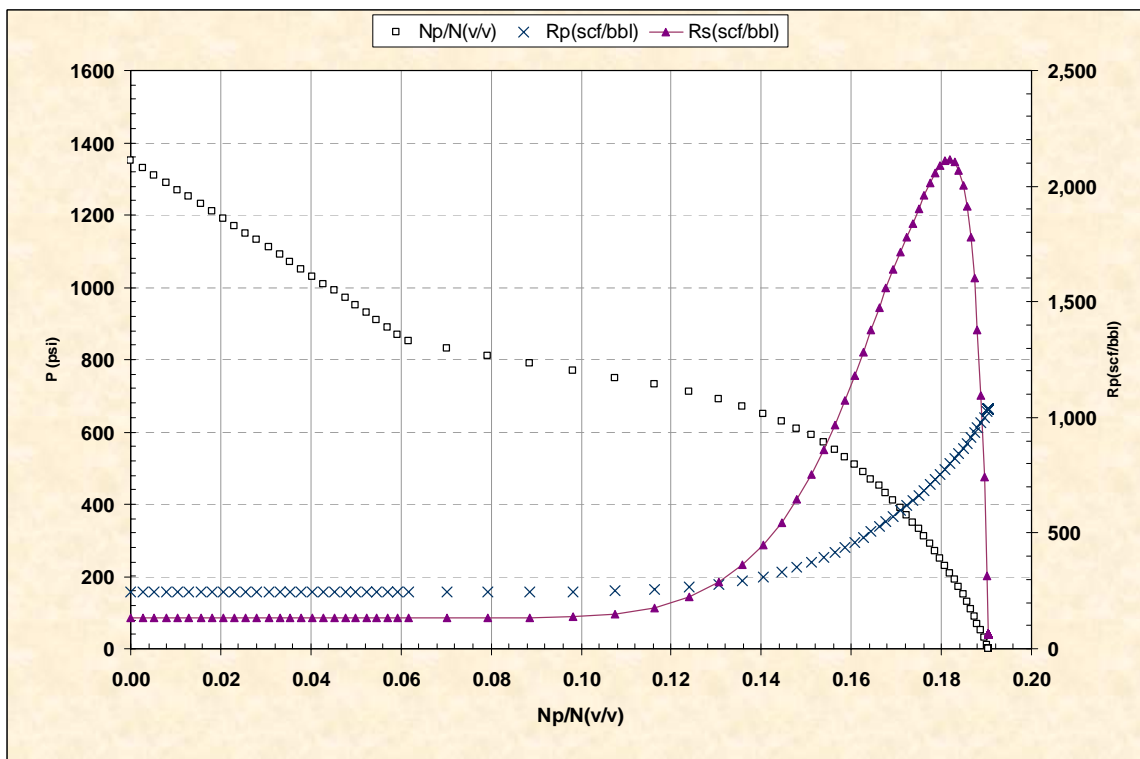


Figure 2 - C – P Rp Rs vs. Np/N

Figure 3-A Rp Rs Qg Gp vs. Pressure

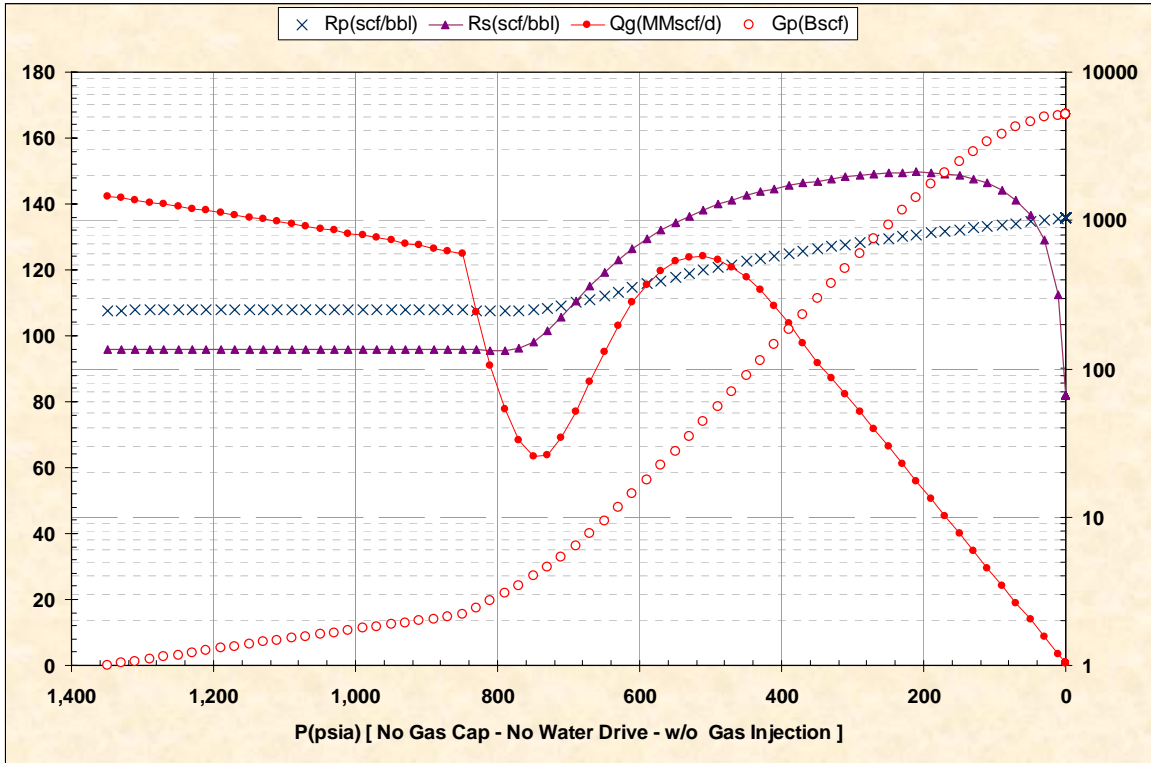


Figure 3 - A – Rp Rs Qg Gp vs. Pressure

Figure 3-B Rp Rs Qg Gp vs. Time

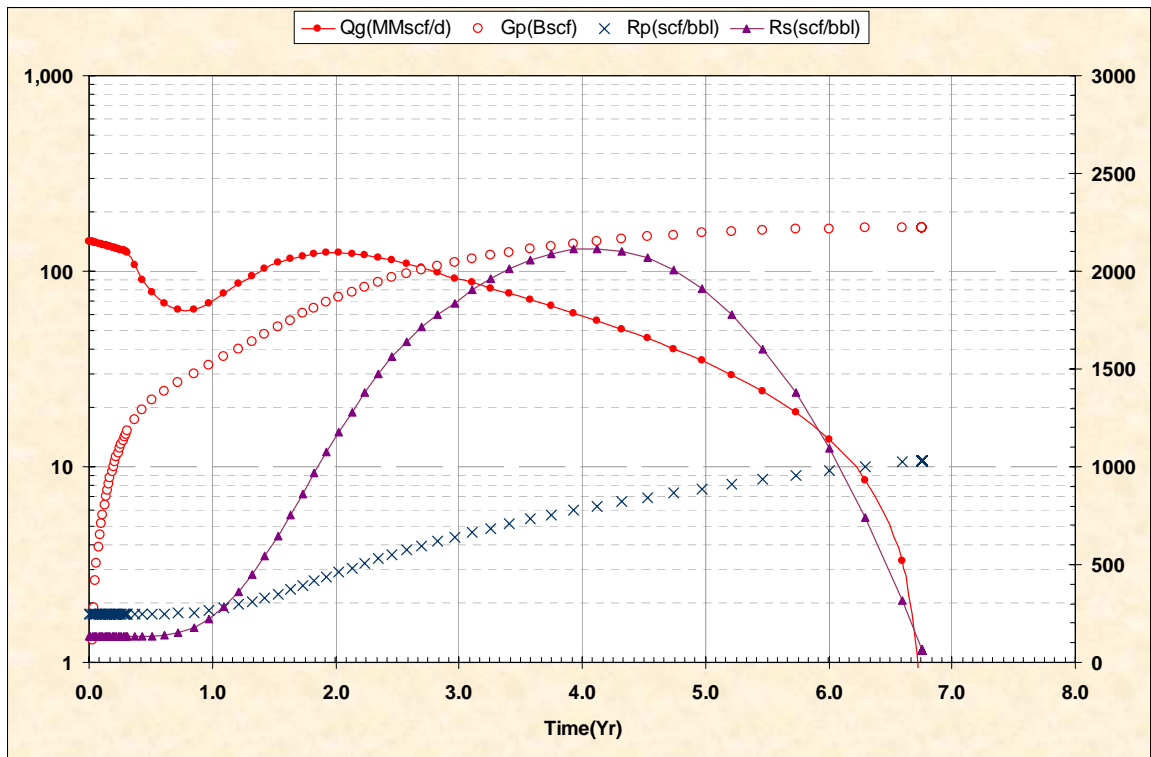


Figure 3 - B – Rp Rs Qg Gp vs. Time

Figure 4-A N_p/N Q_w W_p vs. Pressure

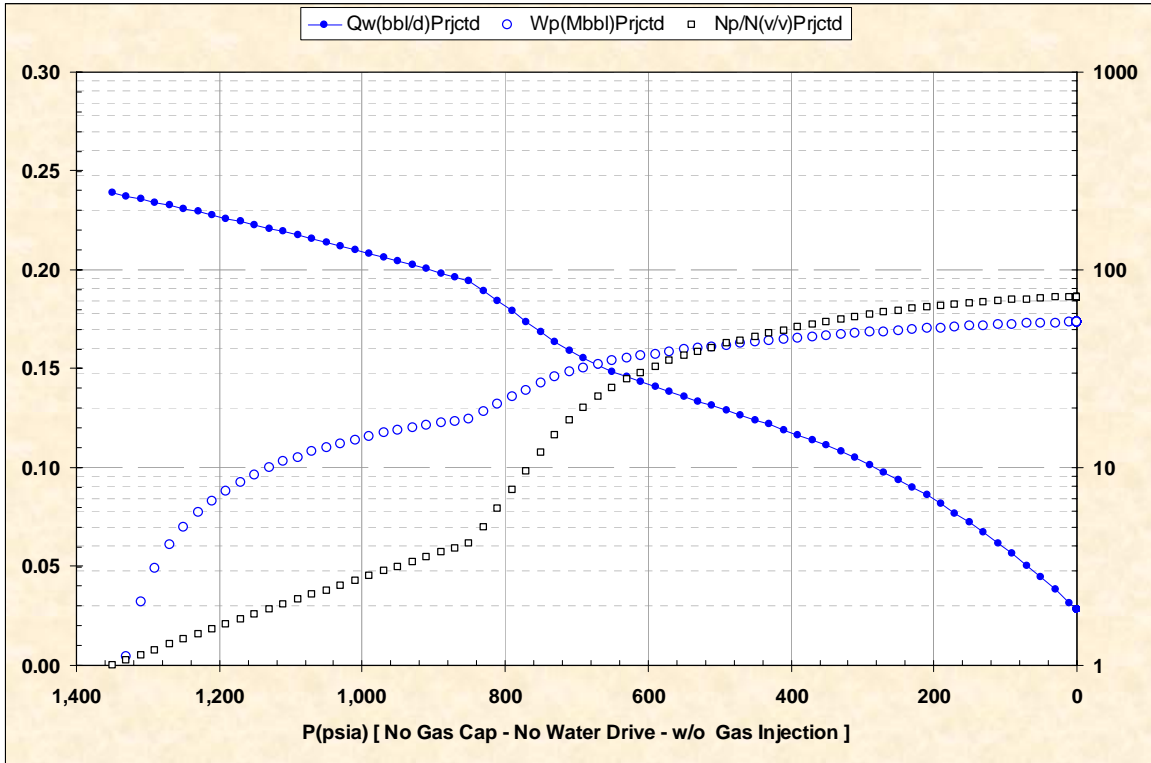


Figure 4 - A – N_p/N Q_w W_p vs. Pressure

Figure 4-B N_p/N Q_w W_p vs. Time

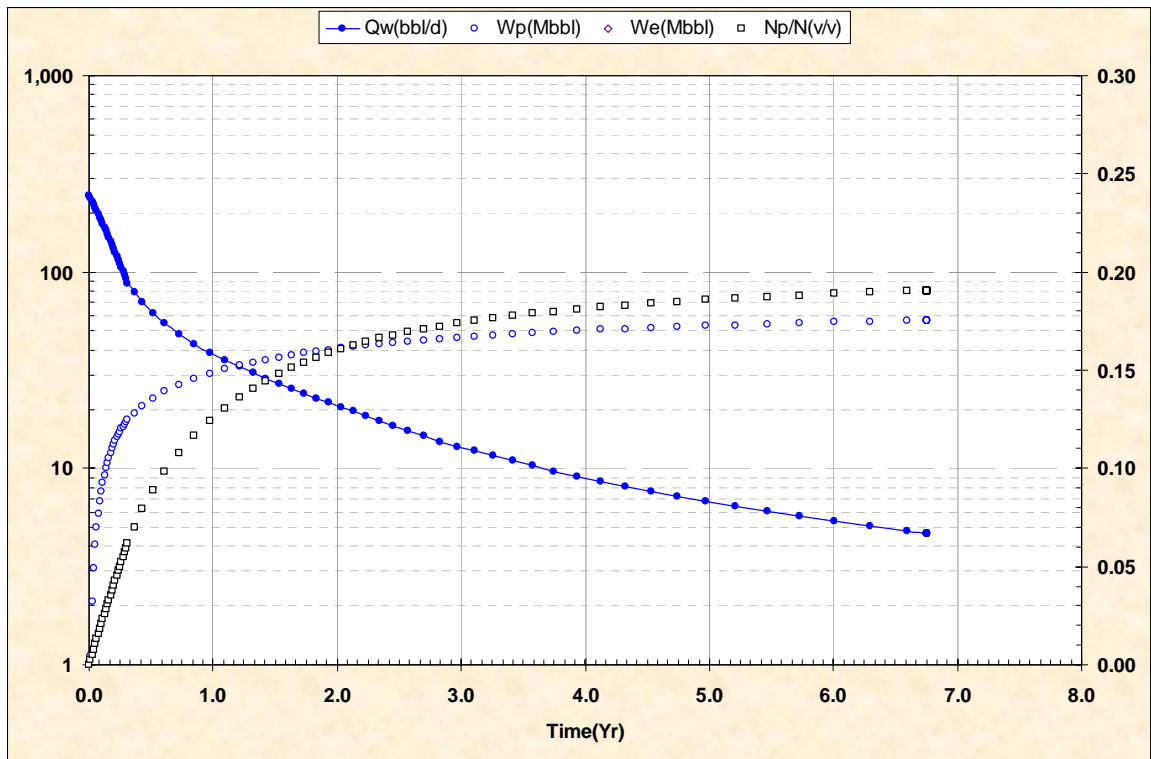
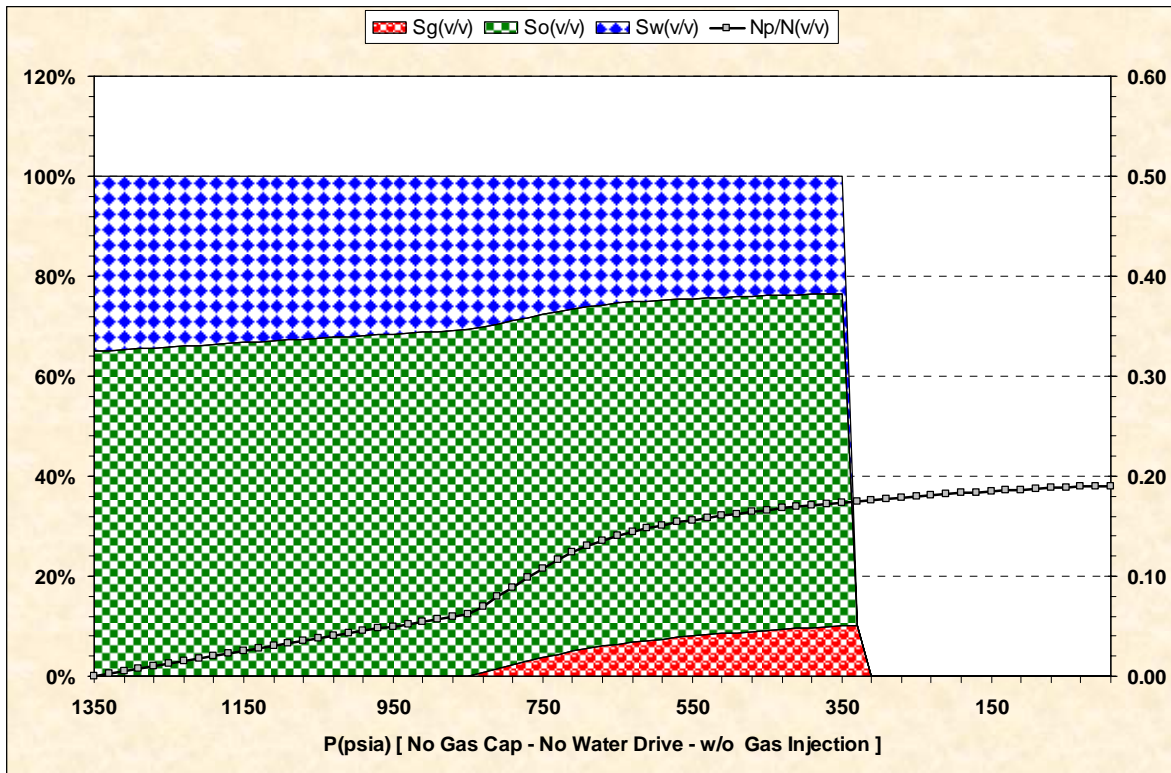


Figure 4 - B – N_p/N Q_w W_p vs. Time

Figure 5-A Sg So Sw & Np/N vs. Pressure**Figure 5 - A – Sg So Sw & Np/N vs. Pressure**

And of course, any petrophysicist / reservoir engineer / production engineer would be interested in the saturation profile. *Figure 5 - A* depicts the fluid saturation profile as a function of reservoir pressure above and below the bubble point pressure, superimposed with N_p/N .

The drive indexes for the pressure interval less than the bubble point with superimpose N_p/N (recovery) is shown in Figures 8-A thru 8-E for comparison of the different types of drive mechanism indicated in the Material Balance Equations as indicated. The relationship between the drive mechanism and the 'primary' recovery factor can easily be seen. Water drive serves to enhance production earlier with respect to time and gas drive definitely increases the 'primary' recovery significantly. The improvement in recovery with respect to increased reservoir energy is intuitive. The following table illustrates the various drive mechanisms and the Material Balance equation switch, MBEQ, used in the FORTRAN program.

Solution Gas Oil Reservoir – Material Balance Equation Switch – MB Equation

MBEQ	0	With Gas Cap	No Water Drive	With Gas Injection
MBEQ	1	No Gas Cap	No Water Drive	
MBEQ	2	No Gas Cap	With Water Drive	
MBEQ	3	With Gas Cap	No Water Drive	
MBEQ	4	With Gas Cap	With Water Drive	

Figure 8-A-1 DDI GDI WDI & Np/N vs. P No Gas Cap & No Water Drive

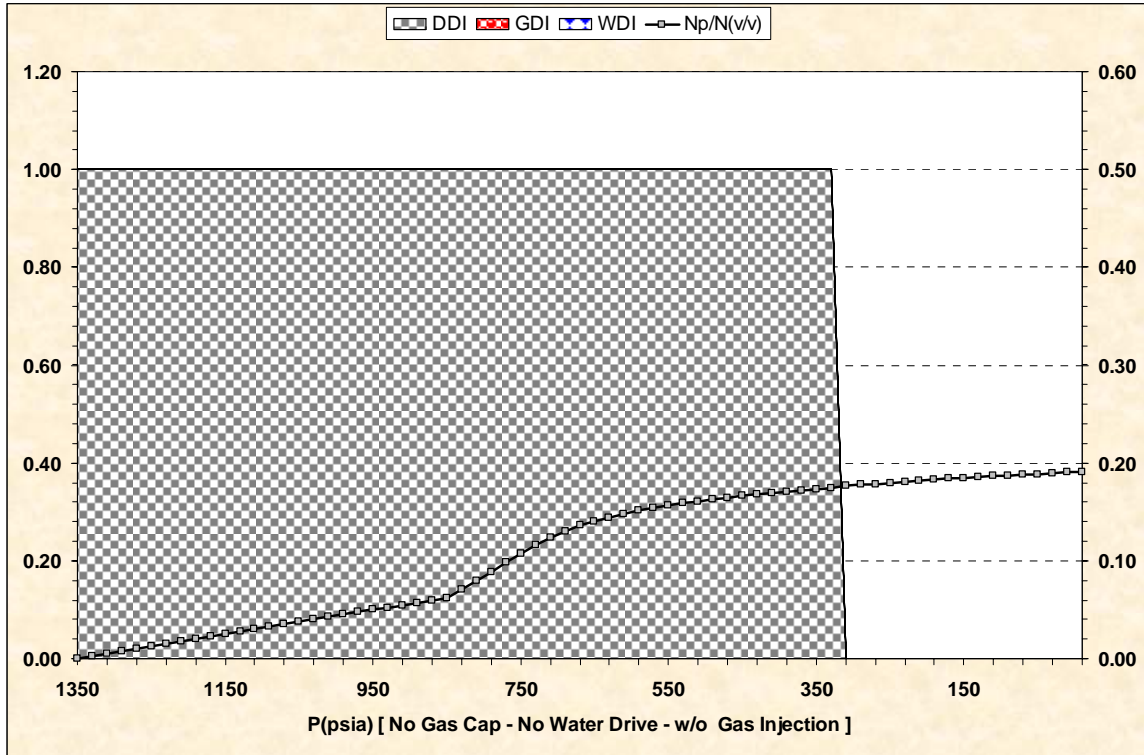


Figure 8-A-1 – DDI GDI WDI & Np/N vs. P No Gas Cap & No Water Drive

Figure 8-A-2 Qo Qg & Qw vs. Np, Gp, Wp No Gas Cap & No Water Drive

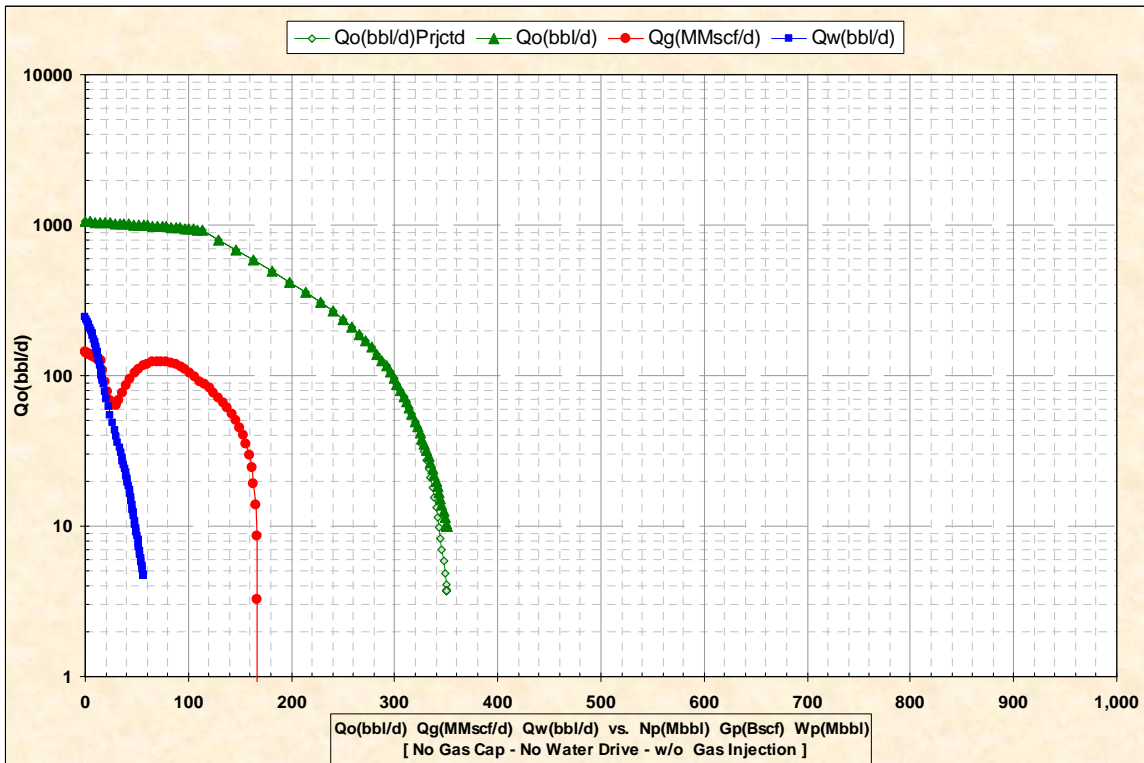


Figure 8-A-2 – Qo Qg & Qw vs. Np, Gp, Wp No Gas Cap & No Water Drive

Figure 8-B-1 DDI GDI WDI & Np/N vs. P No Gas Cap & With Water Drive

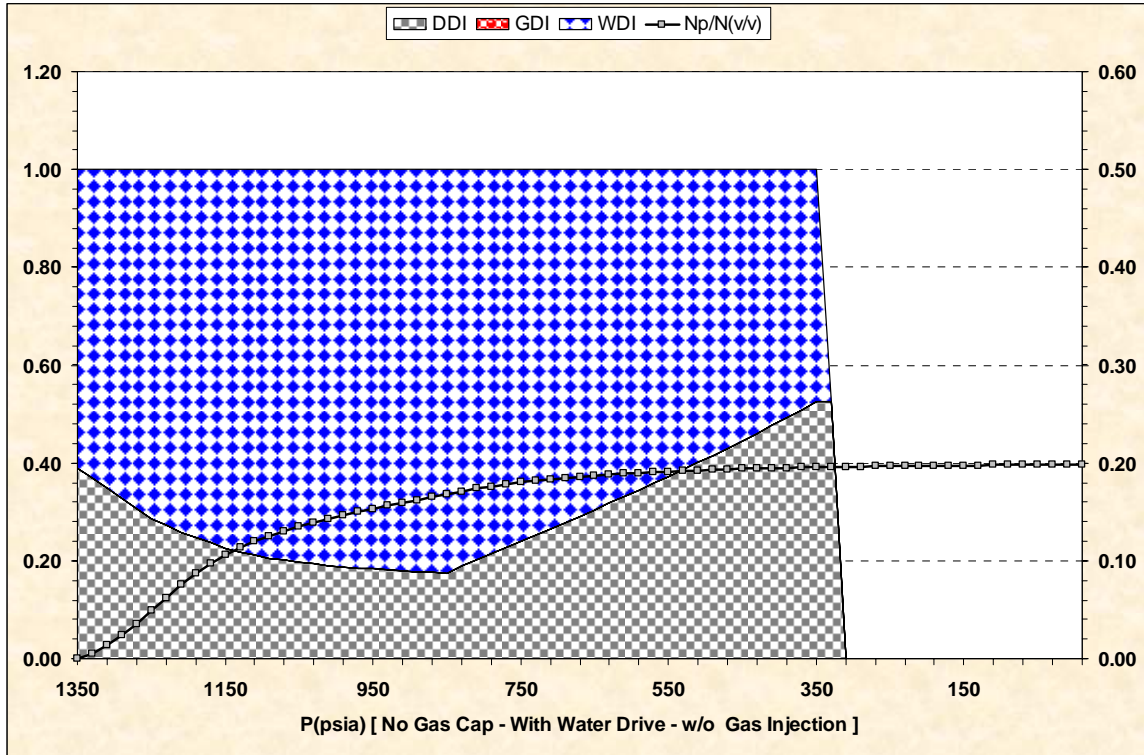


Figure 8-B-1 – DDI GDI WDI & Np/N vs. P No Gas Cap & With Water Drive

Figure 8-B-1 Qo Qg & Qw vs. Np, Gp, Wp No Gas Cap & With Water Drive

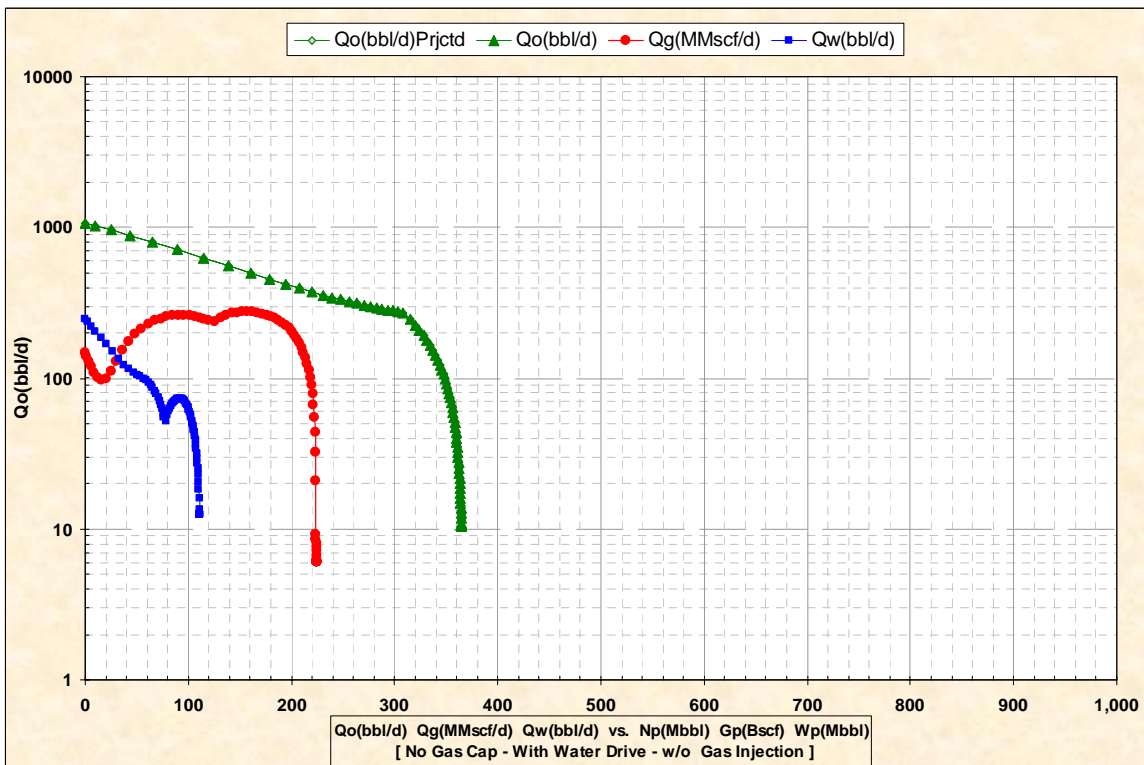


Figure 8-B-1 – Qo Qg & Qw vs. Np, Gp, Wp No Gas Cap & With Water Drive

Figure 8-C-1 DDI GDI WDI & Np/N vs. P With Gas Cap & No Water Drive

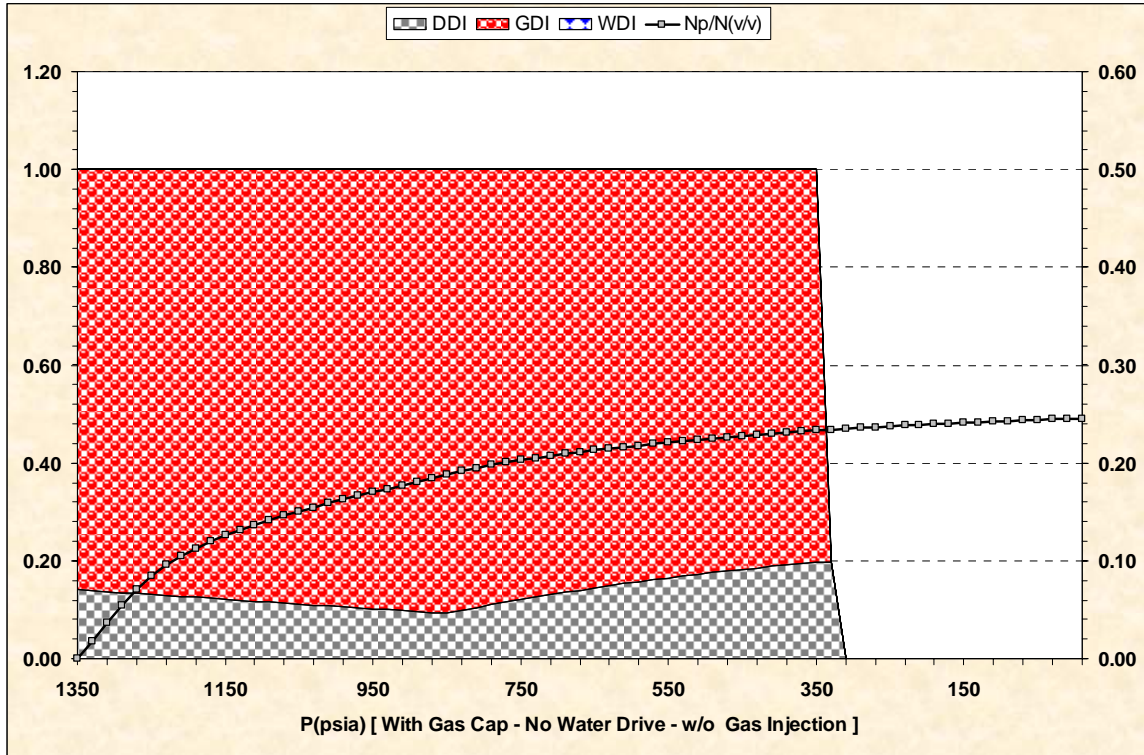


Figure 8-C-1 – DDI GDI WDI & Np/N vs. P With Gas Cap & No Water Drive

Figure 8-C-2 Qo Qg & Qw vs. Np, Gp, Wp With Gas Cap & No Water Drive

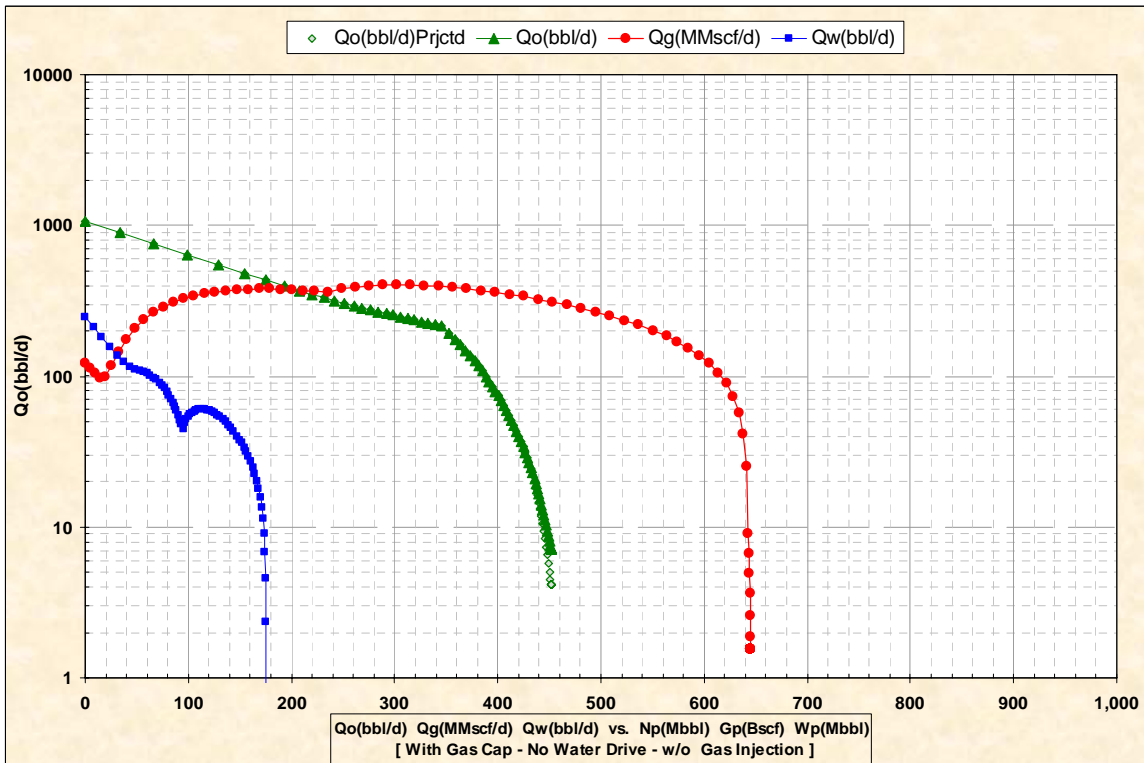


Figure 8-C-2 – Qo Qg & Qw vs. Np, Gp, Wp With Gas Cap & No Water Drive

Figure 8-D-1 DDI GDI WDI & Np/N vs. P With Gas Cap & With Water Drive

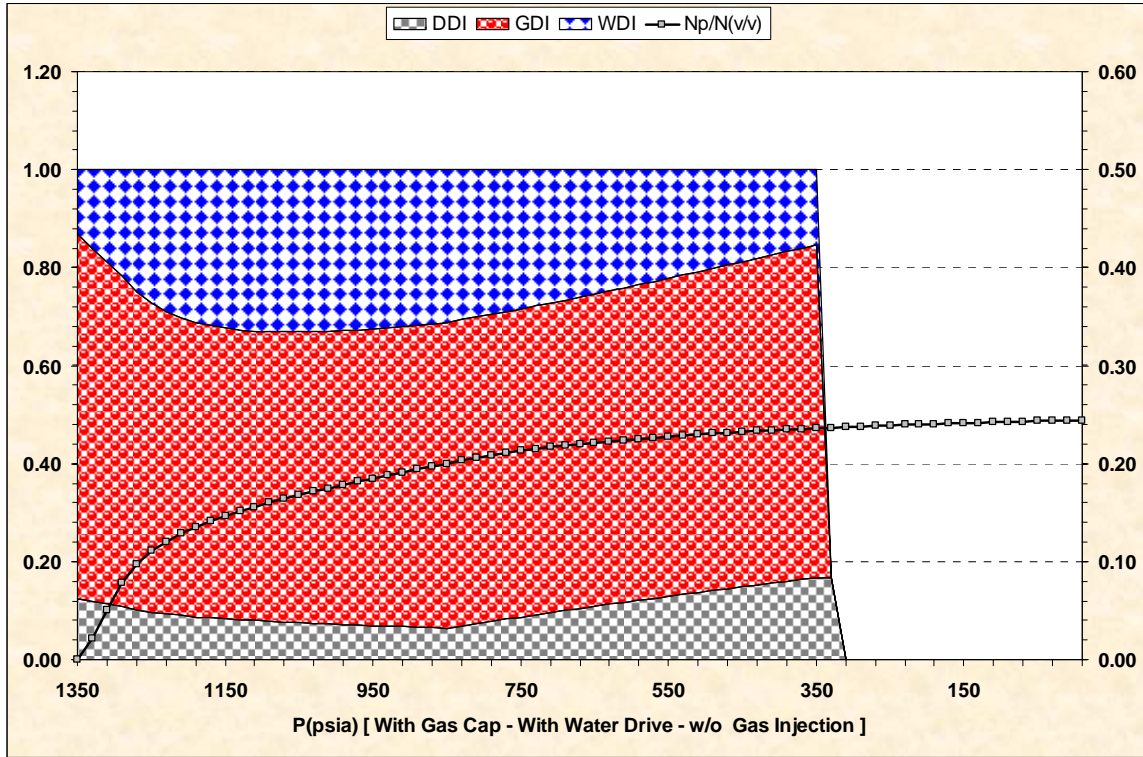


Figure 8-D-1 – DDI GDI WDI & Np/N vs. P With Gas Cap & With Water Drive

Figure 8-D-2 Qo Qg & Qw vs. Np, Gp, Wp With Gas Cap & With Water Drive

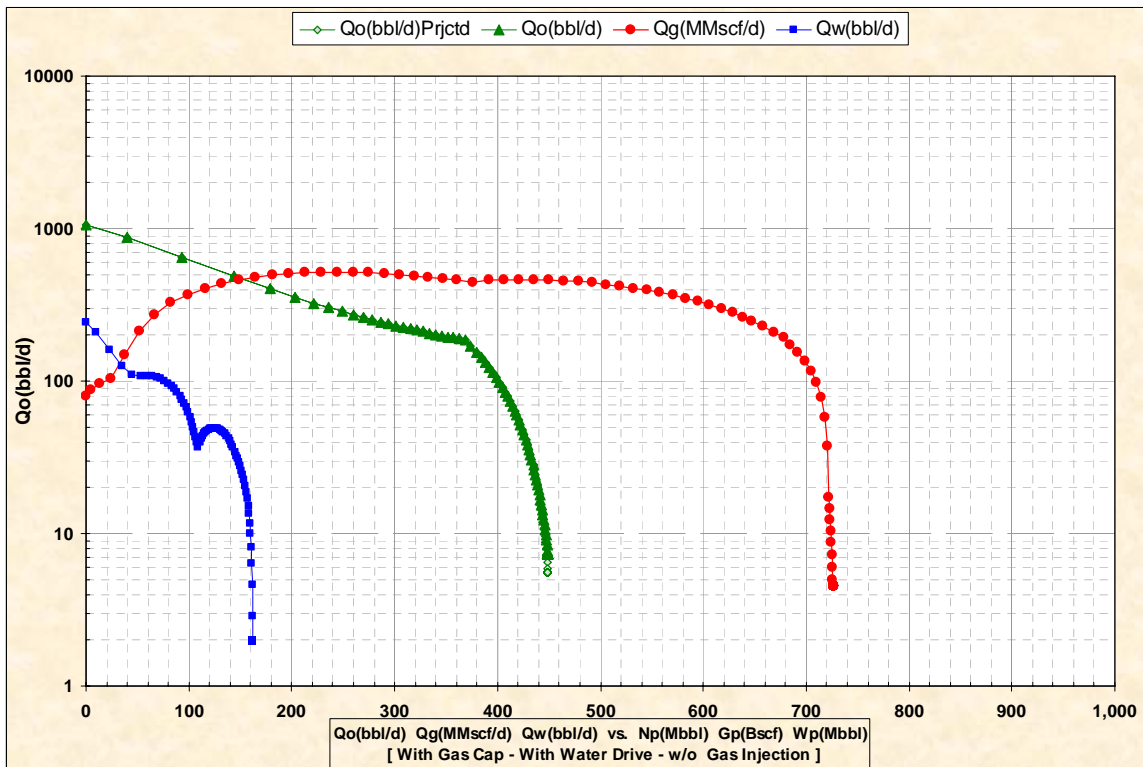


Figure 8-D-2 – Qo Qg & Qw vs. Np, Gp, Wp With Gas Cap & With Water Drive

Figure 8-E-1 DDI GDI WDI & Np/N vs. P With Gas Injection & No Water Drive

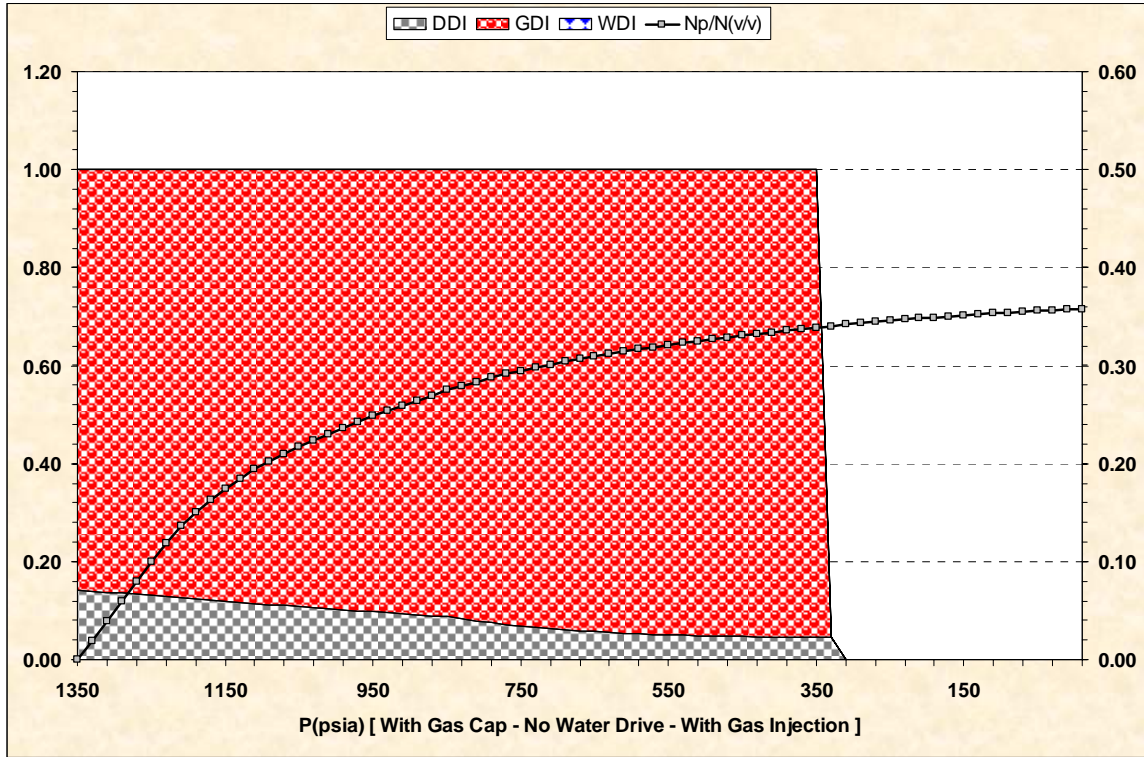


Figure 8-E-1 – DDI GDI WDI & Np/N vs. P With Gas Injection & No Water Drive

Figure 8-E-2 Qo Qg & Qw vs. Np, Gp, Np With Gas Injection & No Water Drive

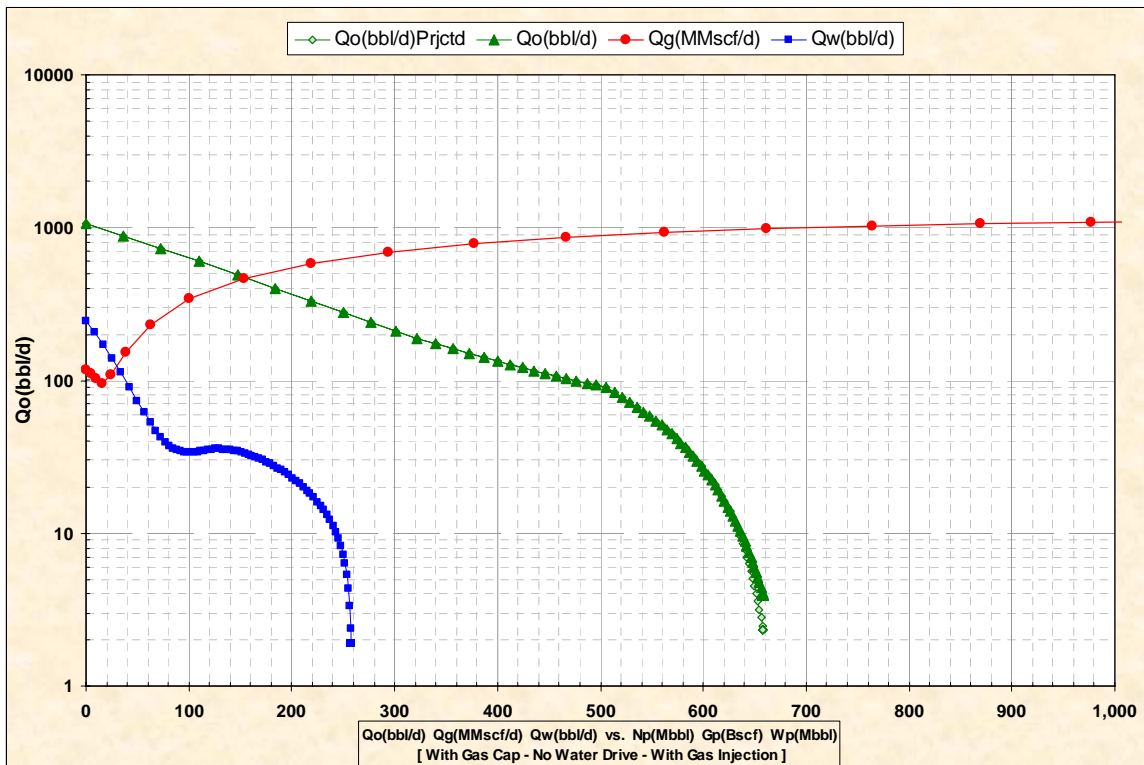


Figure 8-E-2 – Qo Qg & Qw vs. Np, Gp, Wp With Gas Injection & No Water Drive

The expected primary recovery for the reservoir with gas re-injection is significantly improved with respect to the drive mechanisms with out gas re-injection. In practice, a cost benefit analysis should be completed before installing gas injection facilities.

APPENDIX ONE**Nomenclature**

Symbol	Definition	Units
$1/B_{gf}$	Final Gas Formation Volume Factor	SCF/FT ³
$1/B_{gi}$	Initial Gas Formation Volume Factor	SCF/FT ³
A	Reservoir Area	Acres
B_g	Gas Formation Volume Factor	SCF/FT ³
B_{gr}	Gas Formation Volume Factor	SCF/rb
B_{gi}	Initial Gas Formation Volume Factor	SCF/FT ³
B_o	Oil Formation Volume Factor	Bbl/STB
B_{oi}	Initial Oil Formation Volume Factor	Bbl/STB
B_t	Total or 2-Phase Oil Formation Volume Factor	Bbl/STB
B_{ti}	Initial Total or 2-Phase Oil Formation Volume Factor	Bbl/STB
B_w	Water Formation Volume Factor	Bbl/STB
C_f	Formation Isothermal Compressibility Factor or (c_o)	1/psi
C_w	Water Isothermal Compressibility Factor or (c_w)	1/psi
ΔN_p	Oil Production from pressure interval p_{n-1} to p_n	Bbl
Δp	Change in Average Reservoir Pressure	psia
G	Initial Reservoir Gas In Place	SCF
G_f	Volume of Free Gas (Gas Cap) in Reservoir	SCF
$G_{i(n-1)}$	Cumulative gas injection to $p_{(n-1)}$, fraction of G_p	SCF
G_p	Cumulative Produced Gas	SCF
$G_{p(n-1)}$	Cumulative Gas Production to $p_{(n-1)}$	SCF
h	Reservoir Height	Ft
I	Fraction of Produced Gas Injected into Gas Cap	v/v
m	(Initial Reservoir Free Gas Volume) / (Initial Reservoir Volume)	v/v
N	Initial Reservoir Oil In Place	Bbls (STB)
N_p	Cumulative Produced Oil	Bbls (STB)
$N_{p(n-1)}$	Cumulative Oil Production to $p_{(n-1)}$	Bbls
P_r	Average Reservoir Pressure	psia
P_{wf}	Pressure Well Flowing	psia
P_{sc}	Pressure Standard Conditions (14.6960 psia)	psia
θ	Water Encroachment Angle (theta)	degrees
Q_g	Gas Flow Rate	MMscf/d
Q_o	Oil Flow Rate	Bbls/d

R_{ave}	$(R_{R(n-1)} + R_{R(n)}) / 2.0$ Average Instantaneous GOR	SCF/STB
r_e	Effective Radius of Reservoir Pressure Drawdown	Ft
r_e	Reservoir Radius	Ft
r_e/r_d	(reD) Dimensionless Radius	
r_o	Aquifer Radius	Ft
R_p	Cumulative Produced Gas Oil Ratio	SCF/STB
R_r	Instantaneous Solution Gas Oil Ratio	SCF/STB
R_s	Solution Gas Oil Ratio	SCF/STB
R_{si}	Initial Solution Gas Oil Ratio	SCF/STB
R_{si}	Initial Solution Gas to Oil Ratio	SCF/STB
r_w	Radius of Well Bore	Ft
S_g	Gas Saturation (function of pressure and/or time)	v/v
S_L	Total or 2-Phase Liquid Saturation	v/v
S_o	Oil Saturation (function of pressure and/or time)	v/v
S_w	Water Saturation (function of pressure and/or time)	v/v
S_{wi}	Initial Water Saturation	v/v
T_{sc}	Temperature at standard conditions (60.0 °F)	DegF
u_g	Gas Viscosity	cp
u_o	Oil Viscosity	cp
V_f	Initial Void Space	Bbl
W	Initial Reservoir Water	Bbl
W_e	Water Influx into Reservoir	Bbl
W_p	Cumulative Produced Water	STB

Conversions

B_g	$0.02829 (z T / p)$	FT ³ /SCF
B_g	$0.00504 (z T / p)$	rbbl/SCF
B_g	$35.35 (p / z T)$	SCF/FT ³
B_g	$198.4 (p / z T)$	SCF/rbbl

APPENDIX TWO

Figure 6–A Reservoir Schematic

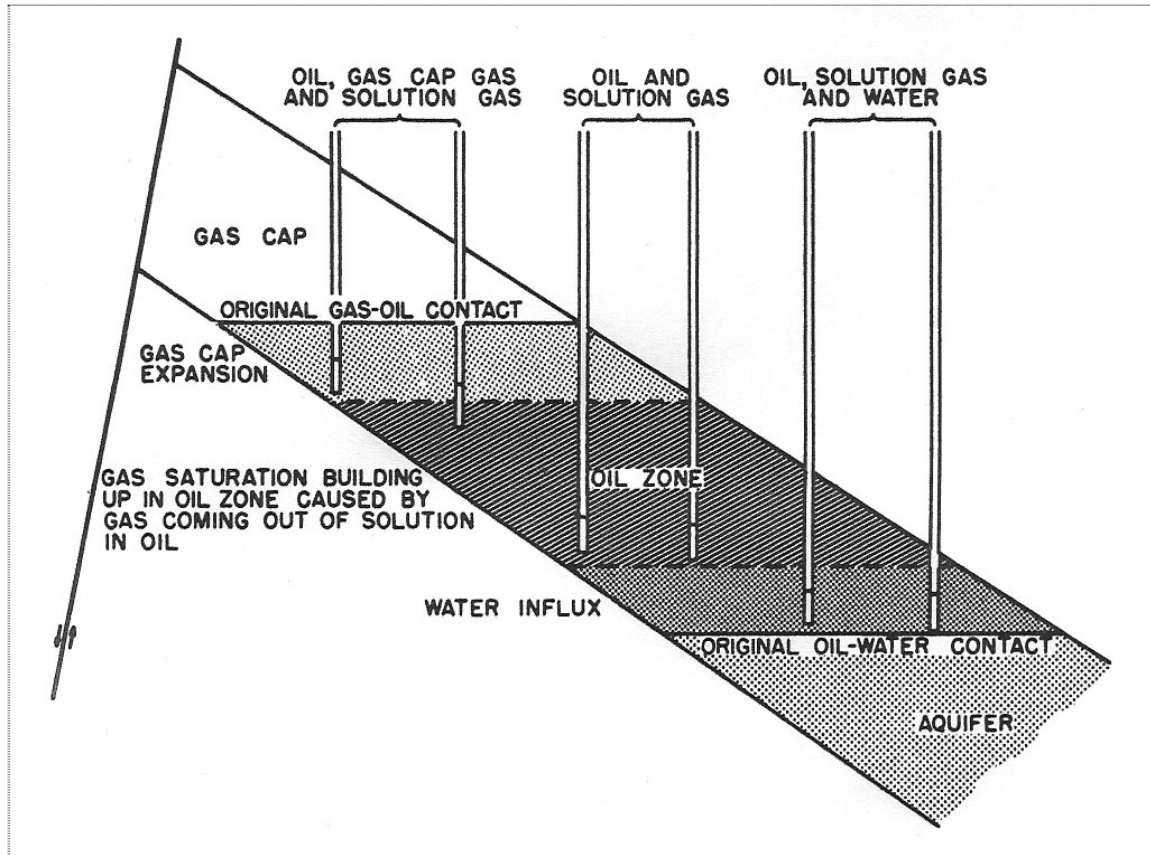


Figure 6 - A – Reservoir Schematic ²

The reservoir schematic is general and serves only to illustrate terms and provide a reference. Each reservoir is structurally unique and has its own distinct fluid characteristics and properties. Along with actual laboratory measurements, numerous petroleum fluid property correlations can be used to approximate the PVT (Pressure – Volume – Temperature) relationships can be ascertained with accuracy to a degree consistent with petroleum engineering applications and development planning.

² Woody, L. D. Jr., & Moscrip, Robert III, "Performance Calculations for Combination Drive Reservoirs," Trans. AIME, 1956, pp 210, 125
 Craft, B. C., & Hawkins, Applied Petroleum Reservoir Engineering

APPENDIX THREE**Exponential Decline**

$$q = q_i e^{-Dt}$$

where $D > 0$

$$D = - \left[\ln \left(\frac{q}{q_i} \right) \right] / t$$

$$t = - \left[\ln \left(\frac{q}{q_i} \right) \right] / D$$

$$t = N_p \left[\ln \left(\frac{q}{q_i} \right) \right] / (q_i - q)$$

$$N_p = (q_i - q) / D$$

$$N_p = t \cdot (q_i - q) / \ln \left(\frac{q_i}{q} \right)$$

$$D = (q_i - q) / N_p$$

Hyperbolic Decline

$$q = q_i (1 + b \cdot D_i \cdot t)^{(-1/b)}$$

where $0 \leq b \leq 1.0$; $D_i > 0$

$$D_i = \left[\left(\frac{q_i}{q} \right)^b - 1 \right] / (b \cdot t)$$

$$t = \left[\left(\frac{q_i}{q} \right)^b - 1 \right] / (b \cdot D_i)$$

$$N_p = \left\{ q_i^b / [(1-b) \cdot D_i] \right\} [q_i^{(1-b)} - q^{(1-b)}]$$

$$N_p = \left\{ t \cdot q_i^b / [(1-b)/b] \left[\left(\frac{q_i}{q} \right)^b - 1 \right] \right\} [q_i^{(1-b)} - q^{(1-b)}]$$

$$D_i = \left\{ q_i^b / [(1-b) \cdot N_p] \right\} [q_i^{(1-b)} - q^{(1-b)}]$$

Harmonic Decline

$$q = q_i / (1 + D_i \cdot t)$$

as Hyperbolic Decline with $b = 1.0$, $D_i > 0$

$$D_i = (q_i / N_p) \ln(q_i / q)$$

$$t = \left[\left(\frac{q_i}{q} \right) - 1 \right] / D_i$$

$$N_p = (q_i / D_i) \ln(q_i / q)$$

$$N_p = \left[(t \cdot q_i) / (q_i / q - 1) \right] \ln(q_i / q)$$

APPENDIX FOUR

Water Influx (W_e) - Radial Flow and Linear Flow

Figure 7 - A shows the dimensionless water influx for the constant terminal pressure case for radial flow used to derive W_e . Table 3-A shows the relevant relationships that are required to apply Figure 7 - A to determine the water influx.

Radial Flow	Linear Flow
$t_D = \frac{K \cdot t}{\phi \cdot \mu \cdot c \cdot r_o^2} * F$	$t_D = \frac{K \cdot t}{\phi \cdot \mu \cdot c \cdot L_o^2} * F$
F = 0.000264 t in hours	F = 0.000264 t in hours
F = 0.00634 t in days	F = 0.00634 t in days
F = 2.309 t in years	F = 2.309 t in years
$c = c_w + c_f$	$c = c_w + c_f$
$U = 1.119 \cdot f \cdot \phi \cdot h \cdot c \cdot r_o^2 \text{ (bbl/d/psi)}$	$U = 0.1781 \cdot w \cdot L \cdot h \cdot \phi \cdot c \text{ (bbl/d/psi)}$
$f = \theta/360 \text{ or } f = \theta/2\pi \text{ radians } \theta = \text{encroachment angle}$	w = Width; L = Length; h = Height
$r_{eD} = r_e/r_o \text{ (Aquifer Radius)/(Reservoir Radius)}$	$r_{eD} = L_e/L_o \text{ (Aquifer Length)/(Reservoir Length)}$
$r_{eD} = r_e / r_o$	$r_{eD} = r_e / r_o$
$W_D = W_D \left\{ t_D, r_{eD} \right\} \text{ [Figure 7 - A]}$	$W_D = W_D \left\{ t_D, r_{eD} \right\} \text{ [Figure 7 - A]}$
$W_e = U \cdot \Delta p \cdot W_D \left\{ t_D, r_{eD} \right\} \text{ (Bbls)}$	$W_e = U \cdot \Delta p \cdot W_D \left\{ t_D, r_{eD} \right\} \text{ (Bbls)}$
$W_e = U \cdot \sum_{j=1}^n (p_{j-1} - p_j) \cdot W_D \left\{ t_D, r_{eD} \right\} \text{ (Bbls)}$	$W_e = U \cdot \sum_{j=1}^n (p_{j-1} - p_j) \cdot W_D \left\{ t_D, r_{eD} \right\} \text{ (Bbls)}$

Table 3-A – Water Influx (W_e) - Radial Flow and Linear Flow

Figure 7-A Water Influx (W_e)³

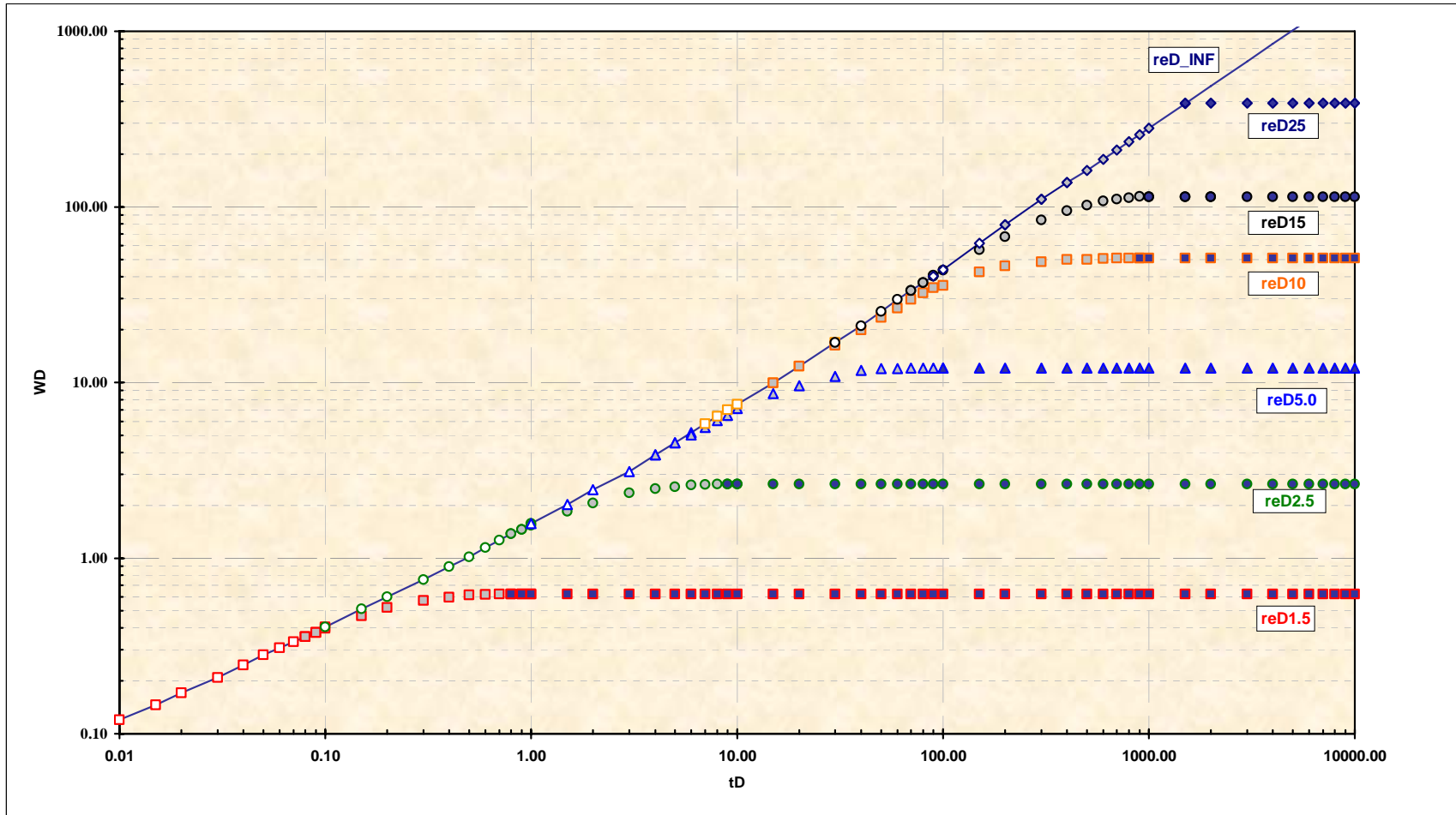


Figure 7 - A – Dimensionless Water Influx, Constant Terminal Pressure Case, Radial Flow

³ Drake, L. P. Fundamentals of Reservoir Engineering, Elsevier Scientific Publishing Co. 1978, pp. 308-312

APPENDIX FIVE

Empirical Permeability Relationships

$$K^2 = C_1 \cdot PHIE^3 \cdot \left(\frac{1 - S_{wirr}}{S_{wirr}} \right)$$

$$K = \left(\frac{C_2 \cdot (1 - V_{cl}) \cdot PHIE^3}{S_{wirr}} \right)^2$$

PHIE is effective porosity and V_{cl} is clay volume as determined from the petrophysical and/or core analysis. The various constants are best determined from linear regression of the log derived data and any available core analysis data. ⁴

Empirical Relative Permeability – K_{rw} & K_{ro}

$$k_{rw} = \left[\frac{S_w - S_{wirr}}{1 - \alpha \cdot S_{wirr}} \right]^\delta$$

$$k_{ro} = \frac{(1 - S_w)^\Delta \cdot [\beta \cdot S_w + (1 - S_w) - \gamma_5 \cdot S_{wirr}]}{(1 - S_{wirr})^\Delta}$$

Drainage Regime:

$$k_{rw} = \left(\frac{S_w - S_{wirr}}{1 - S_{wirr}} \right)^{\Psi_2} \cdot \left(\frac{S_w^{2X_2+1} - S_{wirr}^{2X_2+1}}{1 - S_{wirr}^{2\Gamma_2+1}} \right)$$

$$k_{ro} = \left[1 - \left(\frac{S_w - S_{wirr}}{1 - S_{wirr}} \right) \right]^{\Psi_1} \cdot \left(\frac{1 - S_w^{2X_1+1}}{1 - S_{wirr}^{2X_1+1}} \right)$$

Imbibition Regime:

$$k_{rw} = \left(\frac{S_w - S_{wirr}}{1 - S_{wirr}} \right)^{0.5} \cdot (S_w)^4$$

$$k_{ro} = \left[1 - \left(\frac{S_w - S_{wirr}}{1 - S_{wirr} - S_{or}} \right) \right]^2 \cdot (1.08 - 1.11 \cdot S_{wirr} - 0.73 \cdot S_{wirr}^2)$$

Empirical Relative Permeability – K_{ro} & K_{rg}

$$k_{ro} = \left[1 - \nu \cdot (S_g - \gamma_1 \cdot S_{wirr}) \right]^\omega$$

$$k_{rg} = \left[\eta \cdot (S_g + \gamma_2 \cdot S_{wirr}) \right]^\lambda$$

⁴ K equation is the Wyllie-Rose equation (1950) with correction for clay volume effects added.

Another empirical relationship for gas and oil relative permeability that is a function of both gas saturation and/or liquid saturation and is more sensitive to S_{wirr} is:

$$k_{ro} = \left[(S_L + \gamma_3 \cdot S_{wirr})^4 \right]^\Omega$$

$$k_{rg} = \frac{\tau \cdot (S_g)^\sigma \cdot \left[(1 - \gamma \cdot S_{wirr})^\psi - (S_L - \gamma_4 \cdot S_{wirr})^\sigma \right]}{(1 - S_{wirr})^\psi}$$

The coefficients and exponents are determined by the reservoir engineer and/or petrophysicist. ⁵

⁵ Typical values for the constants in the relative permeability equations for the reservoir herein are:

ψ	5.00	ν	2.33	γ_1	-0.080		
λ	3.70	η	2.66	γ_2	0.100		
Ω	4.00			γ_3	0.000		
ψ	4.00	σ	7.33	γ_4	0.000		
Δ	3.88	β	1.44	γ_4	0.222		
δ	2.00	α	0.900				
X1	0.800	Ψ_1	0.300				
X2	0.020	Ψ_2	1.100				

APPENDIX SIX**INPUT FILE: User Defined File Name**

```

C---|-----1-----|-----2-----|-----3-----|-----4-----|-----5-----|-----6-----|-----7-----|-----
C INPUT.TXT (ASCII File Name - User Defined)
C-----
C-----10-----20-----30-----40-----50-----60-----70-----8
C-----|-----|-----|-----|-----|-----|-----|-----|
PI          1350.0
PBP         850.0
DP          20.0
RW          0.25
RE         660.0
PW          25.0
THTA       360.0
RDSR       744.7
RDSA       2234.2
MBEQ        1.0
GCAP        1.0
GNJR        0.50
PHI(I)      0.315      0.315
SW(I)       0.200      0.200
H(I)        17.0       14.0
K(I)        71.0       41.0
ACRE(I)     40.0       40.0
RW75(I)     0.100      0.100
RTEM(I)     199.9      199.9
C-----|-----|-----|-----|-----|-----|-----|-----|
C-----10-----20-----30-----40-----50-----60-----70-----8
C-----

```

OUTPUT FILE: LSQOUT.TXT

```

CurveFit   SG_KGKO.TXT   LN(Y)~X           NTYPE=  2  Y   =  A*EXP(B*X+C*X**2+...)

A(0)=      .7876544E-05   A(0)=           .0000079
A(1)=      .1889570E+03   A(1)=          188.9570000
A(2)=     -.1388812E+04   A(2)=         -1388.8120000
A(3)=      .5531615E+04   A(3)=          5531.6150000
A(4)=     -.1006028E+05   A(4)=        -10060.2800000
A(5)=      .6523354E+04   A(5)=          6523.3540000
A(6)=      .0000000E+00   A(6)=           .0000000
A(7)=      .0000000E+00   A(7)=           .0000000

R^2         = 1.0000000   AveDev=          4.1469870   % PolyDeg=    5

CurveFit   SG_KO.TXT    Y   ~X           NTYPE=  1  Y   =  A+B*X+C*X**2+...

A(0)=      .1008045E+01   A(0)=           1.0080450
A(1)=     -.1536408E+02   A(1)=          -15.3640800
A(2)=      .9084401E+02   A(2)=           90.8440100
A(3)=     -.1668596E+03   A(3)=          -166.8596000
A(4)=     -.4402498E+03   A(4)=          -440.2498000
A(5)=      .2095331E+04   A(5)=          2095.3310000
A(6)=     -.2173654E+04   A(6)=         -2173.6540000
A(7)=      .0000000E+00   A(7)=           .0000000

R^2         = .9999042   AveDev=          17.3424900   % PolyDeg=    6

```

Material Balance / Forecast / History Match - FORTRAN Program - MATBAL.EXE

CurveFit SG_KG.TXT Y ~X NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .3213808E-02 A(0)= .0032138
 A(1)= -.4826481E+00 A(1)= -.4826481
 A(2)= .1589832E+02 A(2)= 15.8983200
 A(3)= -.1472263E+03 A(3)= -147.2263000
 A(4)= .6288443E+03 A(4)= 628.8443000
 A(5)= -.7689434E+03 A(5)= -768.9434000
 A(6)= .0000000E+00 A(6)= .0000000
 A(7)= .0000000E+00 A(7)= .0000000

R^2 = .9999639 AveDev= 81.5201300 % PolyDeg= 5

CurveFit PSI_VO.TXT Y ~X NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .2653865E+01 A(0)= 2.6538650
 A(1)= -.4571421E-02 A(1)= -.0045714
 A(2)= .1426655E-04 A(2)= .0000143
 A(3)= -.2736485E-07 A(3)= .0000000
 A(4)= .2465005E-10 A(4)= .0000000
 A(5)= -.8442764E-14 A(5)= .0000000
 A(6)= .0000000E+00 A(6)= .0000000
 A(7)= .0000000E+00 A(7)= .0000000

R^2 = .9998388 AveDev= .1837955 % PolyDeg= 5

CurveFit PSI_VOB.TXT Y ~X NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .2008922E+00 A(0)= .2008922
 A(1)= .1399091E-02 A(1)= .0013991
 A(2)= .0000000E+00 A(2)= .0000000
 A(3)= .0000000E+00 A(3)= .0000000
 A(4)= .0000000E+00 A(4)= .0000000
 A(5)= .0000000E+00 A(5)= .0000000
 A(6)= .0000000E+00 A(6)= .0000000
 A(7)= .0000000E+00 A(7)= .0000000

R^2 = .9999999 AveDev= .0013972 % PolyDeg= 1

CurveFit PSI_BO.TXT Y ~X NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .1032752E+01 A(0)= 1.0327520
 A(1)= .4226366E-03 A(1)= .0004226
 A(2)= -.1360643E-05 A(2)= -.0000014
 A(3)= .2608217E-08 A(3)= .0000000
 A(4)= -.2358473E-11 A(4)= .0000000
 A(5)= .8136891E-15 A(5)= .0000000
 A(6)= .0000000E+00 A(6)= .0000000
 A(7)= .0000000E+00 A(7)= .0000000

R^2 = .9999092 AveDev= .0262600 % PolyDeg= 5

CurveFit PSI_BOB.TXT Y ~X NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .1260779E+01 A(0)= 1.2607790
 A(1)= -.1409399E-03 A(1)= -.0001409
 A(2)= .0000000E+00 A(2)= .0000000
 A(3)= .0000000E+00 A(3)= .0000000
 A(4)= .0000000E+00 A(4)= .0000000
 A(5)= .0000000E+00 A(5)= .0000000
 A(6)= .0000000E+00 A(6)= .0000000
 A(7)= .0000000E+00 A(7)= .0000000

R^2 = .9994282 AveDev= .0240355 % PolyDeg= 1

CurveFit PSI_RS.TXT Y ~X NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .1982384E+02 A(0)= 19.8238400
 A(1)= .6384298E+00 A(1)= .6384298

Material Balance / Forecast / History Match – FORTRAN Program – MATBAL.EXE

```

A(2)= -.1704529E-02  A(2)= -.0017045
A(3)= .3337653E-05  A(3)= .0000033
A(4)= -.3101089E-08  A(4)= .0000000
A(5)= .1094481E-11  A(5)= .0000000
A(6)= .0000000E+00  A(6)= .0000000
A(7)= .0000000E+00  A(7)= .0000000

R^2      = .9999068  AveDev= .5060760  % PolyDeg= 5

CurveFit  PSI_VG.TXT  Y ~X      NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .7626730E-02  A(0)= .0076267
A(1)= .2637659E-04  A(1)= .0000264
A(2)= -.9411491E-07  A(2)= -.0000001
A(3)= .1777481E-09  A(3)= .0000000
A(4)= -.1575048E-12  A(4)= .0000000
A(5)= .5305303E-16  A(5)= .0000000
A(6)= .0000000E+00  A(6)= .0000000
A(7)= .0000000E+00  A(7)= .0000000

R^2      = .9996979  AveDev= .2223095  % PolyDeg= 5

CurveFit  PSI_BG.TXT  Y ~X      NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .9870148E+01  A(0)= 9.8701480
A(1)= .3478291E+00  A(1)= .3478291
A(2)= .7255743E-04  A(2)= .0000726
A(3)= -.1582220E-07  A(3)= .0000000
A(4)= .0000000E+00  A(4)= .0000000
A(5)= .0000000E+00  A(5)= .0000000
A(6)= .0000000E+00  A(6)= .0000000
A(7)= .0000000E+00  A(7)= .0000000

R^2      = .9999986  AveDev= .1769580  % PolyDeg= 3

CurveFit  SW_KRO.TXT  Y ~X      NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .1025815E+01  A(0)= 1.0258150
A(1)= .9878426E+00  A(1)= .9878426
A(2)= -.1220467E+02  A(2)= -12.2046700
A(3)= .1805919E+02  A(3)= 18.0591900
A(4)= -.7876586E+01  A(4)= -7.8765860
A(5)= .0000000E+00  A(5)= .0000000
A(6)= .0000000E+00  A(6)= .0000000
A(7)= .0000000E+00  A(7)= .0000000

R^2      = .9995065  AveDev= 31.1262500  % PolyDeg= 4

CurveFit  SW_KRW.TXT  Y ~X      NTYPE= 1 Y = A+B*X+C*X**2+...

A(0)= .5465746E-04  A(0)= .0000547
A(1)= .3721613E+00  A(1)= .3721613
A(2)= -.3692003E+01  A(2)= -3.6920030
A(3)= .1244712E+02  A(3)= 12.4471200
A(4)= -.1394124E+02  A(4)= -13.9412400
A(5)= .5842241E+01  A(5)= 5.8422410
A(6)= .0000000E+00  A(6)= .0000000
A(7)= .0000000E+00  A(7)= .0000000

R^2      = .9999766  AveDev= 17.8637900  % PolyDeg= 5

```

FORTRAN Program – Variables Utilized

C-----			
C	VO	= Viscosity of oil = f(P...), Vo	cp
C	VG	= Viscosity of gas = f(P...), Vg	cp
C	VW	= Viscosity of water = f(P...), Vw	cp
C	RVKH	= Reservoir Permeability Feet, K*H	md
C	KGO	= Relative permeability of Oil Phase f(Sg)	md
C	KGG	= Relative permeability of Gas Phase f(Sg)	md
C	RKGGKO	= Oil/Gas permeability ratio f(Sg)	md
C	KO	= Permeability of oil phase, Ko = Kro*K	md
C	KW	= Permeability of water phase, Kw = Krw*K	md
C	KG	= Permeability of gas phase, Kg = Krg*K	md
C	KRO	= Relative permeability of oil phase, Rko	md
C	KRW	= Relative permeability of water phase, Rkw	md
C	KRG	= Relative permeability of gas phase, Rkg	md
C	OOIP	= Initial oil in place, N	bbbl
C	NOPN	= Fraction oil recovery = Np/N	v/v
C	NP	= Bbls stock tank oil produced @ P and RP, Np	bbbl
C	BG	= Gas formation volume factor = f(P...)	rcf/scf
C	BO	= Oil formation volume factor = f(P...)	bbbl/STB
C	BW	= Water formation volume factor = f(P...)	bbbl/STB
C	BT	= Total BO or 2-phase BO or active BO	bbbl/STB
C		reservoir volume of 1 STB of oil and its	
C		original complement of dissolved gas, Bt	
C	TOPP	= Total oil produced during delta pressure	bbbl
C	TGPP	= Total gas produced during delta pressure	scf
C	NGPX	= Gas produced @ P and RP, Gp	scf
C	DNPT	= Incremental oil production time	yrs
C	DLMB	= Delta material balance, used in iteration	
C	DLOP	= Delta oil production fraction	bbbl
C	DLGP	= Delta gas production fraction	scf
C	TFNP	= Time as a function of production, i.e. pressue	yrs
C	RR	= Instantaneous (2-Phase) Solution gas/oil ratio	scf/bbbl
C		f(Rs,Kg,Uo,Bo,Ko,Ug,Bg)	
C	RP	= Produced or cumulative gas/oil ratio	scf/STB
C	RS	= Solution gas/oil ratio = f(P), Rs	scf/bbbl
C	QO	= Oil flow rate into wellbore, Qo	bbbl/day
C	QG	= Gas flow rate into wellbore, Qg	scf/day
C	QW	= Water flow rate into wellbore, Qw	bbbl/day
C	GP	= Cumulative gas production	scf
C	PP	= Reservoir pressure, P	psia
C	SL	= Total liquid saturation	v/v
C	SG	= Gas saturation, Sg, function of SL	v/v
C	SGX	= Gas saturation, Sg, function of P and/or Time	v/v
C	SOX	= Oil saturation, So, function of P and/or Time	v/v
C	SLX	= Total liquid saturation, function of P and/or T	v/v
C	SWX	= Water Saturation, Sw, function of P and/or Time	v/v
C	TDX	= Dimensionless time	
C	WDX	= Dimensionless water influx	
C	WE	= Water influx	Bbls
C	GI	= Gas Injected GI(i) = GNJR * GP(i)	scf
C	DDI	= Depletion (Solution Gas) Drive Index	v/v
C	WDI	= Water Drive Index	v/v
C	GDI	= Segregation (Gas Cap) Drive Index	v/v
C	BTNJ	= Total BO used with MBEQ=0	
C	BGNJ	= BGNJ=1.0/(BG/5.614583) BG in (rb/scf) for MBEQ=0	rb/scf
C-----			
C	MBEQ = 0	Reservoir With Gas Cap - No Water Drive - With Gas Injection	
C	MBEQ = 1	Reservoir No Gas Cap - No Water Drive - w/o Gas Injection	
C	MBEQ = 2	Reservoir No Gas Cap - With Water Drive - w/o Gas Injection	
C	MBEQ = 3	Reservoir With Gas Cap - No Water Drive - w/o Gas Injection	
C	MBEQ = 4	Reservoir With Gas Cap - With Water Drive - w/o Gas Injection	
C-----			
C	PI	= Initial reservoir pressure	psia
C	PBP	= Buble Point (reservoir oil) pressure	psia

Material Balance / Forecast / History Match – FORTRAN Program – MATBAL.EXE

C	DP	=	Delta pressure; pressure increment	psia
C	RW	=	Wellbore radius; rw	Ft.
C	RE	=	Wellbore drainage radius; re	Ft.
C	RDSA	=	Radius of aquifer used in water influx	Ft.
C	RDSR	=	Radius of reservoir used in water influx	Ft.
C	THTA	=	Water encroachment angle 0 - 360	deg
C	PW	=	Pressure well flowing; Pwf	psia
C	GCAP	=	Ratio of free gas cap to reservoir volume (m)	v/v
C	GNJR	=	Gas injection ratio; portion of Gp reinjected	v/v
C	PHI(i)	=	Average reservoir porosity	v/v
C	SW(i)	=	Average reservoir water saturation	v/v
C	KK(i)	=	Absolute or average reservoir permeability	md
C	HH(i)	=	Height of reservoir interval	Ft.
C	ACRE(i)	=	Drainage area	acre
C	RW75(i)	=	Formation water resistivity at 75 DegF	ohm-m
C	RTEM(i)	=	Formation temperature	DegF

C-----

**INPUT FILES: Fixed Non-User
Defined File Names**

```

C---|----1----|----2----|----3----|----
C SG_KGKO.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      Sg      Kg/Ko
C-----
      0.34      95.0000      1.0
      0.32      65.0000      1.0
      0.30      40.2985      1.0
      0.28      20.6814      1.0
      0.26      11.7696      1.0
      0.24       6.6979      1.0
      0.22       3.8117      1.0
      0.20       2.1692      1.0
      0.18       1.2345      1.0
      0.16       0.7025      1.0
      0.14       0.3998      1.0
      0.12       0.2275      1.0
      0.10       0.1170      1.0
      0.08       0.0520      1.0
      0.06       0.0119      1.0
      0.04       0.0024      1.0
      0.02       0.0002      1.0
C---|----1----|----2----|----3----|----
    
```

```

C---|----1----|----2----|----3----|----
C SG_KG.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      Sg      Kg
C-----
      0.34      0.8075      1.0
      0.32      0.6500      1.0
      0.30      0.5400      1.0
      0.28      0.4327      1.0
      0.26      0.3347      1.0
      0.24      0.2409      1.0
      0.22      0.1657      1.0
      0.20      0.1204      1.0
      0.18      0.0890      1.0
      0.16      0.0623      1.0
      0.14      0.0462      1.0
      0.12      0.0342      1.0
      0.10      0.0220      1.0
      0.08      0.0135      1.0
      0.06      0.0042      1.0
      0.04      0.0013      1.0
      0.02      0.0001      1.0
C---|----1----|----2----|----3----|----
    
```

```

C---|----1----|----2----|----3----|----
C SG_KO.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      Sg      Ko
C-----
      0.40      0.0040      1.0
      0.38      0.0050      1.0
      0.36      0.0060      1.0
      0.34      0.0080      1.0
      0.32      0.0100      1.0
      0.30      0.0134      1.0
      0.28      0.0209      1.0
      0.26      0.0284      1.0
      0.24      0.0360      1.0
      0.22      0.0435      1.0
      0.20      0.0555      1.0
      0.18      0.0721      1.0
      0.16      0.0887      1.0
      0.14      0.1156      1.0
      0.12      0.1503      1.0
      0.10      0.1880      1.0
      0.08      0.2590      1.0
      0.06      0.3532      1.0
      0.04      0.5220      1.0
      0.02      0.7600      1.0
      0.00      1.0000      1.0
C---|----1----|----2----|----3----|----
    
```

```

C---|----1----|----2----|----3----|----
C PSI_VO.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      P psi      Vo cp for P < PBP
C-----
      850.0      1.3901
      800.0      1.4468
      750.0      1.5035
      700.0      1.5602
      650.0      1.6169
      600.0      1.6736
      550.0      1.7303
      500.0      1.7870
      450.0      1.8437
      400.0      1.9004
      350.0      1.9571
      300.0      2.0138
      250.0      2.0705
      200.0      2.1272
      150.0      2.1980
      100.0      2.3080
      50.0      2.4654
C---|----1----|----2----|----3----|----
    
```

```

C---|----1----|----2----|----3----|----
C PSI_VOB.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      P psi      Vob cp for P > PBP
C-----
      850.0      1.3901
      860.0      1.4041
      870.0      1.4181
      880.0      1.4321
      890.0      1.4461
      900.0      1.4601
      910.0      1.4741
      920.0      1.4881
      930.0      1.5020
      940.0      1.5160
      950.0      1.5300
      960.0      1.5440
      970.0      1.5580
      980.0      1.5720
      990.0      1.5860
      1000.0     1.6000
      1010.0     1.6140
C---|----1----|----2----|----3----|----

```

```

C---|----1----|----2----|----3----|----
C PSI_VG.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      P psi      Vg cp
C-----
      850.0      0.01254
      800.0      0.01237
      750.0      0.01220
      700.0      0.01203
      650.0      0.01185
      600.0      0.01168
      550.0      0.01151
      500.0      0.01135
      450.0      0.01118
      400.0      0.01101
      350.0      0.01084
      300.0      0.01067
      250.0      0.01051
      200.0      0.01034
      150.0      0.01006
      100.0      0.00951
      50.0       0.00869
C---|----1----|----2----|----3----|----

```

```

C---|----1----|----2----|----3----|----
C PSI_BO.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      P psi      Bo v/v for P < PBP
C-----
      850.0      1.1407
      800.0      1.1361
      750.0      1.1314
      700.0      1.1268
      650.0      1.1222
      600.0      1.1175
      550.0      1.1129
      500.0      1.1083
      450.0      1.1037
      400.0      1.0990
      350.0      1.0944
      300.0      1.0898
      250.0      1.0851
      200.0      1.0805
      150.0      1.0741
      100.0      1.0640
      50.0       1.0503
C---|----1----|----2----|----3----|----

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```

C---|----1----|----2----|----3----|----
C PSI_BOB.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      P psi      Bob v/v for P > PBP
C-----
      850.0      1.1407
      860.0      1.1394
      870.0      1.1381
      880.0      1.1368
      890.0      1.1355
      900.0      1.1342
      910.0      1.1329
      920.0      1.1316
      930.0      1.1303
      940.0      1.1277
      950.0      1.1264
      960.0      1.1251
      970.0      1.1238
      980.0      1.1225
      990.0      1.1212
      1000.0     1.1199
      1010.0     1.1186
      1020.0     1.1173
C---|----1----|----2----|----3----|----

```

```

C---|----1----|----2----|----3----|----
C SW_KRO.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      Sw  Kro=Ko/K
C-----
      0.00      1.040      1.0
      0.05      1.020      1.0
      0.10      0.955      1.0
      0.15      0.988      1.0
      0.20      0.900      1.0
      0.25      0.800      1.0
      0.30      0.700      1.0
      0.35      0.560      1.0
      0.40      0.400      1.0
      0.45      0.277      1.0
      0.50      0.200      1.0
      0.55      0.140      1.0
      0.60      0.100      1.0
      0.65      0.066      1.0
      0.70      0.044      1.0
      0.75      0.033      1.0
      0.80      0.025      1.0
      0.85      0.015      1.0
      0.90      0.011      1.0
      0.95      0.005      1.0
      0.99      0.001      1.0
      1.00      0.000      1.0
C---|----1----|----2----|----3----|----

```

```

C---|----1----|----2----|----3----|----
C PSI_RS.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      P psi  Rs  scf/b for P < PBP
C-----
      850.0      247.6742
      800.0      237.0292
      750.0      226.2794
      700.0      215.4247
      650.0      204.4652
      600.0      193.4008
      550.0      182.2316
      500.0      170.9575
      450.0      159.5786
      400.0      148.0948
      350.0      136.5062
      300.0      124.8127
      250.0      113.0144
      200.0      101.1112
      150.0       88.5100
      100.0       70.6600
      50.0        46.8200
C---|----1----|----2----|----3----|----

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```

C---|----1----|----2----|----3----|----
C SW_KRW.TXT (ASCII File Name)
C-----
C      X(I)      Y(I)      W(I)
C      Sw  Krw=Kw/K
C-----
      0.00      0.003      1.0
      0.01      0.005      1.0
      0.05      0.006      1.0
      0.10      0.007      1.0
      0.15      0.008      1.0
      0.20      0.009      1.0
      0.25      0.011      1.0
      0.30      0.022      1.0
      0.35      0.033      1.0
      0.40      0.055      1.0
      0.45      0.088      1.0
      0.50      0.122      1.0
      0.55      0.188      1.0
      0.60      0.222      1.0
      0.65      0.288      1.0
      0.70      0.355      1.0
      0.75      0.444      1.0
      0.80      0.511      1.0
      0.85      0.600      1.0
      0.90      0.722      1.0
      0.95      0.855      1.0
      0.99      0.995      1.0
C---|----1----|----2----|----3----|----

```

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