Notes of Material Balance Calculations of Gas-condensate Fields

The usual material balance method used for analyzing past performance and predicting future behavior of dry gas fields is often refered to as the p/Z method. Figure 1 illustrates the principle of this method - cumulative produced gas, G_p, is plotted against p/Z. Provided that the hydrocarbon pore volume remains constant (no water influx, no pore compaction) a straight line should result. The slope of the straight line defines the initial gas in place as indicated by Eq. 1, or the straight line can be

$$p/Z = \frac{p_i}{Z_i} - \left(\frac{p_i/z_i - 15}{G} \right) G_p \qquad (1)$$

extrapolated to p/Z= 15 and the value of the initial gas in place, G, obtained by reading the value of G_p at the intersection.

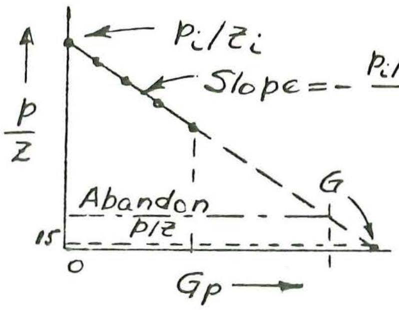


Figure 1.

Equation 1 comes about from a molal material balance. That is, the moles of gas remaining in the reservoir at any pressure is equal to the initial moles in the reservoir minus the moles that have been produced. This molal balance is expressed by Eq. 2.

$$n = n_i - n_p \qquad (2)$$

Equation 1 develops from Eq. 2 by use of the gas law equation

$$n = pV/ZRT \qquad (3)$$

Material balances of gas-condensate fields can be made on the same basis as dry gas field material balances. A plot such as Fig 1 may be used provided (1) the two-phase compressibility factor, Z_2, is used in the p/Z term, and (2) the cumulative production, G_p, accounts for all produced gases plus the produced stock tank oil (condensate). Fluid analysis reports on gas-condensate systems developed by Core Laboratories, Inc. and most other commercial laboratories contain the necessary data to handle the material balance in this manner. Where laboratory data are not available it is possible to make the stock tank oil correction from correlations. However, there seems to be no correlation available with which to determine two-phase Z factors. In this case it becomes necessary to accept an unknown degree of inaccuracy in the material balance by using single-phase Z factors.

The following calculations illustrate a procedure for making a material balance of a gas-condensate field. The reservoir pressure and surface production data used in the example are fabricated data. The fluid property data discussed in the example come from Core Laboratories' fluid analysis report " Reservoir Fluid Study for Good Oil Company, Condensate No.7 Well, Samson County, Texas " The object of the example material balance is to evaluate

1. Initial hydrocarbons in place,
   a. SCF of total gases
   b. Barrels of stock tank oil.

2. Reserves based on an abandonment pressure of 750 psig
    a. SCF of total gases
    b. Barrels of stock tank oil.

Basic assumptions involved in the material balance calculations are :

1. No water influx into the hydrocarbon reservoir
2. No water production
3. No reservoir retrograde liquid production
4. No compaction of reservoir rock.

Table 1 lists the reservoir pressure and production data used in the example. As stated before these are fabricated data.

Table 1 Reservoir Pressure / Production Data

Date	Vol. Avg. Res. Press. psig	Cumulative Production 10^9 SCF Gas	Cumulative Production 10^6 Barrel STO
A	5713	0	0
B	5050	36.52	5.61
C	3380	167.22	24.42
D	2920	246.38	31.39
E	2600	310.50	35.42
F	2350	385.48	38.74
Abandon	750	-	-

As pointed out before, the p/Z vs G_p plot to be developed must account for both gas and stock tank oil production. Probably the easiest way of doing this is to convert the stock tank oil production to an equivalent quantity of vapor and add it to the measured gas production. G_p then expresses all production from the reservoir in terms of standard cubic feet of gas. The equivalent vapor volume of stock tank oil is developed from depletion data given in the fluid analysis report as a function of pressure. This is shown by Fig 2. How to develop Fig 2 is the subject of the next section.

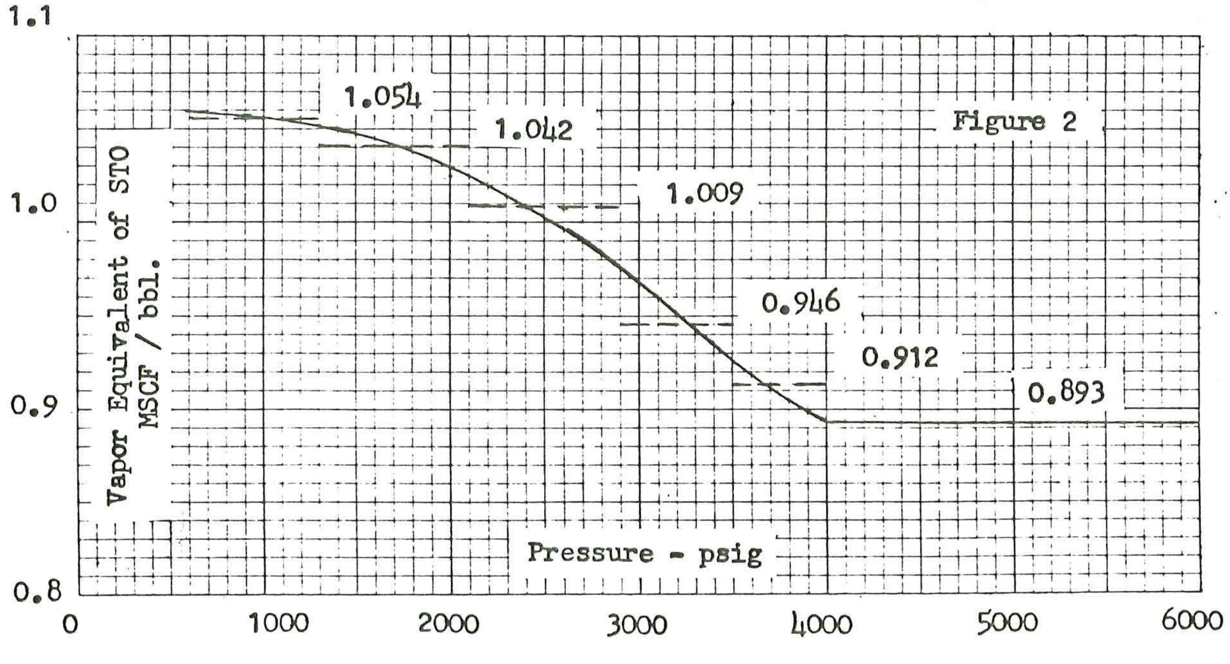
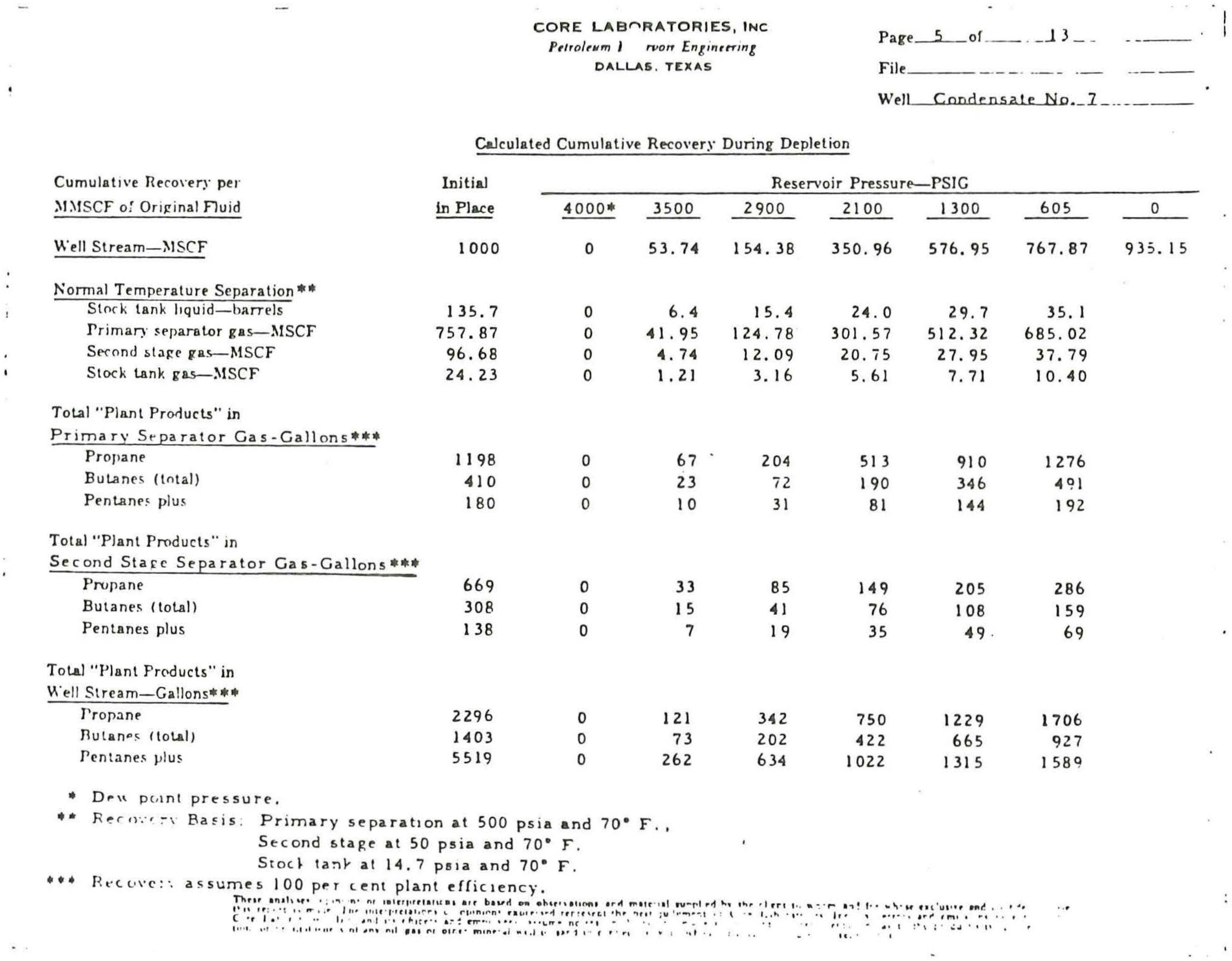


Figure 2

Vapor Equivalent of STO vs Pressure

Figure 3 is a reproduction of page 5 of Core Laboratories' fluid analysis report. The dew point pressure of this system is 4000 psig at 186° F. At all reservoir pressures greater than 4000 psig the vapor equivalent of stock tank oil will have the same value. Refering to the first column of numbers in Fig 3 it is seen that 1000 MSCF of reservoir material produces 878.78 MSCF (757.87 + 96.68 + 24.23) of surface gases plus 135.7 bbl of stock tank oil. The vapor equivalent of stock tank oil is, therefor , (1000 - 878.78)/ 135.7 = 0.893 MSCF/bbl . This value is plotted as the horizontal line at pressures above 4000 psig in Fig 2 .

As pressure declines below the 4000 psig dew point the stock tank oil components held in gaseous solution in the reservoir become progressively lighter in nature. The stock tank oil consequently shows an increasing trend of degrees API, and the vapor equivalent of the stock tank oil also increases. Refering now to the pressure interval 3500 → 2900 psig of Fig 3 , we see that the reservoir material produced during this pressure interval amounts to (154.38 - 53.74) MSCF. This material splits into (140.03 - 47.90) MSCF of surface



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Calculated Cumulative Recovery During Depletion

Cumulative Recovery per MMSCF of Original Fluid	Initial in Place	Reservoir Pressure—PSIG						
		4000*	3500	2900	2100	1300	605	0
Well Stream—MSCF	1000	0	53.74	154.38	350.96	576.95	767.87	935.15
Normal Temperature Separation**								
Stock tank liquid—barrels	135.7	0	6.4	15.4	24.0	29.7	35.1	
Primary separator gas—MSCF	757.87	0	41.95	124.78	301.57	512.32	685.02	
Second stage gas—MSCF	96.68	0	4.74	12.09	20.75	27.95	37.79	
Stock tank gas—MSCF	24.23	0	1.21	3.16	5.61	7.71	10.40	
Total "Plant Products" in Primary Separator Gas-Gallons***								
Propane	1198	0	67	204	513	910	1276	
Butanes (total)	410	0	23	72	190	346	491	
Pentanes plus	180	0	10	31	81	144	192	
Total "Plant Products" in Second Stage Separator Gas-Gallons***								
Propane	669	0	33	85	149	205	286	
Butanes (total)	308	0	15	41	76	108	159	
Pentanes plus	138	0	7	19	35	49	69	
Total "Plant Products" in Well Stream—Gallons***								
Propane	2296	0	121	342	750	1229	1706	
Butanes (total)	1403	0	73	202	422	665	927	
Pentanes plus	5519	0	262	634	1022	1315	1589	

* Dew point pressure.
** Recovery Basis: Primary separation at 500 psia and 70° F.,
Second stage at 50 psia and 70° F.
Stock tank at 14.7 psia and 70° F.
*** Recovery assumes 100 per cent plant efficiency.

Figure 3

gases plus (15.4 - 6.4) barrels of stock tank oil. Therefor, in this pressure interval the average vapor equivalent of the stock tank oil is ((154.38 - 53.74) - (140.03 - 47.99)) / (15.4 - 6.4) = 0.946 MSCF / bbl. This value is plotted in Fig 2 as a horizontal line between pressure values of 3500 and 2900 psig to indicate that it is an average value in that pressure interval.

Similar calculations for the other pressure intervals result in the average vapor equivalent values shown in Fig 2 . Finally, a smooth curve is constructed through the average values so as to preserve the areas under the interval values. Values from the smooth curve are then used in material balance calculations in converting stock tank oil quantities to equivalent gas quantities.

Where specific laboratory data, such as above, are not available with which to develop vapor equivalent values the following equation can be used to calculate values from the API gravity of the stock tank oil.*

$$V_1 \text{ (SCF/STB)} = 250.8 + 9.75\,^\circ\text{API} - 0.006\,(^\circ\text{API})^2 \qquad (4)$$

Two-phase Z Factors

The concept of a two-phase Z factor is foreign to many petroleum engineers. However, it is easy to see that Eq 3 , commonly called the gas law equation, is a gereneral equation of state of the hydrocarbon system and that it can apply to any number of phases as long as V refers to the total phase volumes and n represents the total moles of material in the system. It is to be expected that the pressure - temperature behavior of a two-phase Z factor will not be exactly like that of the familiar single-phase Z factor. It is somewhat surprising, though, how closely the two behaviors match over a wide range of pressure. The reason for using two-phase Z factors in material balance calculations of gas-condensate systems is that it is the total hydrocarbon volume in the reservoir that remains constant during depletion, not just the gas phase volume.

Figure 4 reproduces a page of data by Core Laboratories, Inc. summarizing the step-wise gas depletion test of the Condensate No 7 Well system. The equilibrium gas deviation factors shown correspond to the gas compositions shown above. The two-phase deviation factors correspond to the gas phase whose composition is given in the table plus a quantity of retrograde liquid phase. The amount of retrograde liquid is given in a different table, but at 2900 psig it amounts to 19.3 % of the total system volume. As can be seen, down to 2900 psig there is no appreciable difference in the single-phase and the two-phase deviation factors. At the lower pressures there is considerable difference as well as a different trend with pressure. As indicated above, it is the two-phase Z factor that should be used in plotting p/Z vs G_p .

When two-phase deviation factors are not available, it is probably best to use single-phase values calculated from the composition of the richest gas. The richest gas normally is the initial gas in the reservoir. Thus refering to Fig 4, in the absence of two-phase Z factors the composition of the 5713 psig fluid would be used to generate values at the lower pressures.

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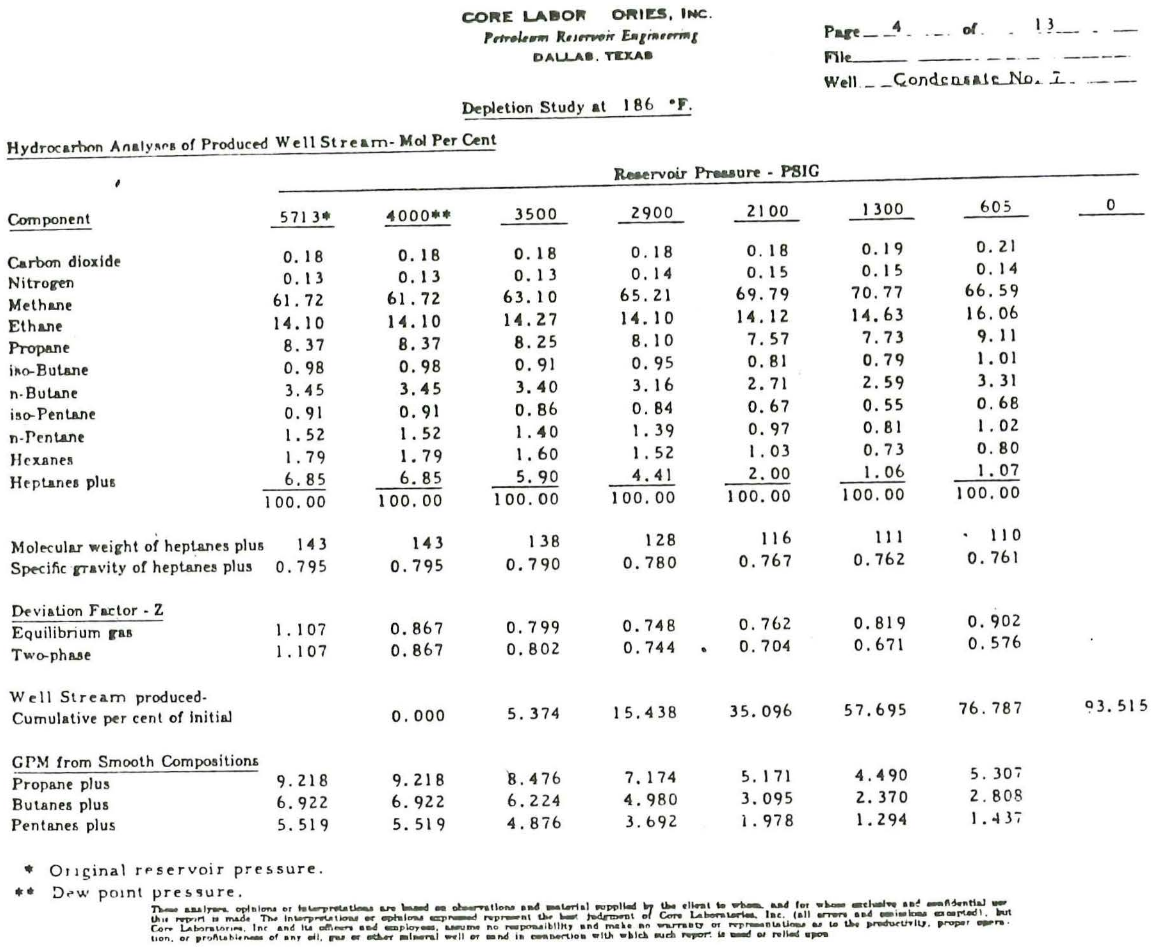
* Curve-fit of data presented by C.K.Eilerts in USBM Monograph 10 (1957)



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Well Condensate No. 7

Depletion Study at 186 °F.

Hydrocarbon Analyses of Produced Well Stream - Mol Per Cent

	Reservoir Pressure - PSIG							
Component	5713*	4000**	3500	2900	2100	1300	605	0
Carbon dioxide	0.18	0.18	0.18	0.18	0.18	0.19	0.21	
Nitrogen	0.13	0.13	0.13	0.14	0.15	0.15	0.14	
Methane	61.72	61.72	63.10	65.21	69.79	70.77	66.59	
Ethane	14.10	14.10	14.27	14.10	14.12	14.63	16.06	
Propane	8.37	8.37	8.25	8.10	7.57	7.73	9.11	
iso-Butane	0.98	0.98	0.91	0.95	0.81	0.79	1.01	
n-Butane	3.45	3.45	3.40	3.16	2.71	2.59	3.31	
iso-Pentane	0.91	0.91	0.86	0.84	0.67	0.55	0.68	
n-Pentane	1.52	1.52	1.40	1.39	0.97	0.81	1.02	
Hexanes	1.79	1.79	1.60	1.52	1.03	0.73	0.80	
Heptanes plus	6.85	6.85	5.90	4.41	2.00	1.06	1.07	
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	
Molecular weight of heptanes plus	143	143	138	128	116	111	110	
Specific gravity of heptanes plus	0.795	0.795	0.790	0.780	0.767	0.762	0.761	
Deviation Factor - Z								
Equilibrium gas	1.107	0.867	0.799	0.748	0.762	0.819	0.902	
Two-phase	1.107	0.867	0.802	0.744	0.704	0.671	0.576	
Well Stream produced- Cumulative per cent of initial		0.000	5.374	15.438	35.096	57.695	76.787	93.515
GPM from Smooth Compositions								
Propane plus	9.218	9.218	8.476	7.174	5.171	4.490	5.307	
Butanes plus	6.922	6.922	6.224	4.980	3.095	2.370	2.808	
Pentanes plus	5.519	5.519	4.876	3.692	1.978	1.294	1.437	

* Original reservoir pressure.
** Dew point pressure.

Figure 4

Material Balance Calculation

Table 2 shows the calculations involved in the material balance of data from Table 1 and Figs 3 and 4. Note that at the last date (F) the equivalent vapor volume of the produced stock tank oil amounts to almost 10 % of the total gases removed from the reservoir. Had the stock tank oil not been included in the analysis the material balance would yield an error of about this magnitude in the initial hydrocarbons in place. A plot of the cumulative gas produced listed in the last column of Table 4 vs p/Z values in the fourth column is shown in Fig 5 . From this plot it is deduced that the initial hydrocarbons in place (surface gases + Stock tank oil equivalent vapor) amounts to $1.14(10^{12})$ SCF . Also, at the specified 750 psig abandonment pressure the cumulative production amounts to $880\ (10^9)$ SCF, leaving $(\ 1140 - 880\ )\ 10^9 = 260(10^9)$ SCF reserve as of date F.

Table 2. Example Calculation for a Gas-condensate Reservoir Material Balance.

① Date	② Avg. Press psia	③ Z	④ p/Z	⑤ Sep.Gas Prod. 10^9SCF	⑥ Interval STO 10^6 bbl	⑦ Avg. Vap.Eq. SCF/STB **	⑧ Cum. Eq.Vap. 10^9 SCF	⑨ G_p 10^9 SCF
A	5728	1.107	5174	0			0	0
B	5065	1.016	4990	36.52	5.61	893	5.010	41.53
C	3395	0.792*	4287	167.22	18.81	900	21.94	189.15
D	2935	0.750*	3913	246.38	6.97	955	28.60	274.97
E	2615	0.727*	3597	310.50	4.03	987	32.57	343.07
F	2365	0.715*	3308	385.48	3.32	1004	35.91	421.39
Aban.	765	0.620*	1234					

* From plot of two-phase Z (Fig 4) vs Pressure.
** From Fig 2.

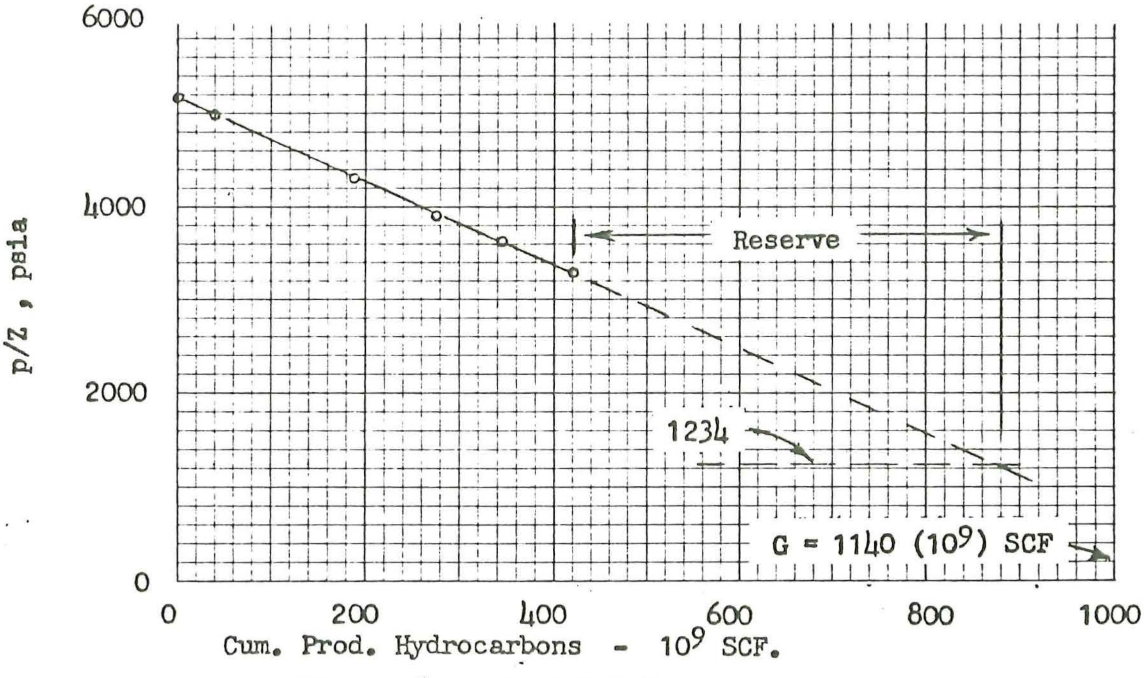

Figure 5. Material Balance Plot

Initial Surface Gases and Stock Tank Oil in Place. In order to separate the initial hydrocarbons in place into surface gases and stock tank oil it is necessary to fix the initial producing gas-oil ratio. As this reservoir system was initially above it's dew point pressure in the reservoir the surface gas oil-ratio should remain constant until the dew point pressure of 4000 psig is reached. As pressure declines below the dew point pressure the surface gas-oil ratio will increase. This increase in surface gas-oil ratio is caused by the heavy hydrocarbons remaining in the reservoir as components of the retrograde liquid phase.

There are two sources of initial gas-oil ratio data ; production data and data from the fluid analysis report. Refering to the production data in Table 1, it is seen that the producing gas-oil ratio during the first time interval (while the reservoir pressure was still above 4000 psig) is $36.52(10^9)$ SCF / $5.61(10^6)$ STB = 6510 SCF / STB . The fluid analysis report value can be determined from the figures in the first column of Fig 3. We see that the gas-oil ratio computes to be (757.87 + 96.68 + 24.23)SCF / 135.7 STB = 6476 SCF / STB. Either of the two values could be used, but selecting the latter one allows one to calculate the initial gas and stock tank oil quantities as follows :

Let x = barrels of stock tank oil initially in place.

Then

$$x \cdot 0.893(10^3) + 6476 \cdot x = 1140(10^9) \text{ SCF.}$$

Therefor

Stock tank oil = $1140(10^9) / (6476 + 893) = 1.55(10^8)$ barrels.
Surface gases = $1.55(10^8) \cdot 6476 = 1002(10^9)$ SCF.

Surface Gases and Stock Tank Oil Reserve. By extrapolation of the p/Z material balance line from date point F to abandonment conditions it was determined that the hydrocarbon material reserve amounts to $260(10^9)$ SCF. To split this quantity into surface gases and stock tank oil quantities requires the same calculation as above. However, in this instance both the stock tank oil equivalent volume factor and the producing gas-oil ratio number must be average values in the pressure range 2350 → 750 psig. A vapor equivalent vs pressure plot has already been developed (Fig 2) and refering to it it can be seen that the average value in the pressure range is approximately 1.040 MSCF / bbl.

To obtain the average gas-oil ratio of the future production requires construction of a surface gas-oil ratio vs pressure chart. The manner of doing this is similar to that used in producing Fig 2 . Data for the chart comes from Fig 3. For example, in the pressure interval 3500 → 2900 psig the average gas oil ratio is (140.03 - 47.90)SCF / (15.4 - 6.4)bbl = 10,237 SCF / STB . Similar calculations for the other pressure intervals listed in Fig 3 yield the values plotted in Fig 6. A smooth curve is placed through the average values to yield the required producing gas-oil ratio vs pressure curve.

From Fig 6 , the average producing gas-oil ratio between 2350 and 750 psig calculates to be about 36,000 SCF / STB. This was obtained by determining the area under the smooth curve in the above pressure interval by Simpson's Rule integration and then dividing the area by the pressure interval width. Using the above two average values and the total hydrocarbon reserve yields :

Let y = barrels of reserve stock tank oil

Then

$$y \cdot 1.040(10^3) + 36{,}000 \cdot y = 260(10^9) \text{ SCF.}$$

From which

Stock tank oil reserve = $260(10^9) / (1040 + 36000)$
= $7.02(10^6)$ barrels
Surface gases = $7.02(10^6) \cdot 36{,}000 = 253(10^9)$ SCF.

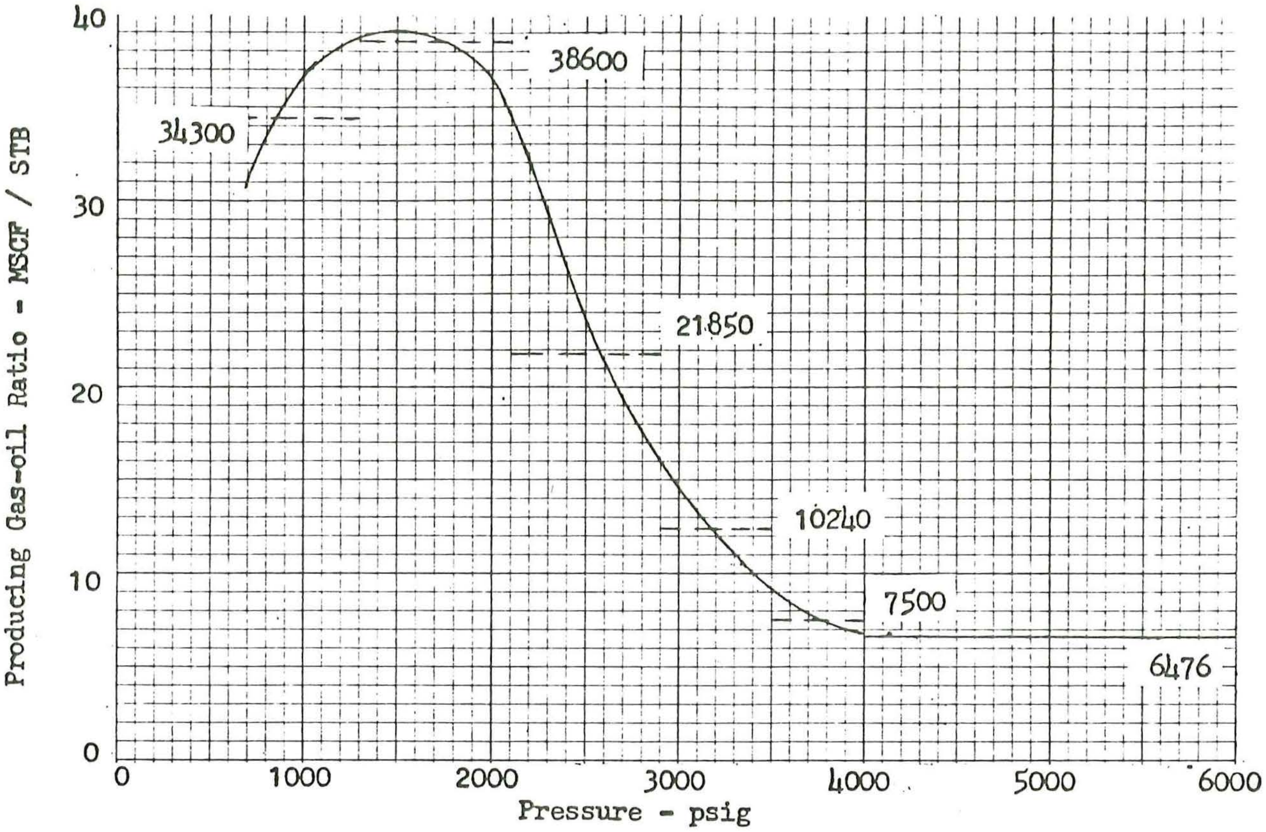

Figure 6 Producing Gas-oil Ratio vs Pressure

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