CHAPTER VIII

APPLICATION TO REAL DATA

For the application to real data, two real cases were selected for study, a two-layered reservoir with one well, and a three-layered reservoir with two wells.

8.1 Case I : Two-layered reservoir with one well

For the case of two-layered with one well, data are from one gas field in the Gulf of Thailand. The well in this study called "BK-6-X" (the real name of this well is not permitted to publish in this study) penetrates two isolated reservoirs. The reservoir characteristics and properties of the two layers are shown in Table 8-1.

Table 8-1 Reservoir characteristics and properties of layers in case I

Layer	Top Structure (mTVD-SS)	Total Net Thickness (m)	ϕ (%)	CO_2 (%)	Estimated Initial Pressure (psia) (from RFT)
1	1709 (or 1737 mTVD-RT)	9.3	23	12	2353
2	1972 (or 2000 mTVD-RT)	27.9	20	21	2855

The well was put on stream on December 13th, 1995. From the pressure build-up test carried out in March 1996, the average permeability of 270 md (average permeability of the system) was obtained from the interpretation.

From all the production tests carried out on this well, the average gas specific gravity and CO_2 concentration are 0.796 and 19.1%. A bottom-hole pressure survey was carried out on March 17th, 1996 resulting in the bottom-hole shut-in pressure (BHSIP) of 2494 psia at gauge depth of 1323 mTMD-RT (or 1295 mTMD-SS). On that day, the WHSIP of 2146 psia was also recorded.

From the recorded BHSIP and WHSIP on March 17th, 1996, the average wellbore-fluid gradient was calculated to be 0.263 psi/m. This gradient was considered as a constant value for the whole production period. At any time of the production period, a BHSIP can be calculated from a known WHSIP and fluid gradient. For this study, the average-wellbore-fluid gradient obtained from the calculation was used. Recorded WHSIP data of BK-6-X are shown in Table 8-2.

The BHSIP at the depth of the middle of each layer was calculated. When the well is shut-in long enough, a BHSIP is assumed to be the average formation pressure at that depth. For this study, the WHSIP recorded after a shut-in period longer than 20 hours was selected. (With a shut-in period longer than 20 hours, a calculated BHSIP at the middle of each layer was considered, in this study, as an average pressure of that layer.)

The pseudo-steady state equation cannot be used to calculate an average reservoir pressure because bottom-hole flowing pressure needed for the pseudo-steady state equation to calculate an average reservoir pressure was not known. From the

Table 8-2 Recorded WHSIP data of BK-6-X

Date	Recorded WHSIP (psia)	Shut-In Duration (hours)
13-Dec-95 (Initial)	2276	-
31-Jan-96	2268	27
20-Feb-96	2220	34
28-Mar-96	2185	32
25-Apr-96	2149	24
29-May-96	2112	29
30-Jun-96	2062	55
24-Jul-96	2028	43
02-Aug-96	2028	27
20-Sep-96	2014	39
17-Oct-96	1993	25
11-Nov-96	1982	31
01-Dec-96	1955	46
10-Jan-97	1931	32
15-Mar-97	1899	24

Table 8-3 Cumulative gas production of BK-6-X

Date	Cumulative Gas Production (MMscf)
13-Dec-95 (Initial)	0
31-Jan-96	228
20-Feb-96	252
28-Mar-96	356
25-Apr-96	634
29-May-96	1075
30-Jun-96	1569
24-Jul-96	1733
02-Aug-96	1733
20-Sep-96	1739
17-Oct-96	1813
11-Nov-96	1816
01-Dec-96	1821
10-Jan-97	1835
15-Mar-97	2243

known BHSIP, a corresponding z-factor were determined by Dranchuk-Abou-Kassem equation. Daily production test data combined with WHFP data yield an estimated daily gas flow rate which in turn will be accumulated to give cumulative production of the well. Table 8.3 shows cumulative gas production of BK-6-X well.

The cumulative gas produced of the well was calculated on the day the WHSIP was recorded so that the calculated cumulative gas produced and BHSIP can be directly used for generating a p/z plot. A p/z plot was initially prepared only for the whole system, not for each layer because total gas flow rate from the well could not be allocated to each layer (For a two-layered reservoir with one well, flow rate allocation can be obtained by using the flow rate allocation equation (equation 7-1) if the size of each layer is known, or can be estimated). The p/z plot of the whole system is shown in Figure 8-1.

From the p/z plot of the whole system, GIIP of 14.7 Bcf was obtained. As it was found from the study of the effects of flow rate and permeability on error of GIIP obtained from a p/z plot using $\bar{p}$ from the pseudo-steady state equation (Chapter VI), the error of GIIP from a p/z plot for the case of 20 MMscf/d with permeability of equal to or more than 100 md is less than 3%. For this case, as previously mentioned, the average permeability of the whole system interpreted from the pressure build-up test was 270 md. From the production history of BK-6-X well, it is found that the maximum production rate was 20 MMscf/d. Therefore, it can be said that the error of GIIP evaluation from the obtained p/z plot of the whole system is also less than 3% if the average reservoir pressures used for generating the p/z plot (the calculated BHSIP)

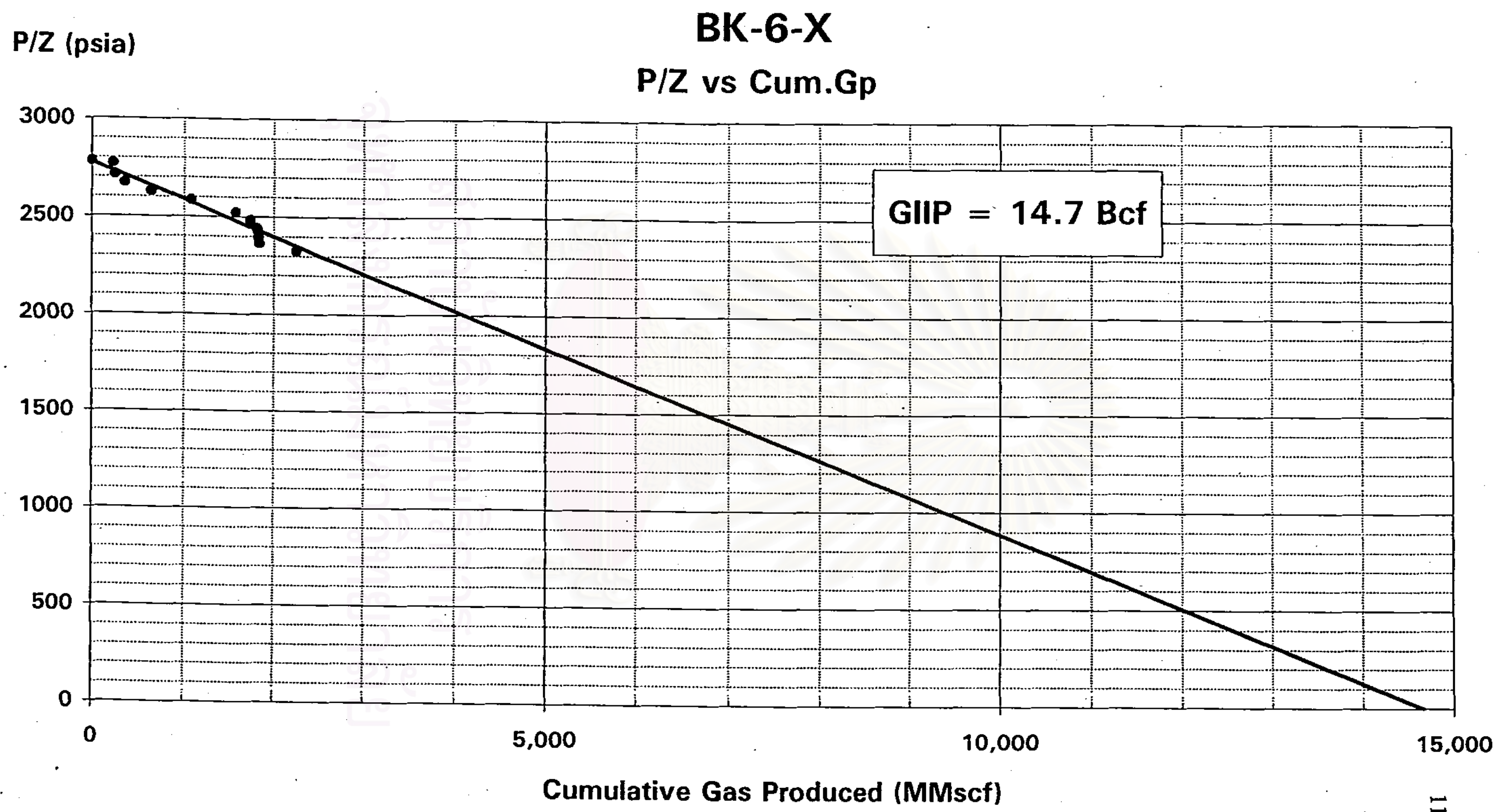

Figure 8-1: The p/z plot of BK-6-X

are closed to the actual average reservoir pressures or the average reservoir pressures calculated from the pseudo-steady state equation.

However, for this study, no further investigation on how accurate the calculated BHSIP's used in the p/z plot was conducted. The estimated error of the obtained GIIP from the p/z plot of the whole system is, therefore, not shown and discussed.

As previously mentioned that initially, only the p/z plot of the whole system was generated; however, finally a p/z plot was generated also for each layer. To allocate gas flow rate to each layer, in this study, the known CO_2 concentration of each layer (from RFT) and of the total gas flow rate of the well (from a production test) were used. By using the CO_2 concentrations of each layer and of the total gas flow rate to allocate the total gas flow rate to each layer, it was assumed that the known CO_2 concentrations of the two layers are constant. From all the production tests of the well, the measured CO_2 of each test was quite constant. Therefore, for this study, it was decided to use the known CO_2 concentrations of the two layers from the RFT (12% mole and 21% mole) and the average CO_2 concentration of all the production tests (19.1% mole) as constant parameters for the whole production period. From the CO_2 concentrations of 12% mole for layer 1 and 21% mole for layer 2, and the average CO_2 concentration (of the total gas flow rate) of 19.1% mole, the proportions of 21% would be allocated to layer 1 and the other 79% to layer 2. The calculation is shown in the following:

Table 8-4 Estimated cumulative gas production of each layer in case I

Date	Estimated Cumulative Gas Production (MMscf)	
	Layer 1	Layer 2
13-Dec-95 (Initial)	0	0
31-Jan-96	48	180
20-Feb-96	53	199
28-Mar-96	75	281
25-Apr-96	133	501
29-May-96	226	849
30-Jun-96	329	1239
24-Jul-96	364	1369
02-Aug-96	364	1369
20-Sep-96	365	1374
17-Oct-96	381	1433
11-Nov-96	381	1434
01-Dec-96	382	1438
10-Jan-97	385	1450
15-Mar-97	471	1772

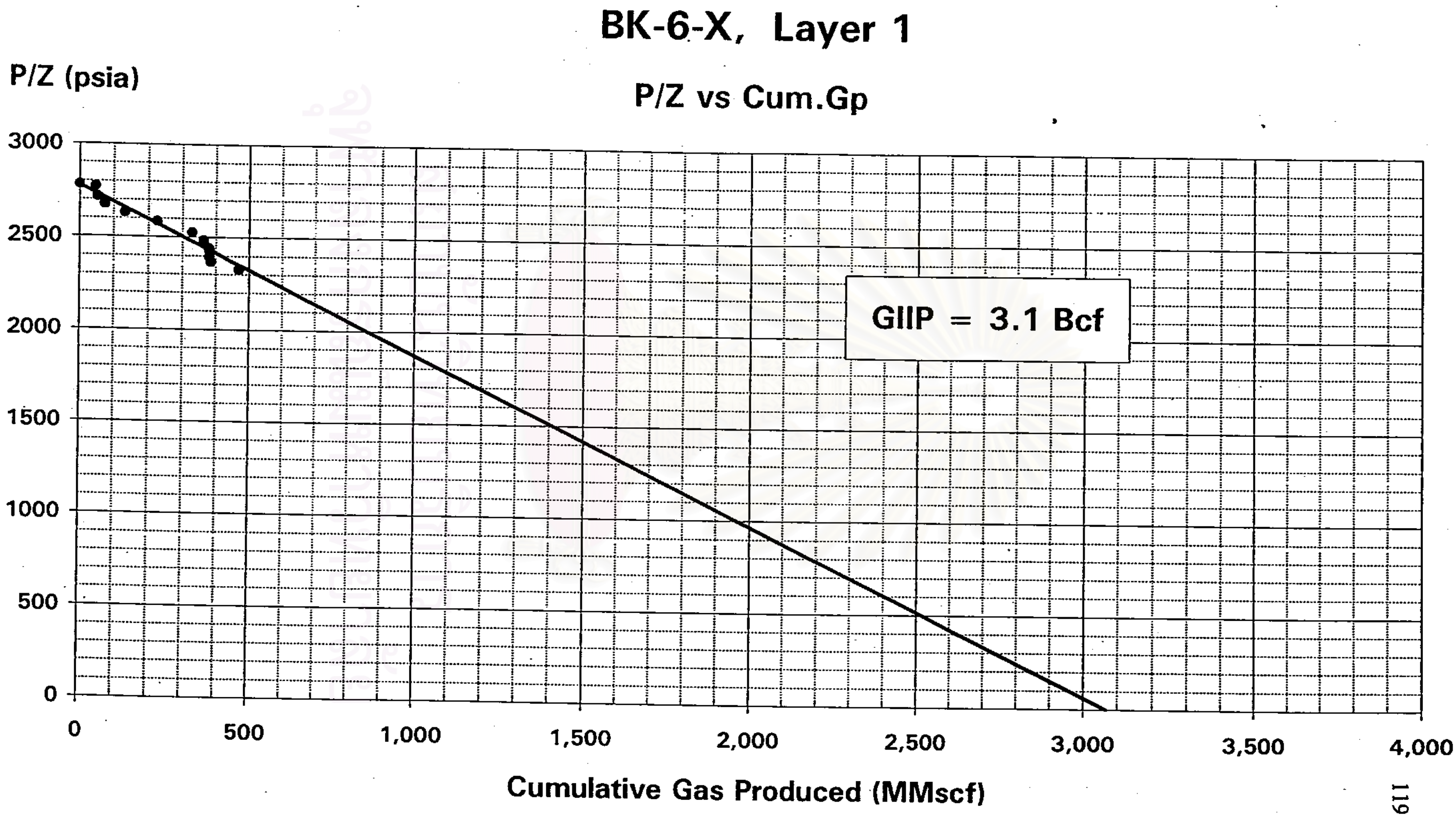

Figure 8-2: The p/z plot of BK-6-X, layer1

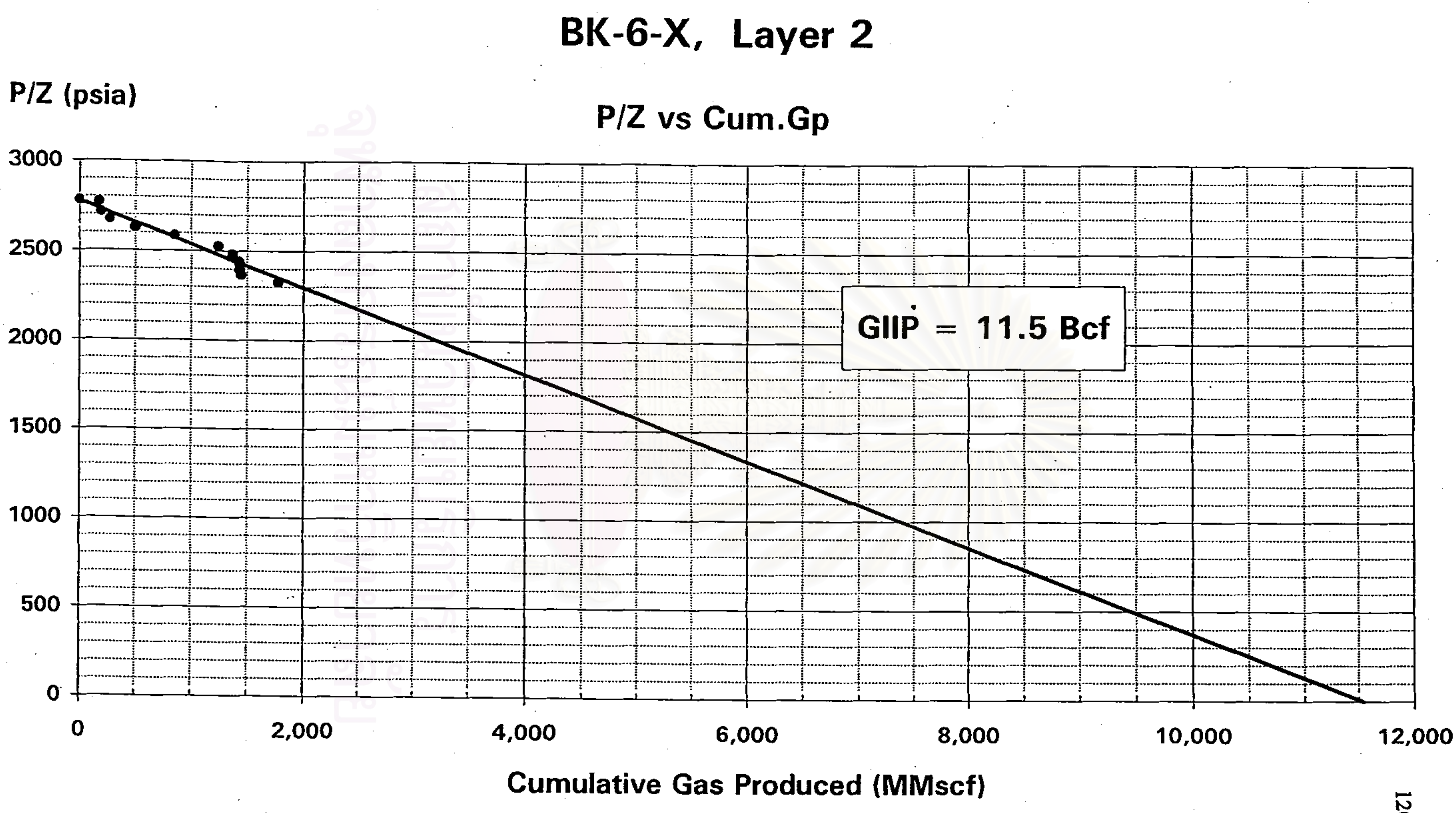

Figure 8-3 The p/z plot of BK-6-X, layer 2

Let x = percentage of the total gas flow rate allocated to layer 1. The proportion of the total gas flow rate allocated to layer 1 (x) can be determined from the equation below,

$$12x + 21(1-x) = 19.1$$

Thus, x = 0.21 or 21 %

By using the obtained proportions allocating the total gas production of the well (shown in Table 8-3) to each layer, cumulative gas produced of each layer could be estimated and shown in Table 8-4. Similar to the determination of an average reservoir pressure of the whole system, an average reservoir pressure of each layer was estimated by using a WHSIP and the calculated average wellbore fluid gradient (0.263 psi/m). The average reservoir pressure of each layer is, in fact, a BHSIP calculated at the middle of each layer. From sets of cumulative gas production and BHSIP data of each layer, a p/z plot of each layer could be, then, generated. The p/z plots of the two layers are shown in Figure 8-2 and 8-3, while the GIIP's obtained from those p/z plots are shown in Table 8-5.

Table 8-5 Estimated GIIP from the p/z plots of the layers in case I

Layer	Estimated GIIP (Bcf)
1	3.1
2	11.5
Total	14.6

The results in Table 8-5 show that the summation of GIIP of each layer obtained from the p/z plots (in the case of using a known CO_2 concentration of each layer (i.e. from RFT) to allocate the total gas flow rate to each layer), 14.6 Bcf, is close to the total GIIP of the system obtained by the p/z plot of the whole system (14.7 Bcf).

If the total GIIP of this system obtained from the p/z plot representing the whole system is acceptable (in the range of the expected actual GIIP of the system), the obtained summation of the GIIP of each layer from the p/z plots of the two layers (in case of using the known CO_2 concentrations of the two layers to allocate the total gas flow rate) should also be acceptable. However, if the GIIP of each layer of this system is needed to be estimated, the GIIP of each of the two layers obtained here can be one to be considered.

From the study, it can be suggested that the GIIP of any layer in any system can be easily estimated, in case that the total GIIP of the system obtained from a p/z plot of that system is acceptable, by multiplying a calculated proportion of that layer used to allocate the total flow rate to that layer (which in this real case study is 0.21 for layer 1, and 0.79 for layer 2 (see the calculation in page 123)) with a known total GIIP of the whole system obtained from a p/z plot of that system. By this way, the estimated GIIP's of layer 1 and layer 2 will be 3.1 (= 14.7 x 0.21) and 11.6 (= 14.7 x 0.79) Bcf, respectively. The mentioned proportion of any layer is, in fact, a volume fraction weighted by CO_2 concentration of that layer. Therefore, either using a calculated proportion of each layer to generate a p/z plot of each layer, or using a calculated proportion of each layer directly with a known GIIP of the whole system, both of the GIIP's (of each layer) obtained from the two calculating procedures are the same (or similar). It would be suggested that the volume of any layer in any system can also be determined if a volume fraction of that layer in the system (ratio of the volume of that layer to the total volume of the system) can be reasonably estimated. The estimated GIIP of any layer can be determined from a product of the total GIIP of the system and the estimated volume fraction of that layer.

8.2 Case II : Three-layered reservoir with two wells

For the case study of a three-layered reservoir with two wells, data used were from one gas field in the Gulf of Thailand. Each of the two wells in this real case study penetrates not all the three layers. One well (BK-4-X) penetrates layer 1 and layer 2, while the other (BK-4-Y) penetrates layer 2 and layer 3 (Figure 8-4). For this system, it was found that no communication among the three layers. The reservoir characteristics and properties of the three layers are shown in Table 8-6.

Table 8-6 Reservoir characteristics and properties of layers in case II

Layer	Top Structure (mTVD-SS)	Total Net Thickness (m)	ϕ (%)	CO_2 (%)	Estimated P_i (psia) (from RFT)
1	1405 (or 1433 mTVD-RT)	14.1	19	n/a	1993
2	1476 (or 1504 mTVD-RT)	7.7	17	n/a	2171
3	1971 (or 1999 mTVD-RT)	47.0	20	n/a	2810

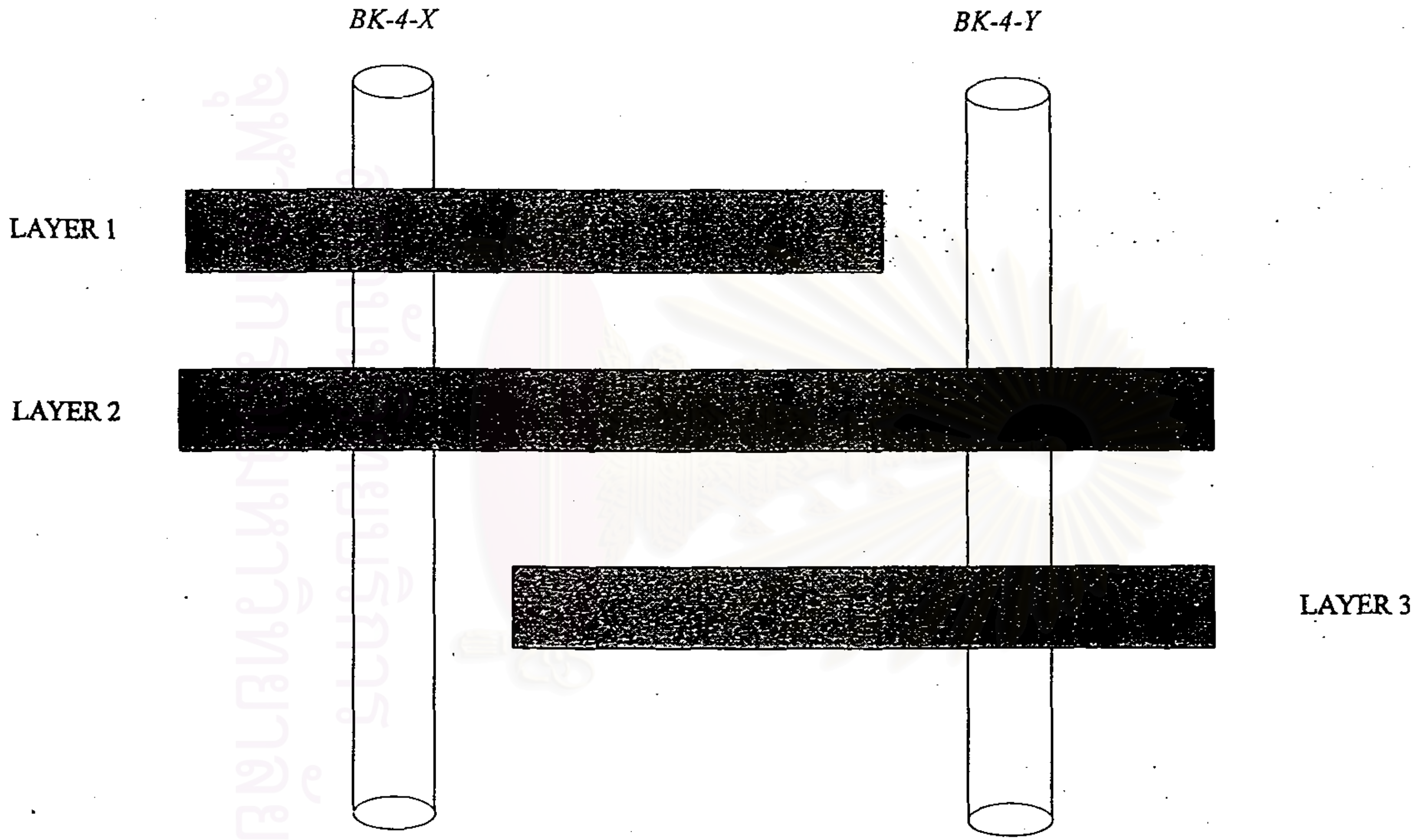

Figure 8-4 Schematic drawing for the real case study of the three-layered reservoir with two wells

The production of the BK-4-X and BK-4-Y wells were started on May 9, 1995 and January 19, 1996, respectively. From all production tests carried out on these two wells, it can be summarized in Table 8-7. Average fluid gradients of the two wells were calculated from WHSIP and BHSIP data of the two wells obtained from bottom-hole pressure surveys carried out in the two wells. The obtained average wellbore fluid gradients of the two wells are also shown in Table 8-7.

Table 8-7 Gas properties and the calculated fluid gradients for case II

Well	Gas properties (average)		Average wellbore fluid gradient (psi/m)
	SG gas (air = 1.0)	CO_2 (%)	
BK-4-X	0.747	4	0.229
BK-4-Y	0.821	20	0.237

The average wellbore fluid gradients shown in Table 8-7 were considered as constant values through the whole production periods.

Similar to the real case study of the two-layered system with one well, BHSIP's of the two wells were calculated from known WHSIP data and the wellbore fluid gradients of those two wells. The recorded WHSIP data of the two wells are shown in Tables 8-8 and 8-9.

Table 8-8 Recorded WHSIP data of BK-4-X

Date	Recorded WHSIP (psia)	Shut-In Duration (hours)
09-May-95 (Initial)	1850	-
21-May-95	1842	32
23-Jun-95	1711	45
14-Jul-95	1700	41
22-Aug-95	1552	24
21-Sep-95	1467	48
28-Oct-95	1384	31
14-Nov-95	1325	70
11-Dec-95	1312	26
30-Jan-96	1250	32
18-Feb-96	1200	29
22-Mar-96	1196	35
12-Apr-96	1135	23
24-May-96	1109	32
03-Jun-96	1114	29
12-Jul-96	1073	41
15-Aug-96	1059	33
21-Sep-96	1042	37
19-Oct-96	1034	27
22-Nov-96	1024	36
31-Dec-96	957	39
29-Jan-97	936	25
14-Feb-97	935	32
14-Mar-97	912	34

Table 8-9 Recorded WHSIP data of BK-4-Y

Date	Recorded WHSIP (psia)	Shut-In Duration (hours)
19-Jan-96 (Initial)	2345	-
23-Jan-96	2339	33
17-Feb-96	2306	27
12-Mar-96	2219	36
07-Apr-96	2163	44
13-May-96	2132	52
02-Jun-96	2078	78
24-Jul-96	2045	26
31-Aug-96	2011	34
18-Sep-96	2016	62
09-Oct-96	2014	51
24-Nov-96	2000	26
30-Dec-96	1988	34
12-Jan-97	1942	39
24-Feb-97	1951	51
17-Mar-97	1935	42

For this real case, only a combined-layer method was applied because the system is too complex to allocate total gas flow rate from each well to each layer. The combined-well method was not used here because the average reservoir pressure of the whole system was difficult to be determined or estimated. For this system, a drainage volume of each well could not be estimated. Therefore, the average reservoir pressure of the whole system could not be determined or estimated even if the average reservoir pressure of the drainage volume of each well was already obtained. Therefore, for this real case study, the combined-layer and separated-well method was used.

A BHSIP, in this study, was calculated for both of the two wells. The obtained BHSIP of any well represented the average reservoir pressure of the drainage volume of that well. (A BHSIP represented the average reservoir pressure of the drainage volume of any well was calculated at the middle of the drainage volume of that well.) From the obtained BHSIP, a z-factor for that BHSIP then could be obtained. In this study, the z-factor was calculated from the Dranchuk-Abou-Kassem equation. From all the production tests carried out on these two wells and known daily WHFP data, daily gas flow rate of the two wells can be estimated. From the estimated daily gas flow rate, cumulative gas productions of the two wells can be obtained. Cumulative gas productions of the two wells are shown in Tables 8-10 and 8-11.

From the cumulative gas produced and the calculated BHSIP of the two wells, a p/z plot of each of the two wells was generated. The p/z plots of the two wells are shown in Figures 8-5 and 8-6.

Table 8-10 Cumulative gas production of BK-4-X

Date	Cumulative Gas Production (MMscf)
09-May-95 (Initial)	0
21-May-95	160
23-Jun-95	556
14-Jul-95	879
22-Aug-95	1283
21-Sep-95	1672
28-Oct-95	2043
14-Nov-95	2281
11-Dec-95	2470
30-Jan-96	2739
18-Feb-96	2959
22-Mar-96	3175
12-Apr-96	3324
24-May-96	3498
03-Jun-96	3526
12-Jul-96	3604
15-Aug-96	3704
21-Sep-96	3826
19-Oct-96	3968
22-Nov-96	4102
31-Dec-96	4231
29-Jan-97	4357
14-Feb-97	4406
14-Mar-97	4435

Table 8-11 Cumulative gas production of BK-4-Y

Date	Cumulative Gas Production (MMscf)
19-Jan-96 (Initial)	0
23-Jan-96	83
17-Feb-96	594
12-Mar-96	1186
07-Apr-96	1761
13-May-96	2366
02-Jun-96	2981
24-Jul-96	3817
31-Aug-96	4409
18-Sep-96	4411
09-Oct-96	4411
24-Nov-96	4428
30-Dec-96	4518
12-Jan-97	4672
24-Feb-97	4885
17-Mar-97	5091

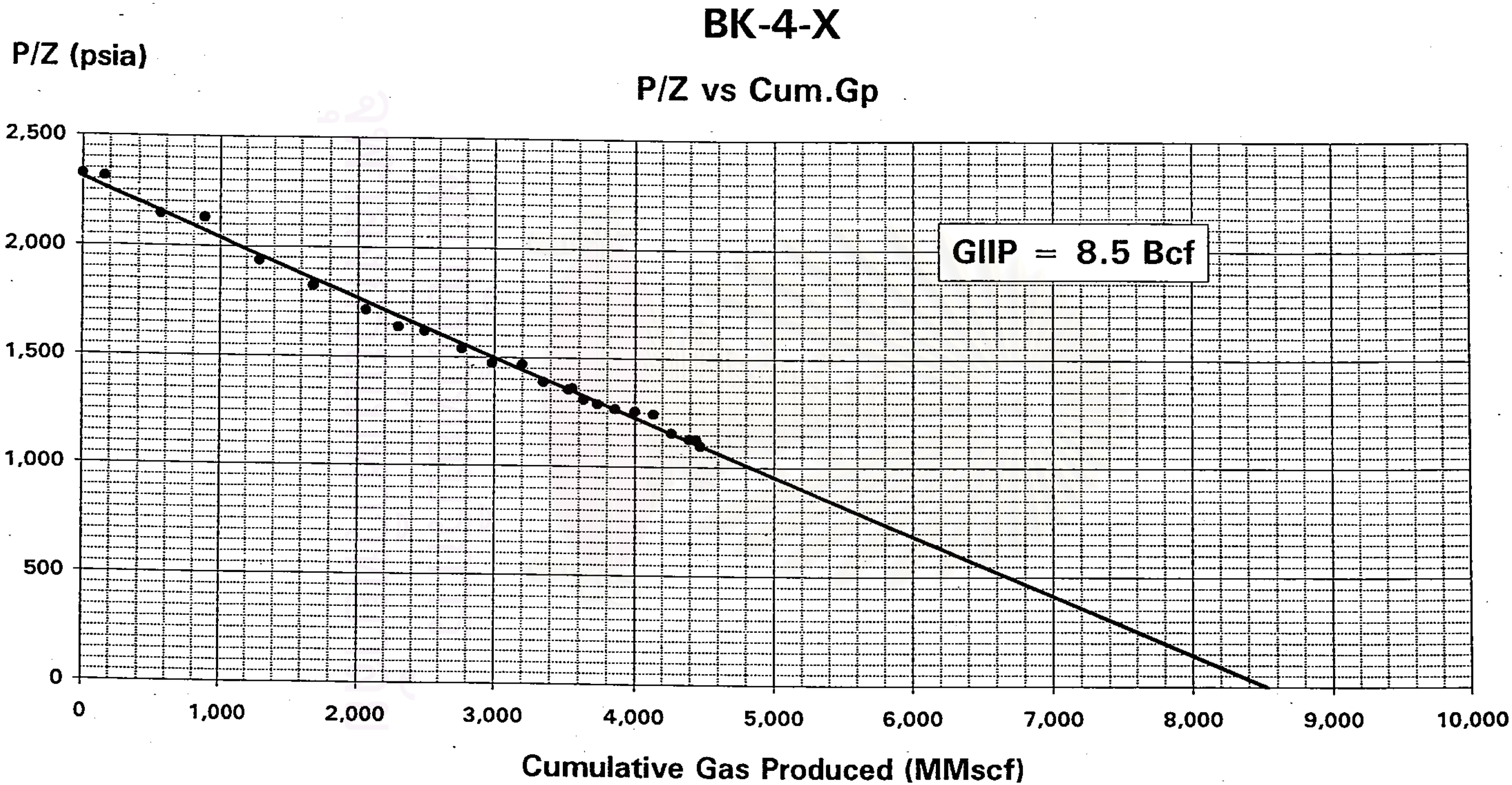

Figure 8-5 The p/z plot of BK-4-X

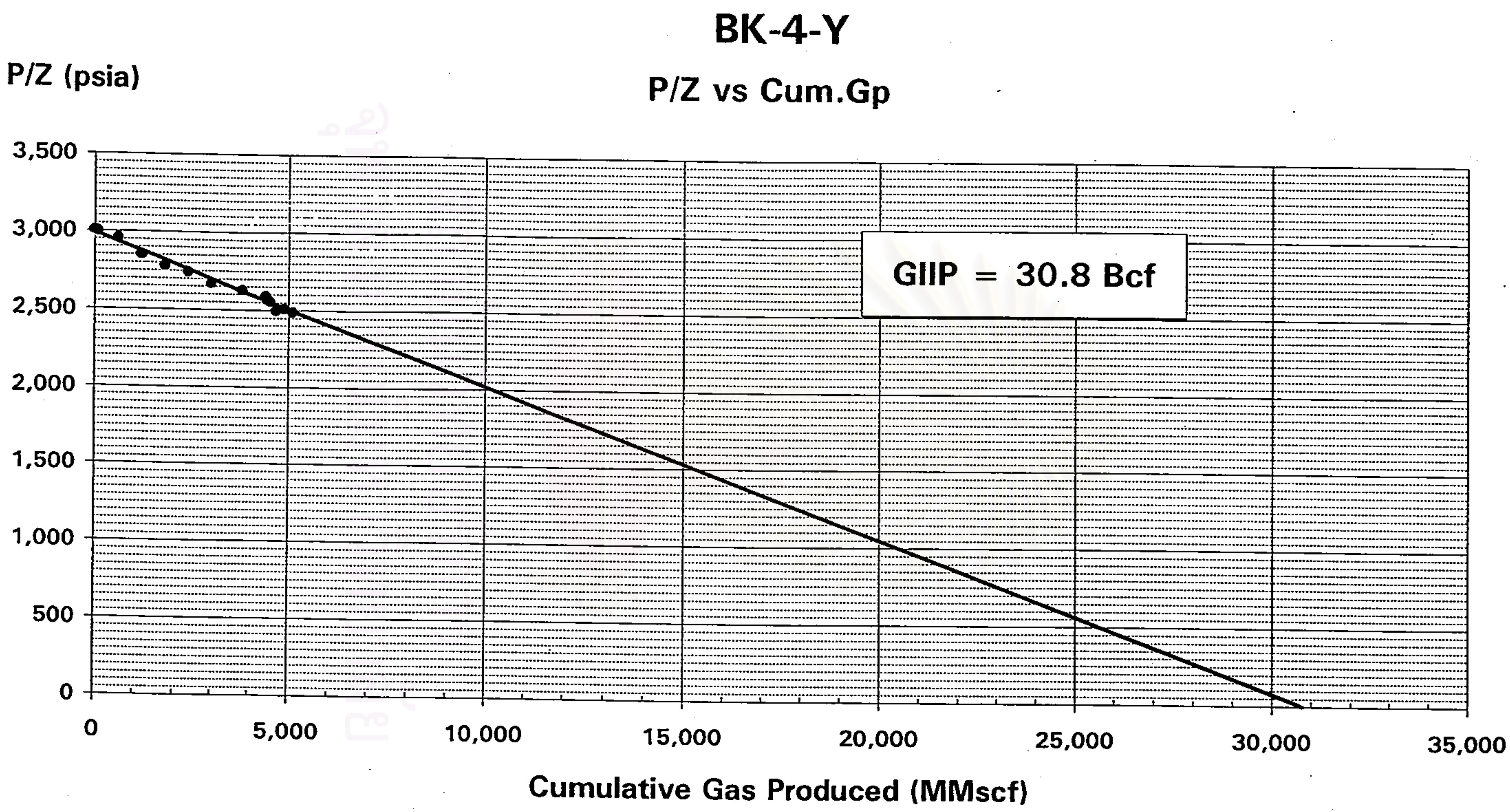

Figure 8-6 The p/z plot of BK-4-Y

From the p/z plot of each well, the obtained GIIP of each well represents the GIIP of the drainage volume of that well. From the p/z plots of the two wells, the GIIP's of the drainage volumes of the two wells are shown in Table 8-12.

Table 8-12 Estimated GIIP from the p/z plots of the wells in case II

	Estimated GIIP (Bcf)
BK-4-X well	8.5
BK-4-Y well	30.8
Total	39.3

As previously mentioned that for a multiple-wells system, if the flow rate of each well in the system is not constant, there will be variation in estimating drainage volume of that well as well as uncertainty of GIIP evaluation (from the p/z plot of that well).

If the flow rate of each well in the system is constant, the drainage volume of each well will also be constant (no change in size of the drainage volume of each well). Therefore, the summation of the drainage volume of each well in the system (for the case that the flow rate of each well is constant) can represent the total volume of the whole system.. In other words, it can be said that the summation of the GIIP of each drainage volume obtained from a p/z plot of each well can represent the total GIIP of the whole system. Fortunately, for this real case study, the gas flow rate of each well is slightly constant (no big variation of the flow rate of each well during the production period). Therefore, the summation of the GIIP of each well obtained from the p/z plot, 39 Bcf (shown in Table 8-12) should represent the total GIIP of the three-layered system with two wells in this real case study.

As previously mentioned that for this case, a separated-layer method was not applied (because to allocate gas flow rate to each layer for such a complex system is difficult, and it needs an advance computerizing system to allocate the gas flow rate such as a reservoir simulator); therefore, only the total GIIP of the whole system could be obtained. However, as previously mentioned, if the volume fraction of any layer in the system can be reasonably estimated, the estimated GIIP of that layer, then, will be obtained.