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SK-2D: A CASE HISTORY ON GEOTHERMAL WELLBORE ENHANCEMENT, MINDANAO GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

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ABSTRACT

Well intervention through casing perforation and acid treatment was performed on well SK-2D to improve its productivity. Post-acid completion tests conducted indicate significant permeability improvement in the perforated intervals and stimulation of the mud-damaged payzones, although initial discharge tests showed contribution from the stimulated bottom zone was masking the potential two-phase feed from the upper perforated sections.

Subsequent short-term discharge tests and eventual commissioning of the well show recovery of the two-phase upper payzone and a remarkable output improvement. Wellbore simulation using flowing pressure-temperature-spinner (PATS) logs and discharge data suggests possible optimization of well utilization by controlling the bottom liquid feed zone and maximizing the contribution of the two-phase zone.

1. BACKGROUND

The Philippine National Oil Company Energy Development Corporation (PNOC-EDC) has used acid treatment in its geothermal wells since 1993. Malate *et al.* (1997) and Buñing *et al.* (1995) discuss the company's various experiences in the application of this technology. In some instances, another well intervention technique namely casing perforation has been applied in conjunction with acid treatment. The first application in the Philippines was made on well SK-2D, one of the production wells for the first 52-MWe Mindanao Geothermal Power Plant in Southern Philippines.

The stimulation job was divided into two stages, namely, a) perforation and acidizing of the cased off payzone and b) acidizing of the open hole section. The first stage required the isolation of the open hole section by a rubber (bridge) plug set at the top of the 7 5/8" slotted liner. Isolation was necessary to ensure efficiency of acid injection into the perforated casing. Acidizing followed completion testing of the perforated intervals.

The second stage of the stimulation job was performed after the upper section had been tested. This procedure, although lengthy, actually provided valuable information on the success of the first stage stimulation and the individual capacities of the shallow steam zone and the combined payzones in the open hole section.

2. WELL CHARACTERISTICS

Production well SK-2D was drilled directionally to a total depth of 1837.6 meters Measured Depth (mMD) and was completed on May 15, 1993. Completion tests within the slotted liner interval, 1227.8 to 1768.6 mMD, yielded a marginal injectivity index (II) of 21 l/s-MPa, good transmissivity (kh) of 20 darcy-meters but a positive skin (s) of 27. The well was found to be non-commercial after its initial discharge capacity tests despite the persistent drilling losses in both the cased off and open hole sections.

Figure 1 shows the stable shut-in temperature (KT) and pressure (KP) of SK-2D that were derived from Kuster gauge measurements. The profiles, when superimposed with the boiling-point-with-depth curve for pure water, suggest a two-phase condition within the cased off section of the well. It was therefore suspected that the low output of SK-2D was caused by drilling-induced wellbore damage in the open hole section and by the inadvertent casing off of a potential production zone.

3. CASING PERFORATION

Drilling records, and temperature and pressure data from completion and check-up surveys were used as initial information in designing the casing perforation job. Preliminary targets were then correlated with geological structures in the area to minimize the probability of targeting localized structures. Deep-penetrating perforating charges capable of 24 inches penetration into cement (API RP-43) were used to ensure communication around the 12-1/4 inches inside diameter (ID) borehole (cased with 9-5/8 inches K-55 steel casing). Entry hole diameter of each charge measured about 0.45 inch, equivalent to about 1.9 square inches of perforated cross-sectional area per foot interval. Charges were shot using 12 shots per foot in 6 inch outside diameter (OD) expendable casing guns. A "big hole" (BH) charge option was considered but later rejected due to its limited penetration into cement (maximum of 6 inches, which was attainable expectedly only on the low side of the casing).

Perforation was conducted with the well extremely overbalanced (with the help of the temporary plug), by keeping a 7.0 MPag (1,000psig) pumping pressure at the time of detonation. With successful communication with a permeable horizon, the pressure would decline and not recover, even with continued pumping. With limited permeability in the accessed zone, the pressure was expected to initially drop but gradually recover with continued pumping. Failure to connect with a permeable zone would cause the pressure to drop initially and immediately rebound to original level with continued pumping. This enabled immediate determination of communication between the wellbore and formation after the charges had been shot.

While initial perforation targets were influenced by the observation of drilling losses and temperature "kicks", refinement was achieved through a combination of Cement Bond (CBL)/Variable Density (VDL) logs and electronic Pressure-Temperature and Spinner (PATS) logs taken just before the perforation job commenced (See Figure 1). It has to be emphasized here that PNOC-EDC uses standard mechanical clock-driven Kuster temperature and pressure gauges in its regular downhole surveys.

The CBL/VDL logs were done to verify the cement condition behind casing vis-à-vis the observed temperature kicks. The electronic temperature and pressure logs were conducted four hours after completing the quenching operation. The new temperature profile then displayed intervals of relatively faster heating which the authors relate with closeness to or communication with potentially permeable zones. As Figure 1 illustrates, two long bands of target (690-870m, and 910-1120m) have been reduced to six short and separated intervals located as close as possible to total loss circulation (TLC) zones and to zones of rapid temperature build-up in the new logs.

4. ACID TREATMENT

The perforated zones were treated with a mixture of 10%HCl-5%HF mainflush solution to dissolve the mud and cement sheath near the wellbore. The mainflush acid volume used was equivalent to 933 liters per meter (75 gals/ft) thickness of target zone to be stimulated, following the same technique used on previous acid jobs conducted by PNOC-EDC (Malate *et al.*, 1997; Buñing *et al.*, 1995). Injection of the mainflush was preceded by a preflush solution of 10%HCl equivalent to 622 liters per meter (50 gals/ft) of payzone for a 933 l/m mainflush dosing rate.

The mainflush was immediately followed by a postflush (overflush) of water for "scavenging" of the dissolved minerals and for rinsing the injection tubing and metal casings of unspent acid in the wellbore. The postflush volume is estimated to be at least twice that of the acid mainflush. The same procedure was repeated in the treatment of the open hole target intervals. Table 1 contains the acid volumes used, injection rates, and the target depths.

5. RESULTS OF STIMULATION

Improvement indicators used in the analysis of the stimulation results include step-increases in injectivity index and other permeability parameters, reduction in wellbore and/or pumping pressures during the tests, increase in relative spinner responses across payzones, and a more pronounced temperature kick across confirmed payzones. The final and most important measure of wellbore improvement, however, is the productivity of the well.

The stimulation results have been grouped in such a way as to reflect the step-improvement between stimulation stages. These are summarized in Table 2, where the injectivity, kh, and skin of the wellbore before and after the job are listed.

Table 2 clearly shows the progressive wellbore improvement brought about by the stimulation job. The observed increase in the permeability of the well between its original completion and the test done before the perforation job might have been the result of several clearing discharges on the well. It nevertheless remained damaged as indicated by its positive skin taken during the two tests.

Figure 2 also illustrates the combined effect of casing perforation and acid treatment of the perforated intervals. The abrupt change in the pressure gradient around 700 mMD, accompanied by a steep spinner response (rps) and deflection in the temperature profile of the well during pumping tests have been observed in past measurement of wells with confirmed gas or steam entry into the wellbore. It is therefore postulated that during this test (Figure 2), the perforated interval around 700 mMD was feeding two phase fluid, and possibly gas, which was immediately quenched by continuous injection of cold water. This is also suspected to have led to the failure of the injectivity test after the casing perforation job. Minimal relative acceptance of injected water at the perforated interval around 730-739 mMD and at 956-965 mMD is manifested in the spinner log. Major permeability on the other hand is indicated by the spinner and temperature profiles across the perforated intervals between 1050 and 1073 mMD.

The specific contribution of either the casing perforation or the subsequent acid treatment of the perforated intervals could not be determined. An injectivity test was attempted right after the perforation job, with the tool set close to the shallowest perforation interval. The test failed with a negative injectivity slope which is attributed to the possible collapse of the two phase column during pumping.

A post-acid spot discharge test conducted in the well produced an output of around 4.3 MWe or a 430% increase in power output at the desired operating wellhead pressure of 1.02 MPag (See Table 3). The well was unable to attain this output prior to the stimulation with the maximum discharge pressure reaching only 0.95 MPag.

The significant increase in power output suggests successful stimulation of the damaged permeable zones and the perforated sections. Although there was a remarkable gain in massflow, the minimal improvement in discharge enthalpy was below expectations and discharge data suggests that the bottom feedzone was masking the two-phase feed contribution from the perforated production casing.

A post-stimulation medium term discharge (MTD) test that lasted for about two months was then conducted to determine the production characteristics of the well under different throttled conditions using back pressure plates (BPP). Discharge test results showed an increasing trend in enthalpy combined with a decreasing trend in massflow at higher wellhead pressures. However, the mixture enthalpy remained low and just comparable to the level during the pre-acid discharge.

The behavior of the enthalpy trend suggests that it could be increased further with throttling (higher wellhead pressures) to suppress the bottom liquid feed up to the maximum discharge pressure of around 2.1 Mpag, at which point flow would collapse. Suppression of the bottom feed has been found to result in an increase in the two-phase contribution from the perforated sections, and thus increase the discharge enthalpy. As the massflow continues to drop, however, so shall its steam and water components which counteracts any gain in steam fraction from the upper zones. It was therefore worth quantifying the exact contributions of the liquid and two-phase zones during discharge and how they behaved at different throttled conditions.

6. FLOWING PATS SURVEYS

Flowing surveys were conducted using the PATS logging tool to determine downhole wellbore and discharge characteristics during discharge. The well was discharged at three different wellhead pressures from throttled to near full bore and a survey was performed for each condition. The test wellhead pressures and their corresponding bore outputs measured are shown in Figure 3. The flowing PATS profiles obtained for each condition produced similar responses characterized by the step increase in temperature and spinner response (rps) pertaining to an increase in massflow due to the entry of fluid into the wellbore. Figure 4 shows the PATS down pass profiles at throttled discharge condition using back pressure plate (BPP) A5.

Seven production zones were identified from the profiles obtained. Four from the perforated sections (691-713, 730-739, 956-965 and 1050-1073 mMD), and three from the open hole (1450-1500, 1600-1650 and 1700 mMD to bottom). The profiles obtained also showed liquid conditions from the bottom until about 900 mMD where flashing began and two-phase conditions developed. This was clearly shown by the flowing pressure gradient that started to decline from this depth accompanied by a sharp increase in spinner response (rps). This indicated a change in fluid density as the fluid phase flashed from liquid to two-phase. Measured pressures above this flashing depth had also reached saturation levels. A momentary drop in spinner response which quickly recovered was also noticed at the onset of flashing. This is known as the "slow zone" caused by liquid hold-up in deviated wellbores brought about by the difference in liquid velocity and gas velocity in two-phase flow.

The single-phase region also includes the lower perforated sections from 956-1073 mMD which were expected to be the source of two-phase flow along with the upper perforated sections. However, the liquid-dominated contribution of these lower perforated sections was of higher temperature (above 240^{o}C) compared to the open hole zones (225^{o}C).

The upper perforated zones from 691-739 mMD were within the region of flashing. Within this section, spinner response increased further and an irregular spinner profile developed which was typical of flashing flow. This confirmed the two-phase entry from this section. The increasing trend in spinner response and decreasing pressure and temperature continued up to the wellhead.

The individual contributions of the production zones were quantified using a method discussed in earlier literature by Maceda et al (1997) and Spielman (1994) applied to the PATS data obtained from the flowing surveys (See Table 4). This involved the calibration of the PATS logging tool to determine the impeller rotation in response to changing logging velocities at fixed flow rates and hole diameter, and calculation of the Reynold's number for fluid flow correction. Note that the method used was only applicable to single-phase flow and hence was only used directly to calculate the inflows from the liquid feeds (below 956 mMD). The contribution of the two-phase feed from the upper perforated sections (691-739 mMD) was derived by subtracting the total liquid inflow from the total discharge massflow measured (bore output).

The estimated flows from the production zones confirmed the immense liquid input from the open hole and the lower perforated section, and the small two-phase contribution from the upper perforated zones. At a large wellhead opening, the bottom zone contributed 50% of the total discharge followed by the lower perforated zone at 26%. The two-phase contribution of the upper perforated zone was a mere 8%, which explained the low enthalpy discharge at low wellhead pressure. With increased throttling, there was a reduction in liquid input by as much as 82% and an increase in the two-phase inflow by 27%. Furthermore, the proportion of the two-phase component was now substantially higher and accounted for 41% of the entire massflow. This suggests that further increase in the two-phase flow and a greater steam fraction can be achieved if the bottom liquid feedzone would be further reduced or even completely eliminated by plugging.

7. WELLBORE SIMULATION

To investigate the effect of further reducing the contribution of the bottom liquid feed, primarily on the behavior of the upper two-phase flow and to the total discharge, wellbore simulation was applied on SK-2D using its current downhole characteristics and discharge data.

A steady-state, deepest feed/up wellbore simulation was performed on the perforated well to match the measured flowing temperature and pressure profiles obtained during the discharge testing. The commercial wellbore simulator WELLSIM (GENZL, 1997) was used, assuming that the conditions did not vary significantly with respect to time. Fluid condition along the wellbore is determined at discrete depths using WELLSIM's own set of two-phase flow correlations (Hadgu and Freeston) or a choice from standard sets of flow correlation such as Orkiszewski and Aziz. For SK-2D, the Hadgu and Freeston two-phase flow correlation was deemed most appropriate. The enthalpy of each feed zone was estimated using the temperature and pressure profiles obtained from the flowing surveys and the calculated individual massflow contributions from the spinner response correlation (See Table 4). The simulation results for the throttled discharge condition (BPP-A5) are shown in Figure 5.

The simulation results produced a good match of the measured data and confirmed the earlier interpretation of a single-phase (liquid) fluid entry from the bottom to about 960 mMD where flashing occurs. The calculated enthalpy was lowest at the bottom feed zone at less than 1000 kJ/kg, increasing slightly to about 1200-1300 kJ/kg at 1050 mMD as the fluid travelled up the wellbore and mixed with higher temperature, higher enthalpy liquid feed at the lower perforated zone. The fluid continued up the wellbore from the flash point as a two-phase medium, its enthalpy attaining the measured values during discharge tests as the two upper perforated zones (691-713 and 730-739 mMD) contribute high enthalpy two-phase massflows. The estimated enthalpy for these zones was about 2650 kJ/kg.

Subsequent wellbore simulation of SK-2D was conducted to determine the optimum utilization of the well by controlling the bottom low enthalpy liquid feedzone and maximizing the contribution from the upper two-phase zone. The complete elimination (plugging) of the deepest zone at 1700-bottom was simulated by modifying the input well geometry to exclude this zone and specifying 1600-1650 mMD to be the new deepest feed zone, thus creating a "new well". The productivity indices (PI) of each feed zone were also calculated and used in the output prediction of the new well. Several deepest feed/up runs were conducted by assuming different discharging bottom feed zone pressures. Constant feed enthalpy and PI were also assumed for each feed zone.

The simulated results are shown in Table 5 and also presented in Figure 3. The simulated individual contributions of each feed zone in the new well indicated that, as the wellhead pressure decreased (1.09 to 0.62 MPag), the total massflow increased (57.8 to 80.6 kg/s). The highest massflow contribution came from the lowest perforated zone at 1050-1073 mMD. However, it was observed that at the same lowering of wellhead pressures, all feed zones showed a decreasing massflow contribution (ex. lowest perforated zone: 40 to 36%) except for the two upper perforated zones which exhibited an increasing trend from 3 to 9% and 3 to 6%, respectively.

The simulation runs also showed that the flash zone dropped from 960 mMD in the original well to about 1060 mMD for the "new well". This suggested that the liquid feed coming from the lowest perforated zone (1050-1073 mMD) in the original well had become two-phase in the new well configuration. The maximum discharge pressure for the "new" well was determined to be about 1.09 MPag, close to A5 discharge condition (See Figure 3).

At similar wellhead pressures, the simulation results indicated higher total massflows and total enthalpies for the new well compared to the original. These effected higher total steam flows and power potential. At the operating wellhead pressure of 1.02 MPag, these elevated values translated to an increase of about 2 MWe in power potential and around 10 kg/s in total massflow.

The implication of the above results is that by eliminating the major bottom liquid feed of SK-2D, a significant improvement in the overall discharge characteristics of the well can be achieved. The "new well" can produce a steam flow and corresponding power output level higher than the original well at the desired wellhead operating condition of 1.02 MPag. Thus, an optimum utilization of the well is achieved.

8. SUMMARY AND CONCLUSION

Acid treatment and casing perforation of SK-2D yielded a very significant improvement in the wellbore with an increase of 4.3 MWe in output. Despite the additional gain in permeability at the perforated and subsequently acidized zones, the well has maintained major production from its original payzones in the open hole interval.

The contribution of casing perforation in the successful stimulation of SK-2D can not be discounted however as the potential for the two-phase or steam production from the perforated zones still remains with the confirmed permeability of these zones. It is possible to gain production from the perforated intervals by flowing the well at a throttled condition.

Even better utilization of SK-2D could be attained by controlling the bottom low enthalpy liquid feed zone and maximizing the contribution from the upper two-phase zone as demonstrated using wellbore simulation.

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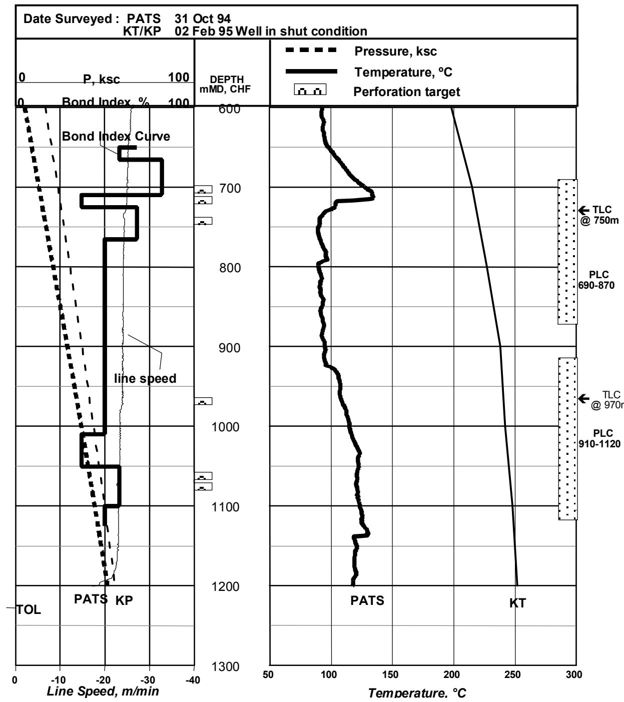

Figure 1. CBL, electronic temperature and pressure and KT/KP profiles used to refine perforation targets.

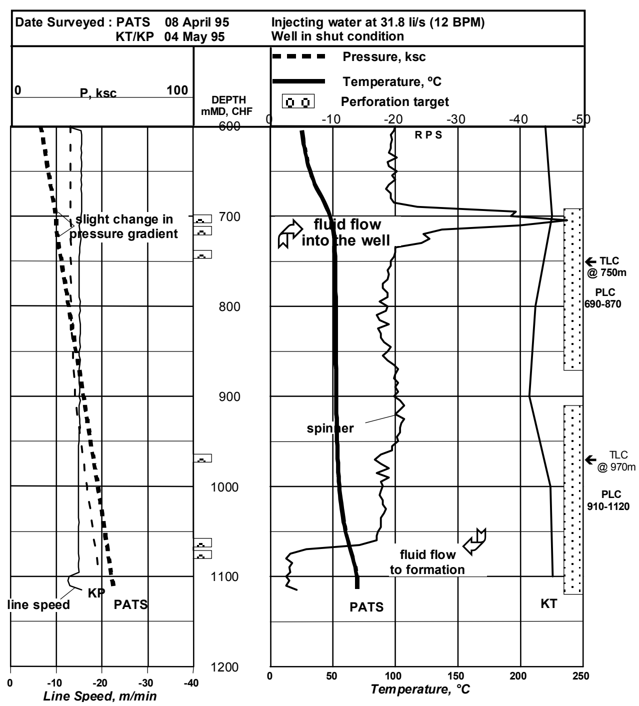

Figure 2. Results of post-perforation completion test with bridge plug set near the production casing shoe.

Table 1. Summary of acid treatment data.

Target zones (mMD)	MainFlush Acid Vol. (l)	Average Pump Rate (l/sec)	Ave. Pump Pressure (MPa)
691-713*	9,869	24.0	2.8
730-739*	9,536	23.6	2.9
956-966*	9,411	24.0	2.9
1050-1073*	9,058	24.4	2.9
1450-1500	46,719	24.0	2.8
1600-1640	37,487	24.0	2.8
1700-bottom	56,334	24.0	2.8
*perforated			

Table 2. Improvement in the wellbore characterisitcs.

Parameters	Injectivity (l/s-MPa)	kh (d-m)	Skin (s)
Original	21	20	27
Pre-Perforation[a]	40	24	27
Post-Perforation Post-Acid[a] plugged	61[b]		
Post-Perforation Pre-Acid open hole	70 99[b]		
Post-Perforation Post-Acid	124 215[b]	30	-5.6

Notes

[a] Completion conducted using PATS, the rest with Kuster.

[b] All measurements taken at 1500 mMD except those marked b.

Table 3. Comparison of pre-acid and post-acid bore outputs.

	Wellhead Pressure (MPag)	Mass Flow (kg/s)	Enthalpy (kJ/kg)	Power Output (MWe)
Pre-acid	0.83	15.0	1073	Non commercial
Post-acid	1.02	44.2	1127	4.3

Table 4. Massflow contributions of production zones at different wellhead pressures.

	Wellhead Pressures (MPag)					
	1.80	%	1.20	%	0.88	%
Total Massflow (kg/s)	18.6		44.0		66.9	
Perf. Section						
691-713 m 730-739 m	7.6	41	3.5	8	6.0	9
956-965 m 1050-1073 m	3.0	16	12.3	28	17.4	26
Open Hole:						
1450-1500 m	2.1	11	3.6	8	5.4	8
1600-1650 m	2.4	13	4.4	10	4.7	7
1700-bottom	3.5	19	20.2	46	33.4	50

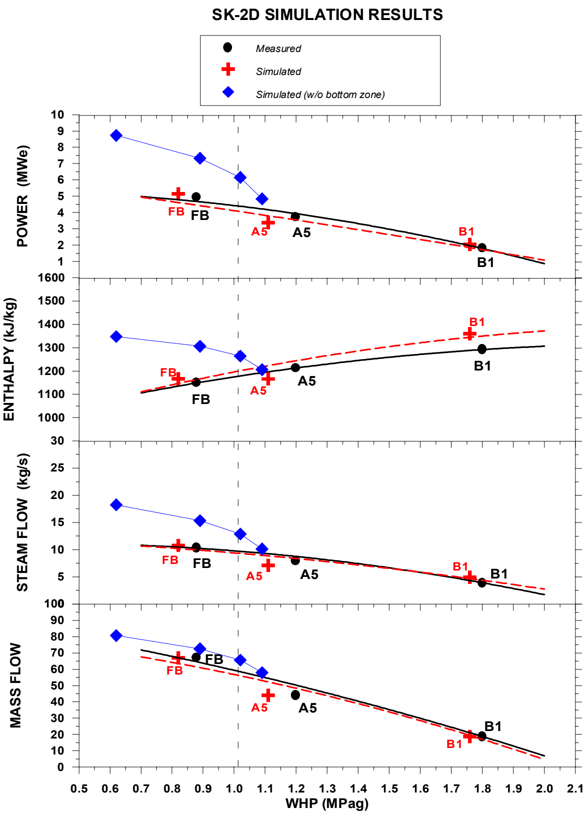

Figure 3. Bore output measurements for SK-2D at different wellhead conditions.

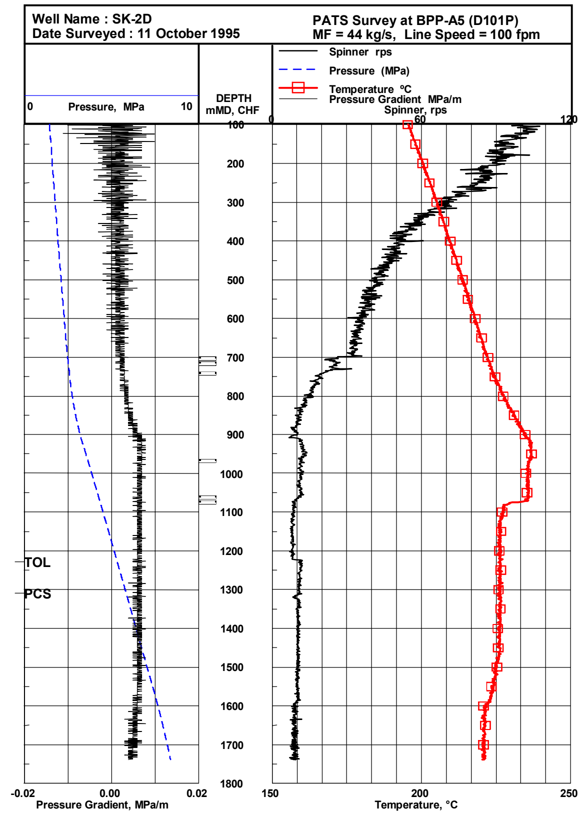

Figure 4. PATS log of SK-2D while discharging at 1.20 Mpag wellhead pressure (BPP A5).

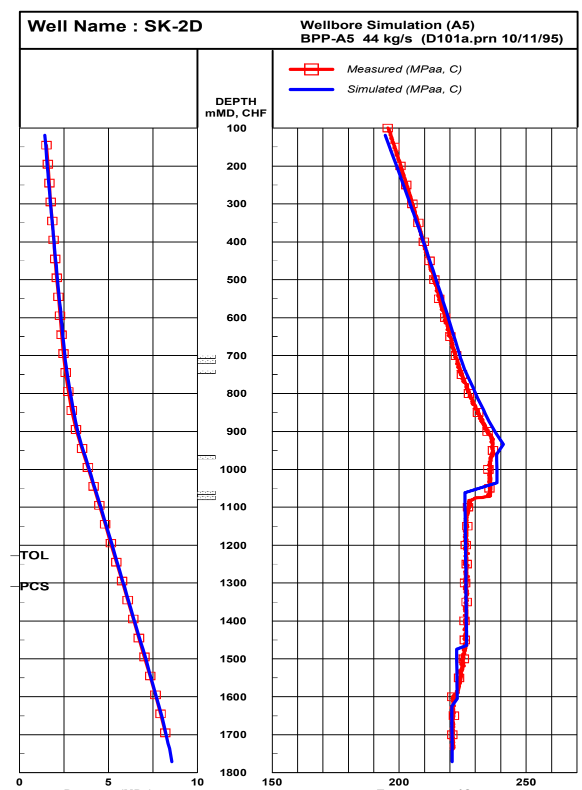

Figure 5. Results of wellbore simulation while discharging at 1.20 Mpag wellhead pressure.

Table 5. Massflow contribution of production zones at different wellhead pressures of the "new well".

	Wellhead Pressures (MPag)					
	1.09	%	0.89	%	0.62	%
Total Massflow (kg/s)	57.8		72.5		80.6	
Perf. Section:						
691-713 m	1.9	3	5.3	7	7.2	9
730-739 m	1.5	3	3.7	5	4.8	6
956-965 m	3.6	6	4.2	6	4.6	6
1050-1073 m	23.2	40	26.6	37	28.8	36
Open Hole:						
1450-1500 m	11.1	19	13.1	18	14.1	17
1600-1650 m	16.5	29	19.6	27	21.1	26