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PRODUCTIVITY ANALYSIS AND OPTIMIZATION OF WELL SK-2D MINDANAO I GEOTHERMAL PROJECT, PHILIPPINES

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ABSTRACT

Well intervention through casing perforation and acid treatment was performed on well SK-2D to improve its productivity. Completion tests indicated stimulation of the mud-damaged payzones, although initial discharge tests showed that contribution from the stimulated bottom zone was masking the potential two-phase feed from the upper perforated intervals.

Subsequent series of short-term discharge tests suggest recovery of the two-phase upper payzone and remarkable improvement in the output of the well. Wellbore simulation of SK-2D using flowing temperature-pressure-spinner (TPS) logs and discharge data projects possible optimization of well utilization by controlling the bottom liquid feed zone and maximizing the contribution from the upper two-phase zone.

BACKGROUND

Buñing et al., (1997) discussed the well intervention technique conducted on production well SK-2D in the Mindanao 1 Geothermal Production Field to improve its productivity. This was accomplished by tapping the steam dominated zone initially identified behind the production casing through casing perforation, and treating the damaged permeable zones caused by mud during drilling through acidizing. The well was subsequently tested and discharge data indicated a significant improvement in mass flow and only a minimal increase in discharge enthalpy.

The power output was estimated at 4.3 MWe at the desired operating wellhead pressure of 1.02 MPag. The well was unable to attain this prior to the stimulation with the maximum discharge pressure reaching only 0.95 MPag (See Table 1).

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

Table 1. Comparison of pre and post-acid bore outputs.

The increase in output suggests successful stimulation of the damaged permeable zones and the perforated sections. However, the minimal improvement in enthalpy was below expectations and discharge data suggests that the bottom feed zone was masking the two-phase feed contribution from the perforated production casing. Temperature-pressure-spinner (TPS) surveys were then conducted at flowing conditions at different wellhead openings to initially quantify the contribution of the perforated and the open hole sections. Wellbore simulation was then performed using mainly the data generated from the flowing surveys in an effort to determine the optimum utilization of the well whereby the two-phase contribution can be maximized.

DISCHARGE TESTING

After the perforation and acidizing, production well SK-2D was discharged for about two months and was tested under different throttled conditions with back pressure plates. The stabilized bore outputs are summarized in Table 2. Discharge results showed an increasing trend in enthalpy at higher wellhead pressures. It appears that the lower enthalpy fluid

Wellhead Pressure (MPag)	Mass Flow (kg/s)	Enthalpy (kJ/kg)
0.70	72.1	1155
1.10	36.8	1107
1.70	19.0	1266
1.90	12.3	1276

The known low enthalpy source was the liquid dominated bottom zone while the high enthalpy fluid presumably came from the shallow perforated zones. This observation established the likely presence of the two-phase contribution from the perforated zones. However, the enthalpy remained low despite its increase, just comparable to the level during the pre-acid discharge. The expected significant improvement in enthalpy from the two-phase contribution of the perforated zones was not attained. Hence, the large mass flow (almost double the pre-acid.) was still dominantly liquid. Although the steam flow increased compared to pre-acid values, the steam fraction did not significantly change. It is likely that the liquid-rich bottom feed still dominated, more so at less throttled conditions or at lower wellhead pressures, and was overcoming the two-phase contribution from the perforated zone.

This well production model creates a mixed low enthalpy discharge representative of the dominant liquid feed at the bottom zone. However, the behavior of the enthalpy suggests that it could be further increased by throttling the well to suppress the bottom liquid feed and allow the shallow two-phase zone to produce. The consequence of this, however, is that the mass flow also decreases as it approaches the maximum discharge pressure after which the well will choke. The maximum discharge pressure for SK-2D was about 2.1 MPag from the post-acid discharge test results. If the mass flow drops, so shall its steam and water components which counteracts the increase in steam fraction. Hence, any gain in steam flow attained from the higher steam fraction may just be offset and even overcome by the loss from the mass flow reduction. 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.

FLOWING SURVEYS

Flowing surveys were conducted using an electronic temperature-pressure-spinner (TPS) logging tool to characterize and quantify the contribution of the different feed zones. The well was discharged at three different wellhead pressures from throttled to near full bore and a survey was performed for each. The test wellhead pressures and their corresponding bore outputs measured are shown in Table 3. Selected TPS down pass profiles from the surveys at different wellhead pressures are illustrated in Figures 1 to 3.

Wellhead Pressure (MPag)	Mass Flow (kg/s)	Enthalpy (kJ/kg)
1.80	18.6	1292
1.20	44.0	1213
0.88	66.9	1149

surveys.

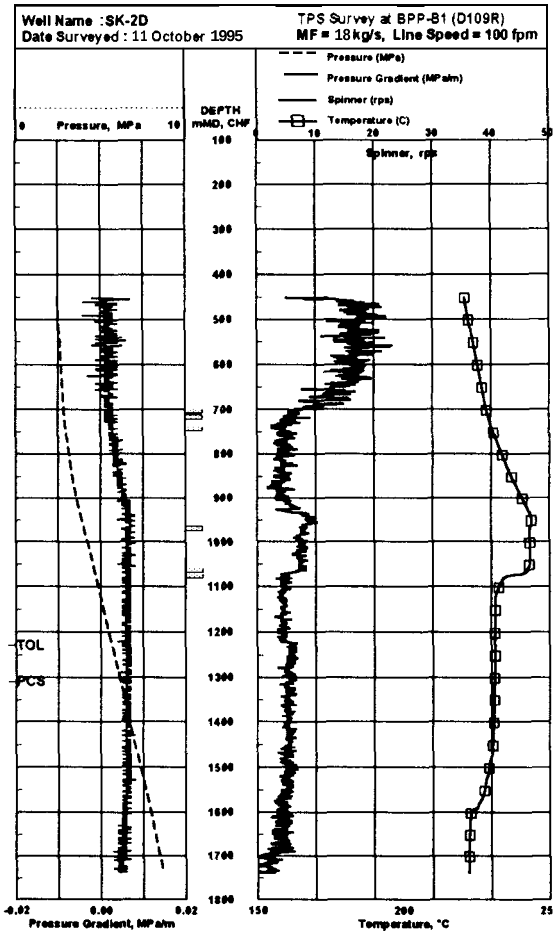

Fig. 1. TPS log of SK-2D while discharging at 1.80 MPag wellhead pressure.

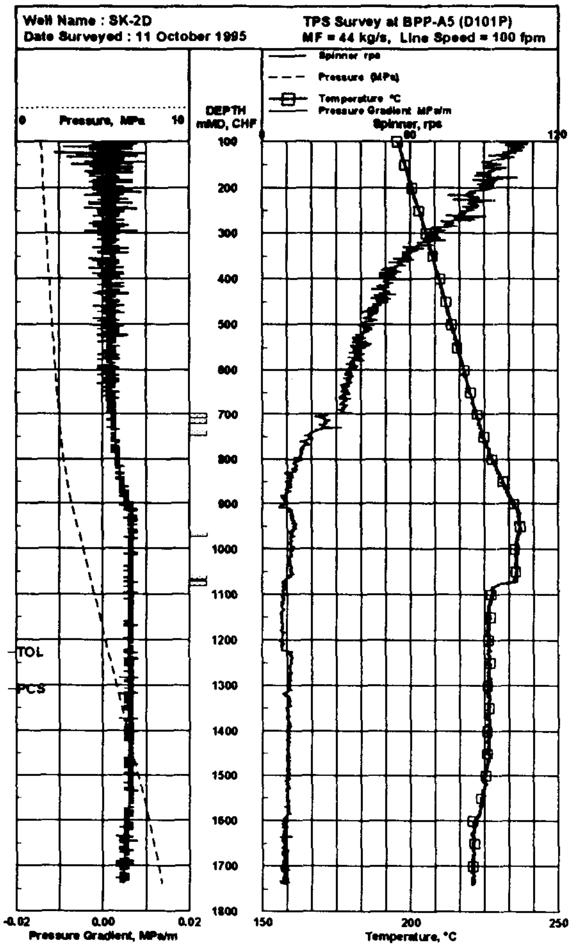

Fig. 2. TPS log of SK-2D while discharging at 1.20 MPag wellhead pressure.

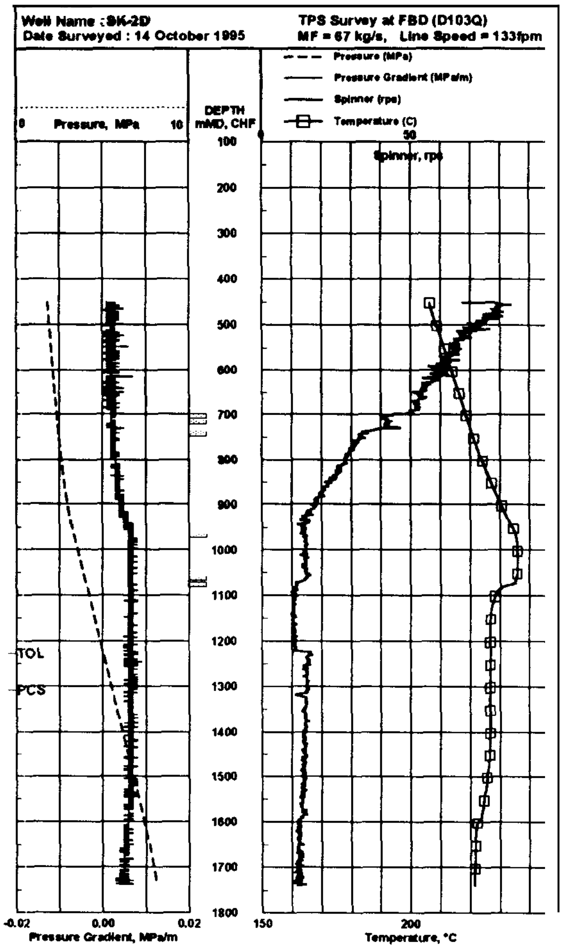

Fig. 3. TPS log of SK-2D while discharging at 0.88 MPag wellhead pressure.

The profiles showed liquid conditions from the bottom until about 900 mMD (meters measured depth) where flashing began and two-phase conditions developed. This was clearly shown by the flowing pressure gradient which started to decline from this depth accompanied by a sharp increase in spinner response (rps).

This indicated a change in fluid properties (e.g. density) as the fluid phase transformed 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.

Seven production zones were identified. 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). These were marked by the step increase in temperature and spinner response pertaining to an increase in flow due to the entry of fluid into the wellbore. Since the flowing pressure gradient did not change from the bottom up to the flashing depth (900 mMD) despite the increases in spinner response, all zones within this interval must be contributing only single-phase (liquid) fluid.

Note that this region 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°C) relative to the open hole zones (225°C). In fact, the highest downhole flowing temperatures lie within these lower zones.

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 downhole flowing characteristics were compared at different wellhead pressures. From higher to lower wellhead pressure, there was an obvious increase in spinner response which was due to increasing mass flow. Furthermore, the slope of the spinner profile from the flash depth declined which could be related to the decreasing enthalpy and reduction in two-phase conditions as the wellhead opening was increased and wellhead pressures decreased.

Temperatures did not significantly vary from the bottom up to 1600 mMD which was likely due to the relatively cold bottomhole conditions. Above 1600 mMD, the temperature increased with decreasing wellhead pressure as expected.

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 TPS data obtained from the flowing surveys (See Table 4).

				ıres	MPag	
	1.80	%	1.20	%	0.88	%
Total Mass Flow (kg/s)	18.6		44.0		66.9	
Perforated Section: 691-713 m 730-739 m	7.6	41	3.5	8	6.0	9
1050-1073 m			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

Table 4. Mass flow (kg/s) contributions of production zones at different wellhead pressures.

This involved the calibration of the TPS 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 mass flow (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 relatively minimal two-phase contribution from the upper perforated zones. At a large wellhead opening, most of the liquid came from the bottom zone which constituted 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 mass flow. This suggests that a more significant increase in the two-phase flow and a greater steam fraction can be achieved if the liquid feed would be further reduced and even completely eliminated (as in plugging).

WEI RE TION

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 temperature and pressure profiles measured by flowing surveys during the discharge testing using WELLSIM, assuming that the conditions did not vary significantly with respect to time. WELLSIM is a commercial wellbore simulator that can handle liquid, two-phase or superheated steam types of geothermal fluids. Dissolved solids and non-condensable gas contents maybe represented in the form of NaCl and CO_2, respectively. WELLSIM also allows multiple feed zone configuration and multiple diameter changes of the casing, liner and/or open hole. Calculations proceed from the top of the well down to the deepest feed (wellhead/down simulation) or vice versa (deepest feed/up), whichever of wellhead or deepest feed zone condition is specified. Fluid condition along the wellbore is determined at discrete depths down or up using WELLSIM's own set of correlation (Hadgu and Freeston) or a choice from standard sets of flow correlation such as Orkiszewski and Aziz. For SK-**2D**, the Hadgu and Freeston correlation was deemed most appropriate.

Using the temperature and pressure profiles logged from the flowing surveys (Figures 1 to **3)** and the calculated individual mass flow contributions from the spinner response (Table **4),** the enthalpy of each feed zone was estimated. Heat loss to the formation was assumed negligible and NaCl and CO_2 contents were set to zero. The simulation results for discharge through BPP-A5 are shown in Figure **4.**

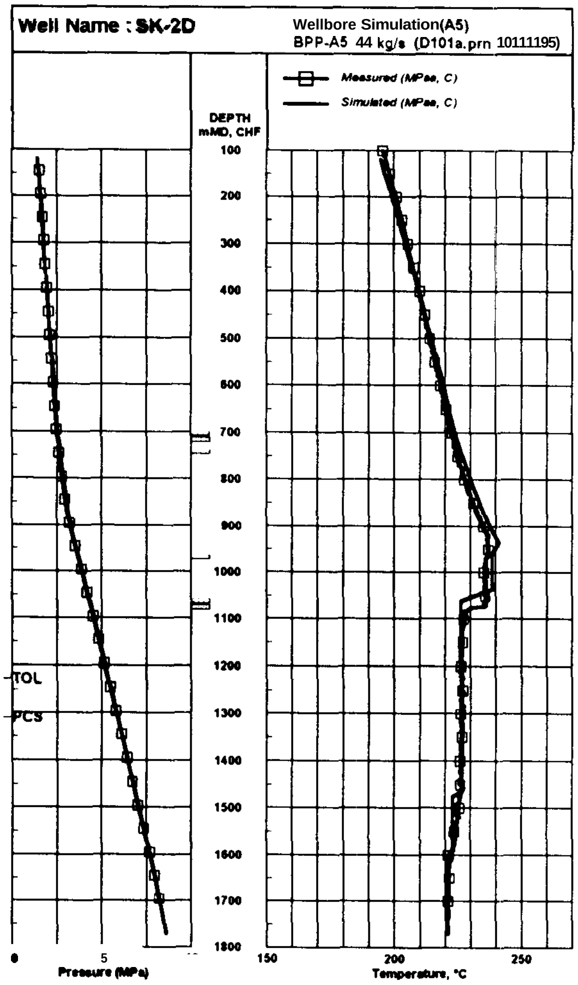

Fig. 4 Wellbore simulation of SK-2D while discharging at 1.20MPag wellheadpressure

The simulation results confirmed the earlier interpretation of a single-phase (liquid) fluid from the bottom to about **960 mMD** where flashing occurs. This included mass flows from the open hole feed zones (1450-1500, **1600-1650** and **1700-bottom)** and the lowest perforated zone **(1050-1073 mMD).** The estimated 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 traveled 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 mass flows. 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 feed zone 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 prediction of output of the new well. Several bottom 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 simulation results are shown in Table ***5*** and Figure ***5***. The simulated individual contributions of each feed zone in Table **5** indicated that for the new well, as the wellhead pressure decreased **(1.09** to **0.62** MPag), the total mass flow increased **(57.8** to **80.6** kg/s). The highest mass contribution came froin 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 mass flow 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 for the "new well" dropped to **1060 mMD** from **960** mMD in the original well. This suggested that the liquid feed corning from the lowest perforated zone

(1050-1073 mMD) in the original well had become two-phase at the new well configuration.

	Wellhead Pressures (MPag)					
	1.09	%	**0.89**	%	**0.62**	%
Total Mass Flow **(kg/s)**	**57.8**		**72.5**		**80.6**	
Perforated 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
1700-bottom	-	-	-	-	-	-

Table 5. Mass flow (kg/s) contributions of production zones at different wellhead pressures of "newwell".

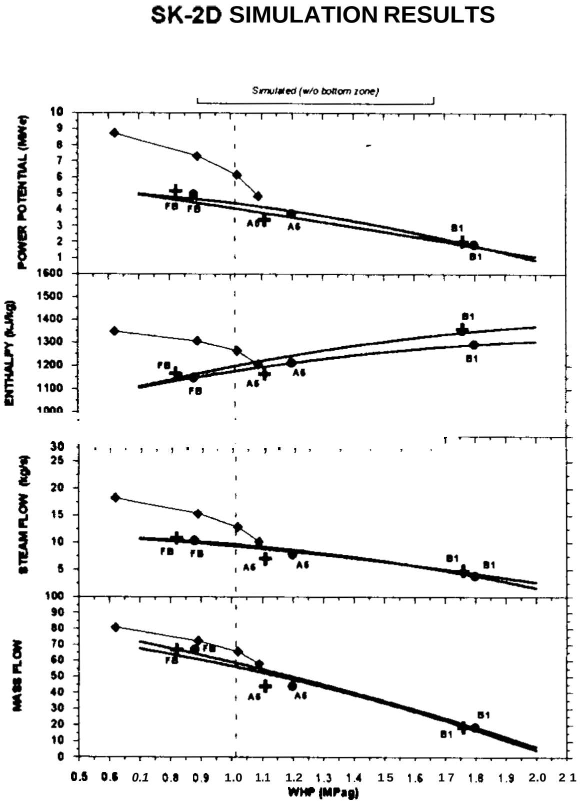

Fig. 5 SK-2D bore output simulation results: without bottom feed

The maximum discharge pressure for the "new" well was determined to be about **1.09** MPag, close to **A5** discharge **(See** Figure **5).**

At similar wellhead pressures, the results indicated higher total mass flows 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 and **10 kg/s** in power potential and total mass flow, respectively. A summary is presented in Table **6.**

	Original Well	"New Well"
Mass Flow, kg/s	**60**	**70**
Steam Flow, kg/s	10	14
Enthalpy, kJ/kg	1200	1275
Power Potential, MWe	4.5	**6.5**

*Table 6. **Comparison of well output at 1.02 MPag operating wellhead pressure.***

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 operating condition of **1.02** MPag. Thus, an optimum utilization of the well is achieved.

CONCLUSION

The estimated flows from the production zones of SK-2D confirmed the immense liquid input from the open hole and the lower perforated section, and the relatively small two-phase contribution from the upper perforated zones. Such interpretations were confirmed with wellbore simulation.

Wellbore simulation was further utilized to evaluate the optimum utilization of the well by controlling the bottom low enthalpy liquid feed zone and maximizing the contribution from the upper two-phase zone. It was determined that higher steam and mass flows can be attained by eliminating the bottom zone. Steam and corresponding power production from the "new well" is higher than the original well at the desired operating condition. Power production is therefore maximized.

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