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Use of Pressure-Temperature-Spinner Surveys to Characterize Geothermal Production Well Behavior

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ABSTRACT

In the Mak-Ban and Tiwi geothermal fields operated by Philippine Geothermal Production Company, Inc. (PGPC), there is now a significant database of Pressure-Temperature-Spinner (PTS) surveys conducted in both steam and two-phase production wells as well as injection wells. Normally a series of surveys are run on a well, including uplogs and downlogs at two or more logging speeds to characterize the flow conditions and provide the necessary information to convert the measured spinner velocities to mass flow. Stationary runs may also be conducted at various locations to check if flow is occurring at that location and if it is upflowing or downflowing.

In the majority of wells, the results from the PTS surveys normally indicate that downhole flow conditions are stable and the surveys are relatively easy to analyze to provide information on permeable zone locations and thermodynamic conditions. However, in both Mak-Ban and Tiwi, there are a number of wells that exhibit unstable well behavior and this is normally manifested by cycling or spikes in the wellhead pressure and associated changes in production flow rates and enthalpies although in some wells, changes in wellhead conditions may not be apparent. PTS surveys have been run to help characterize the downhole conditions in these wells and the results obtained have in many cases been quite surprising in terms of how dynamic the conditions can be in the wellbore. In some wells, very unstable spinner responses have been measured in regions of the well that suggest counterflow is occurring. In other wells, there are significant changes in the PTS profiles from one survey to the next as the fluid changes from being predominantly two-phase to almost single-phase liquid while the survey is being conducted. In many of these cases, quantitative analysis may not be possible but the surveys still provide qualitative information that helps in understanding the well's characteristics.

1. INTRODUCTION

The use of Pressure-Temperature-Spinner (PTS) surveys to characterize downhole conditions in geothermal production and injection wells has long been a standard practice in the geothermal industry (e.g. Spielman, 1994). Operated by Philippine Geothermal Production Company, Inc. (PGPC), Mak-Ban and Tiwi geothermal fields which are situated in the provinces of Laguna & Batangas and in Albay, respectively, has now a significant database of hundreds of these surveys conducted in both steam and two-phase production wells as well as injection wells. Normally a series of surveys are run on a well, including uplogs and downlogs at two or more logging speeds to characterize the flow conditions and provide the necessary information to convert the measured spinner velocities to mass flow. Stationary runs may also be conducted at various locations to check if flow is occurring at that location and if it is upflowing or downflowing.

PGPC has a process in-place to help ensure that the wells are performing at their maximum capacities. This process is facilitated through proper instrumentation of active wells and selected surface facilities that will provide information such as flow rates and pressures at a high frequency. The goal of this well monitoring is to ensure that the wells are operating at their expected performance and identify any deviations as soon as possible. For instance, for production and injection performance, actual well measurements should be within expected deliverability curves based on surface production or hydraulic model, and maximum capacities at specified operating wellhead pressure. If there is a significant change in production performance or deviation from well deliverability and injectivity, the well will be proposed for PTS survey to characterize the downhole condition of the well causing the deviations.

In PTS surveys from stable wells, the temperature and pressure profiles from the various runs are normally the same or very similar while the spinner velocity profiles have the same or similar shapes but are displaced from each other due to the different logging speeds and direction (uplog or downlog). For these wells, the data can be analyzed using the method presented in Acuña and Arcedera (2005), where the pressure gradient and spinner velocity profiles are used to calculate mass flow and enthalpy profiles in the wells, assuming homogeneous flow, and wellbore simulation is then used to match the various profiles to provide information on the locations, flow and thermodynamic conditions at the indicated feedzones (FZ). Good results have generally been obtained using this analysis technique although there can be issues if the quality of the pressure and spinner data results in significant fluctuations in the calculated mass flow and enthalpy profiles. There may also be anomalies in the profiles in the upper cased section of the well if the discharge enthalpy is <500 BTU/lb (<1,165 kJ/kg), which is believed to indicate excess liquid holdup that is not accounted for when assuming homogeneous flow conditions. Downflowing intervals are also present in a number of Mak-Ban production wells during production and are characterized by liquid pressure gradients, isothermal conditions and negative spinner responses.

2. CASE STUDIES

2.1 Improving Well Productivity

Analysis of PTS surveys has proven to be valuable in assessing downhole conditions that may lead to identification of opportunities that could maximize steam production. In several cases, PTS surveys have been used to support implementation of wellwork opportunities (e.g. rig workovers) or come up with operational strategies to improve well productivity. This is being highlighted by the case studies presented in this section.

2.1.1 Bulalo 99 (Bul-99)

The Mak-Ban geothermal resource has both "shallow" and "deep" reservoirs that are separated by a low permeability formation called the Andesite Lava Marker (ALM), which occurs at ~1,400 m below sea level (bsl). The barrier has enhanced the pressure differential between the shallow and deep reservoirs, which has caused flow instability and downflows in wells under flowing conditions (Sunio, *et al.* 2015). Drilled to 1,957 m bsl in 1996, Bul-99 is open to both reservoirs and in recent years, the well has had stable production, predominantly from a steam zone in the shallow reservoir. However, in June 2018, high-frequency data indicated an instantaneous drop in flowing wellhead pressure (FWHP) and a subsequent tracer flow test (TFT) validated ~7 kg/s drop in steam production which was accompanied by a significant increase in brine and corresponding drop in enthalpy from 2,000 kJ/kg to 1,000 kJ/kg (Figure 1).

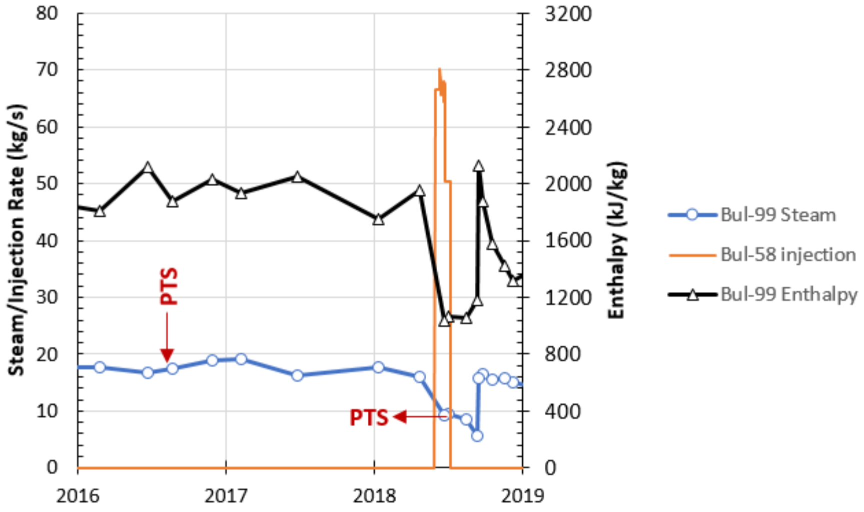

Figure 1: Production of Bul-99 and Bul-58 injection.

A PTS survey was conducted on July 17, 2018 to investigate associated changes in downhole conditions. Prior to this, the latest PTS survey of the well was on August 15, 2016 which captured the period of relatively higher steam production. A graphical comparison of the two PTS surveys is presented in Figure 2 where the spinner data is already expressed in terms of fluid velocity.

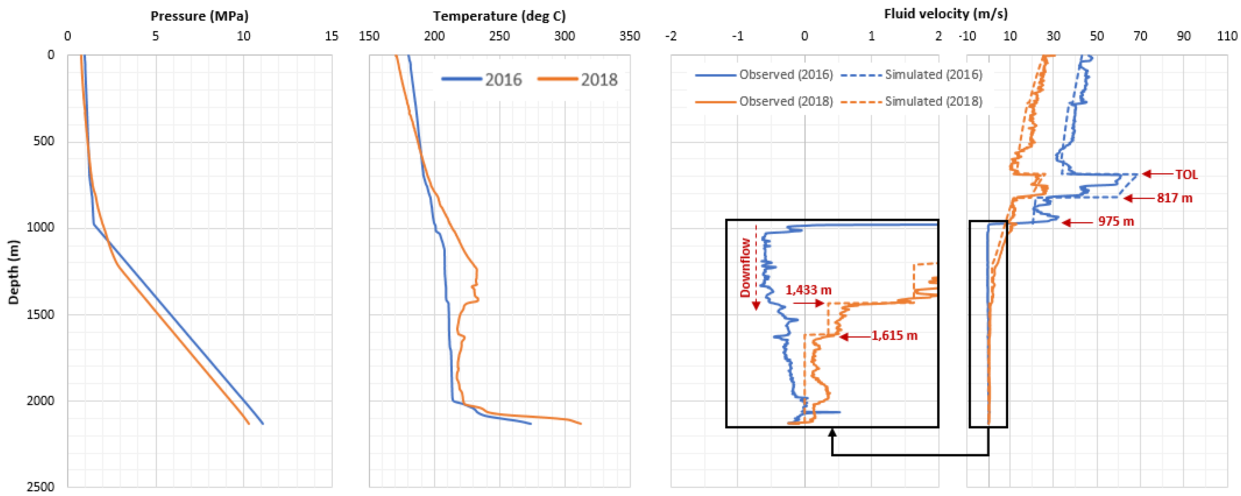

Figure 2. 2016 and 2018 PTS surveys of Bul-99.

In 2016, the well's stable production was characterized by two feedzones located at 817 and 975 m measured depth (MD) and a downflow from 975 m MD, as suggested by the positive and negative fluid velocities above and below 975 m MD, respectively. The downflowing fluid, which is interpreted to be exiting at the deeper part of the wellbore, was also indicated by the presence of relatively isothermal conditions and sudden increase in temperature below 2,000 m MD.

The 2018 PTS survey indicated significant changes in downhole conditions that would explain the lower steam production of Bul-99 during this time. The spinner data pointed to the absence of downflow as suggested by the entirely positive fluid velocity profile. In addition, two deeper production zones (at 1,433 and 1,615 m MD), which were not apparent in 2016, "kicked off" and produced low enthalpy fluids which consequently altered the well's flowing pressure profile.

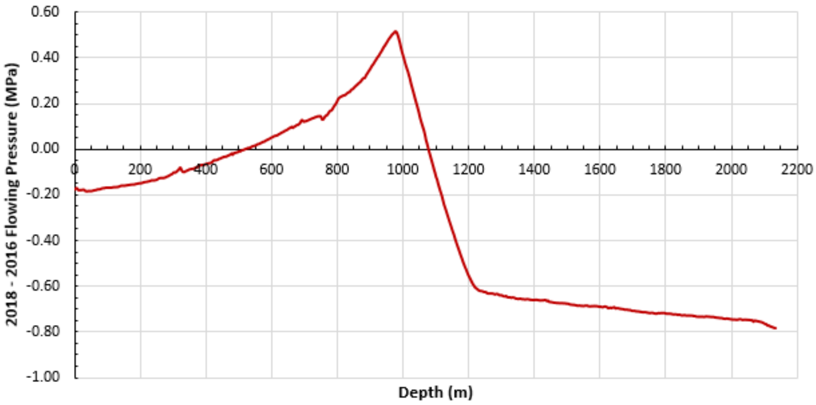

Figure 3. Difference in Bul-99's flowing wellbore pressure.

The difference in flowing pressure between the 2016 and 2018 surveys is shown in Figure 3 and it is interesting to note that the maximum increase in wellbore pressure occurred at the location of the deeper production zone (975 m MD) in 2016.

The magnitude of the pressure increase (~0.5 MPa) was sufficient to entirely suppress this zone in 2018 since the complete interpretation of the matched PTS profiles, as summarized in Table 1, suggested no detectible additional mass production at this depth. The production from the shallower zone at 817 m MD (all-steam) was also reduced by 75% in 2018 due to the additional back pressure (0.25 MPa) caused by production from the predominant low enthalpy zones at 1,433 and 1,615 m MD. In conclusion, the lack of downflow and dominance of the deep low enthalpy zones that altered the wellbore pressure explained the drop in production of Bul-99 in June 2018.

Table 1. 2016 and 2018 Upflow and Downflow Conditions of Bul-99.

Year	Upflow (FZ depth, mass rate, enthalpy)	Downflow (FZ depth, mass rate, enthalpy)
2016	817 m MD – 10.1 kg/s (2,791 kJ/kg) 975 m MD – 20.2 kg/s (1,396 kJ/kg)	975 m MD – 31.5 kg/s (861 kJ/kg)
2018	817 m MD – 2.5 kg/s (2,791 kJ/kg) 1,433 m MD – 40.3 kg/s (1,000 kJ/kg) 1,615 m MD – 11.3 kg/s (942 kJ/kg)	None

The production changes in Bul-99 were correlated to a temporary injection well, Bul-58, which is inferred to be hydraulically connected to the production well. The relatively high injection rate of ~66 kg/s (Figure 1), nine days before the noted drop in Bul-99's steam production, is interpreted to have caused a transient pressure increase into the deeper low enthalpy zones of Bul-99, which could have stimulated their production. This led to the recommendation to cease injecting into Bul-58 in July 2018.

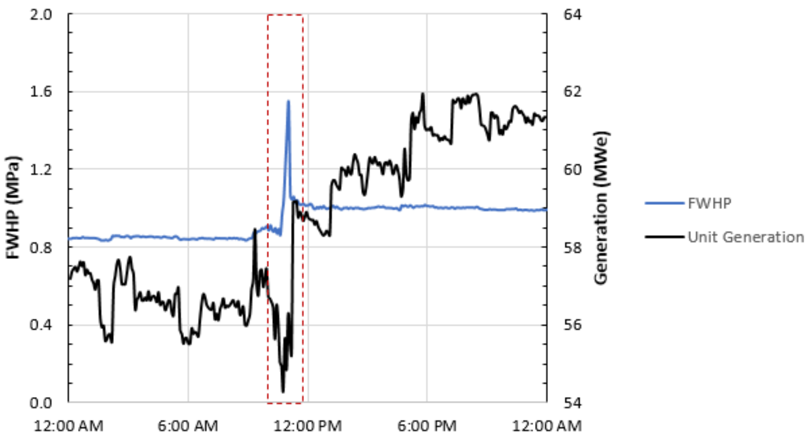

Figure 4. Successful **stimulation of Bul-99 through throttling.**

With Bul-99 still not showing indications of recovery even after shut-in of Bul-58 for more than a month, it was recommended to throttle Bul-99 to potentially re-initiate the downflow at 975 m MD and return the well to the conditions in 2016. This recommendation relied on the idea that the well is under a metastable condition and that the downflow can be initiated by introducing a temporary pressure stimulus that may alter wellbore dynamics. Observations in some other Mak-Ban wells affected by downflows seem to support this theory wherein accidentally subjecting a well to slightly elevated pressure during operational upset conditions would cause the downflow to occur in the wellbore and "kill" the deeper feedzone/s (Sunio, *et al.* 2015). The temporary throttling of Bul-99 was executed on September 16, 2018 and hi-frequency monitoring of pressure and generation data (Figure 4) proved that the well was successfully stimulated by the throttling, as shown by the increase in FWHP from 0.85 MPa to 1.0 MPa and the increase in generation from 57 MW to 61 MW. This was also validated by the succeeding TFT's conducted in Bul-99, as shown in Figure 1. Note though that the decrease in enthalpy towards the end of 2018 with steam rate being relatively stable is still subject for further analysis.

2.1.2 Bariis 11 (Bar-11)

Bar-11 is a production well drilled in 2008 to tap the Bariis upflow of the Tiwi geothermal resource. Cased deep to seal off the known acid horizon in the area (Vicedo, *et al.* 2008), Bar-11 is producing from the deep liquid resource where pressures and temperatures have been observed to be generally stable. However, production data of the well, as shown in Figure 5, pointed to an accelerated steam decline starting in 2013 which had been interpreted to be primarily due to wellbore obstruction attributed to scaling. The well ceased to flow in Dec 2015 and a rig scale drillout (SDO) was executed in April 2016 which brought the well back to its 2010/2011 steam rate production.

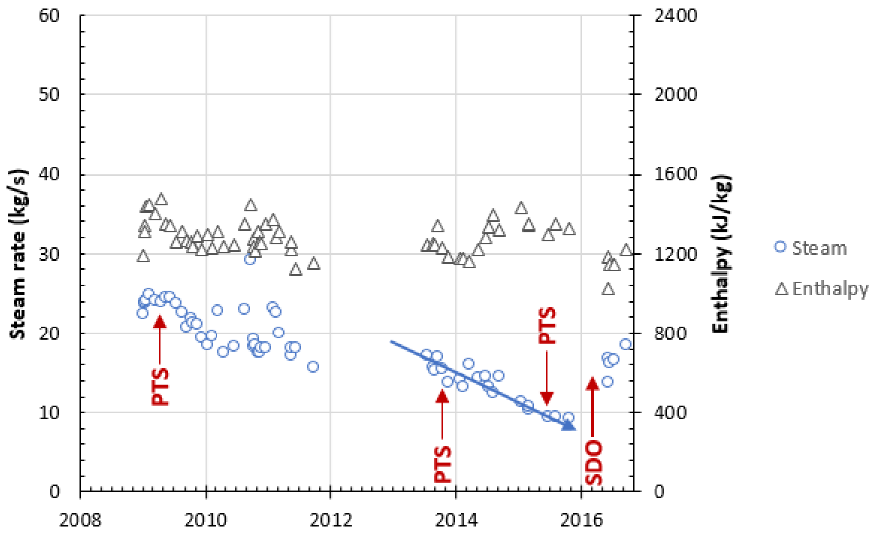

Figure 5. 2008-**2016 Production of Bar-11.**

A total of three flowing PTS surveys were conducted in Bar-11 from 2008 to 2015. These surveys were instrumental in providing additional information that eventually justified the economic investment in 2016. Table 2 summarizes the matched feedzone locations of the well and the % mass contribution of each through time.

Table 2. Feedzone location **and production of Bar-11.**

Feedzone Depths (m MD)	**Mass rate (kg/s) and % contribution by mass**		
	2009	**2013**	**2015**
1,402		1.9 *(3%)*	1.3 *(4%)*
1,737	2.5 *(3%)*		4.8 *(14%)*
1,838*			28.4 *(82%)*
1,966	7.6 *(8%)*	20.2 *(29%)*	
2,073	81.4 *(89%)*	46.6 *(68%)*	

**close to the maximum clear depth of the PTS survey (1,871 m MD)*

The baseline PTS in 2009 clearly established the main feedzone at 2,073 m MD, which is very close to the well's total depth (TD) at 2,088 m MD. In 2013, near the start of the well's accelerated decline, the October PTS survey still showed the majority of production coming from the deep zones but suggested reduced production from the main feedzone and an increase in the % mass contribution of the secondary zone at 1,966 m MD. The 2013 flowing pressure profile, as shown in Figure 6, registered a noticeable pressure drop from 1,920 to 1,963 m MD, which was interpreted as a potential wellbore restriction. In 2015, the total mass flow rate had further decreased and the June PTS survey was not able to go down beyond 1,871 m MD. There was still mass coming from the two lower feedzones but with the cease-flow incident in December 2015, it was concluded that the two deepest zones were already fully obstructed.

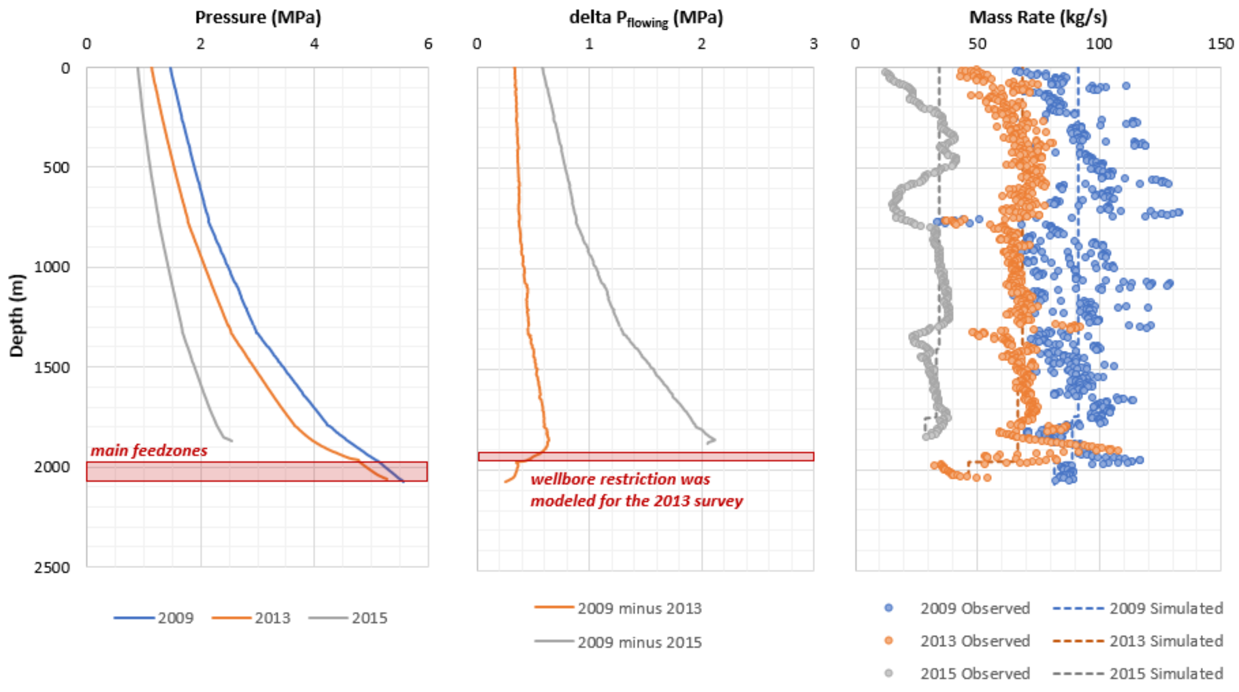

Figure 6. Flowing pressure profiles and interpreted **mass rates from Bar-11 (2009, 2013 and 2015 surveys).**

The historical PTS surveys of Bar-11 clearly demonstrated that the production of the well was impaired by the development of obstruction in the wellbore (validated to be scales during the workover) due to the shallowing maximum clear depth, decreasing production from the blocked feedzones, and imposing wellbore restriction to better match downhole data (i.e. flowing pressure). Note that the significant scatter in the "observed" massflow rates is due to similar variations ("noise") in the spinner response, which is affected by the tool used, and may also be affected by diameter changes within the portion of the well with slotted production liner. The scatter does not indicate the locations of inflows and outflows and so for the "simulated" massflows, constant values are used based on the average of the "observed" responses.

The successful workover of Bar-11 in 2016 resulted to the well regaining its previous production and validated the stability of the deep resource in Bariis although the issue of wellbore scaling remains to be a concern and mitigations are being explored to arrest the decline of wells in the area to ensure maximum production.

2.2 Characterizing Unstable Wells

Both Mak-Ban and Tiwi Geothermal fields are considered to be mature and well-developed fields, which have both been operating for 40 years. Mature fields typically experience more unstable well behavior and interzonal flows because of the pressure drawdown resulting from extraction and the differences in enthalpies and permeabilities between feedzones and in Mak-Ban and Tiwi, this is a common situation. The instability of these wells are normally manifested by regular or irregular cycling and spikes in FWHPs and flow rates at the surface. However, in some wells, instability is not observed in the surface FWHP and flow rates, and has only been discovered when surveyed with PTS.

Instability in the wellbore is characterized by PTS surveys having changing profiles with time (pressure, temperature, and/or spinner responses), and the results have proven to be quite surprising in terms of how dynamic the conditions can be in the wellbore during such a survey. In some wells, very unstable spinner responses have been measured in regions of the well that suggest counterflow is occurring while in other wells, there are significant changes in the PTS profiles from one survey to the next as the fluid changes from being predominantly two-phase to almost single-phase liquid while the survey is being conducted. Still others have profiles that are in a complete transient state such that it is very difficult to interpret physically how the condition was achieved, given the thermodynamic properties of the fluid; for example, the existence of liquid gradients above and below a steam gradient.

In the following sections, data from four wells with unstable profiles are presented and discussed to provide examples of the range of conditions encountered in Mak-Ban and Tiwi wells.

2.2.1 Bulalo 91 (Bul-91)

Drilled in 1992, Bul-91 is a production well in the Mak-Ban field affected by shallow recharge (SR). Its production history (Figure 7) manifests steam rate fluctuations categorized as "high" and "low" flow conditions which are characterized by lower and higher fluid enthalpies, respectively.

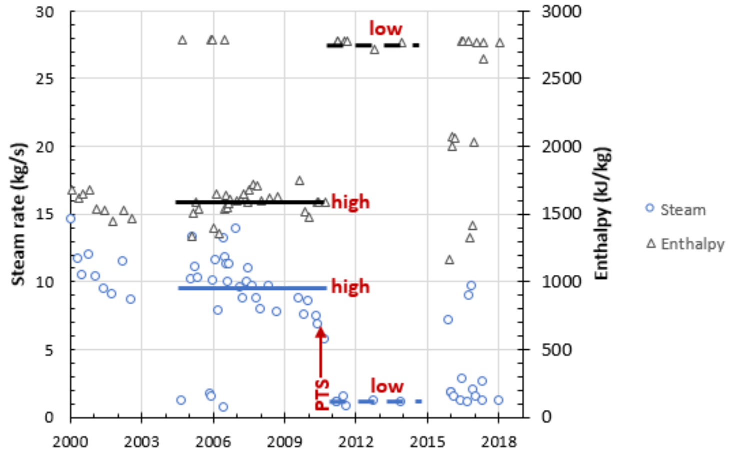

Figure 7. 2000-2018 Production of Bul-91.

In addition to TFT data, hi-frequency FWHP data also provide indications about the condition of the well. Spikes in FWHP (Figure 8) signifies that the well is at high flow condition. A PTS survey was conducted on August 17, 2010 to determine the location of the SR inflow and other possible cooler inflows, with the survey showing different profiles for the uplog and downlog runs, and for selected points where the tool was held stationary (Figure 9). The uplog pressure profile showed four separate gradients and these are referenced as 1 to 4 in Figure 8; (1) steam gradient from wellhead 0 m MD down to 522 m MD; (2) two-phase gradient from 522 m MD to 730 m MD; (3) steam gradient from 730 m MD to 978 m MD and (4) liquid gradient from 978 m MD to 2,155 m MD total depth.

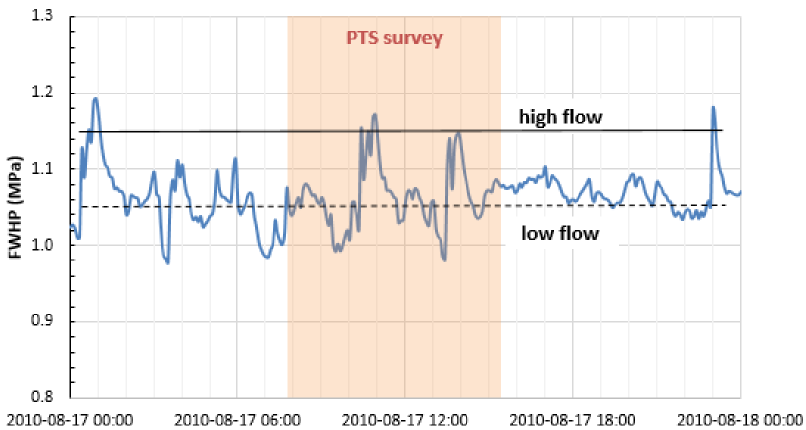

Figure 8. Hi-freq FWHP data of Bul-91 on Aug 17, 2010.

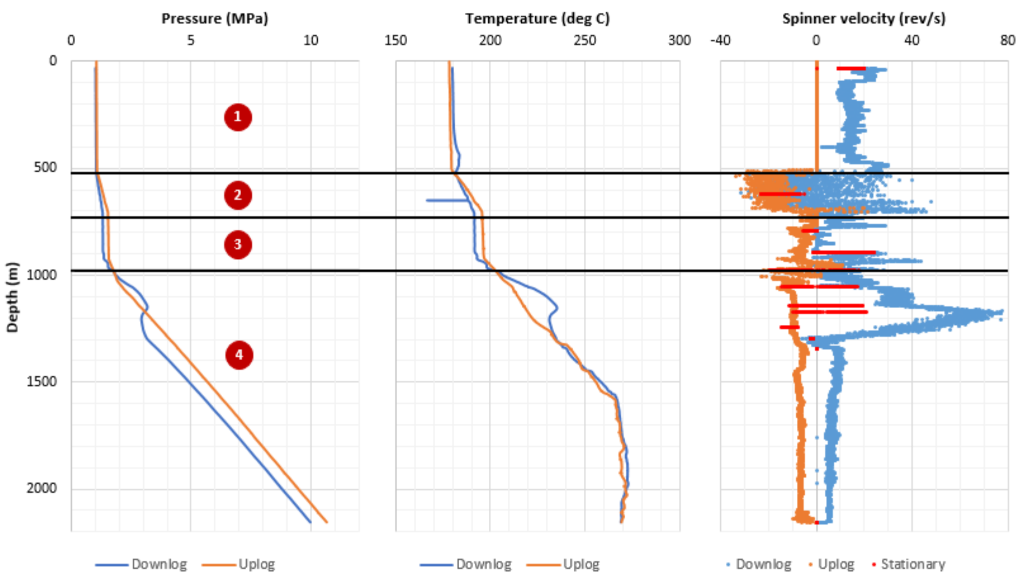

Figure 9. PTS data of Bul-91 in 2010.

In terms of the spinner response, the rotational velocity at (1) showed a positive spinner response indicating that steam is flowing up and the well is at low flow condition (higher enthalpy fluid). The stationary spinner data at (2) showed a more negative to positive velocity indicating both upward and downward fluid motion which was still at the cased portion of the well. The spinner detects the steam that is flowing up and liquid flowing down. However, the spinner data at (3) showed a positive spinner velocity and the pressure profile indicates steam is flowing up. The pressure profile does not show any evidence of liquid which is interpreted to mean that the liquid from (2) was flowing down the sides of the casing and was not detected by the spinner since the steam occupied the majority of the space. The inflow of liquid is suspected to be coming from a casing break at 487 m MD.

The spinner's stationary rotational velocity is showing both positive and negative responses at (4) which suggests that counterflow is occurring. The bottomhole pressure also changed during the downlog and uplog which were 10.0 MPa and 10.7 MPa, respectively, without any surface manipulations suggesting transient condition of the well.

2.2.2 Matalibong 06 (Mat-06)

Mat-06 is a shallow production well in the Tiwi field that has been producing superheated or saturated steam since it was drilled in 1990. In 2010, a flowing PTS survey was conducted and the dataset was successfully matched, as shown in Figure 10, by establishing steam zone entries with properties summarized in Table 3.

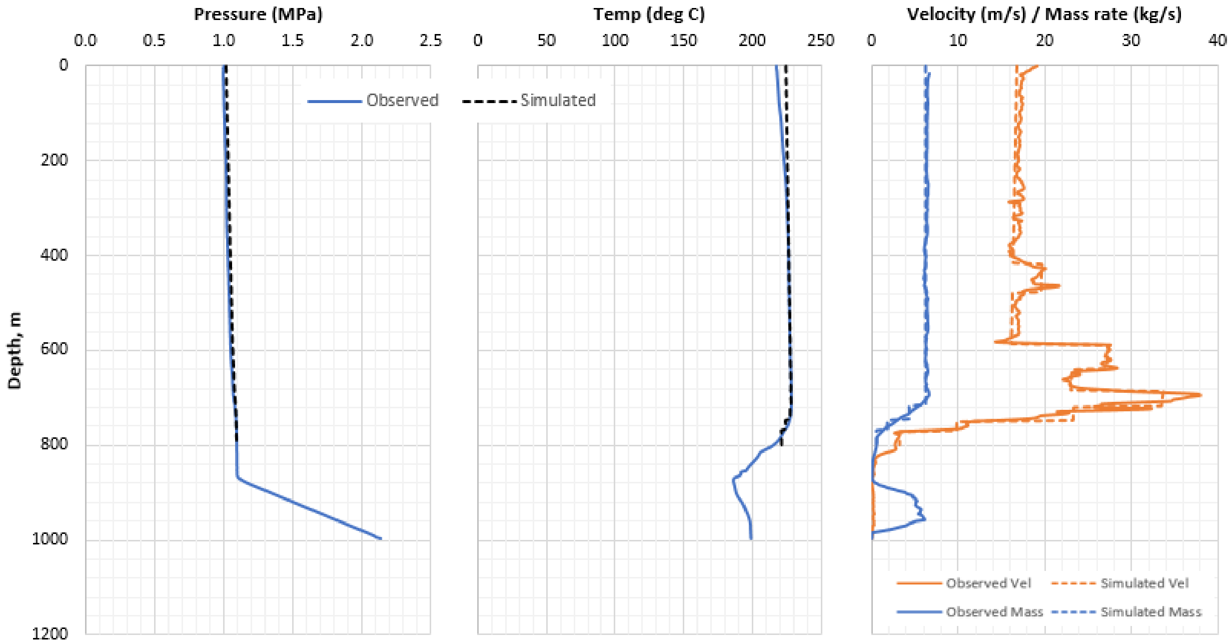

Figure 10. 2010 PTS Analysis of Mat-06 (Observed vs Simulated).

Table 3. 2010 Feedzone Properties of Mat-06

Depth (m MD)	Mass rate (kg/s)	Enthalpy (kJ/kg)
716	1.9	2,896
747	2.5	2,896
768	1.3	2,884
799	0.6	2,873

During the 2010 survey, the well's static liquid level was detected at 869 m MD which is 70 m below the deepest steam entry at 799 m MD. The liquid level in this area of the production field has been continuously monitored because of its rising trend due to a combination of increasing deep reservoir pressure and declining steam zone pressure (Menzies, *et al.* 2009). This phenomenon has caused several Matalibong wells to turn two-phase (from all-steam production) as the steam zones are being "flooded". By the end of 2018, Mat-06 was one of the two remaining all-steam wells in the area due to its relatively shallower steam zone depths.

On December 30, 2018, Tropical Depression "Usman" hit Tiwi with record rainfall, causing landslides that damaged some of the production and injection piping and required shutting in of most of the production wells. In early 2019, Mat-06 was re-discharged and TFT sampling indicated intermittent brine production from the well, which was not expected.. A flowing PTS survey was therefore run in March 2019 to provide insights on the downhole conditions, especially the liquid level in the wellbore. Per standard procedure, 4 logs (2 uplogs and 2 downlogs) were conducted. The pressure profiles from the 2019 and 2010 surveys are shown in Figure 11.

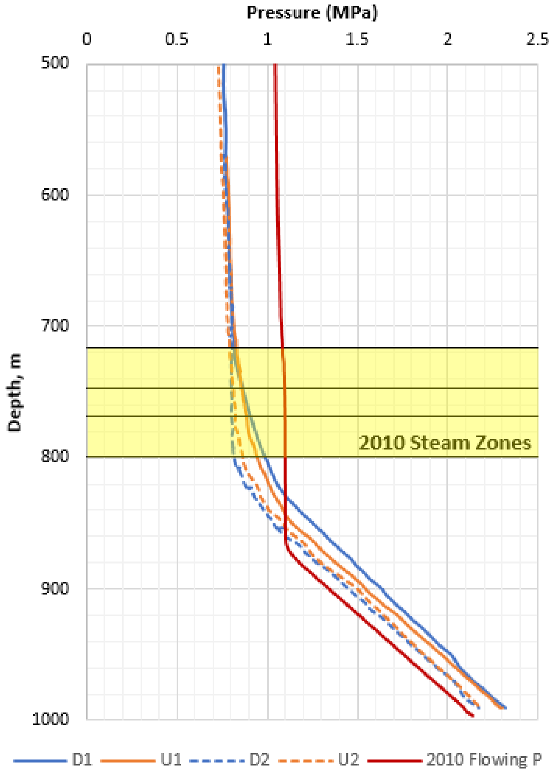

Figure 11. 2010 and 2019 flowing pressures of Mat-06.

The pressure surveys indicate that the liquid level in the wellbore has noticeably increased relative to the 2010 depth, due to an increase in deep liquid pressures (possibly due to the shutdown) and lowering of the FWHP from 1.0 MPa to 0.7 MPa. It is further remarkable that the four logs registered different pressure profiles wherein the 2nd downlog and uplog (D2 and U2) suggest that all the identified feedzones from the 2010 model are still producing steam while the existence of a two-phase gradient during the 1st downlog and uplog (D1 and U1) is indicative that the well is producing brine during this period. It is therefore apparent that the liquid level is within the established steam zones of Mat-06, which would explain its intermittent brine production. It is interesting to note that this fluctuating behavior was captured during the PTS survey that only lasted for less than 2 hours.

Figure 12. 2010-2019 Production of Mat-06.

The potential reduction in steam rate of Mat-06 when it is producing brine is not yet clearly established since the steam rate data obtained during the first half of 2019 continue to suggest stable steam production from the well since 2010 (Figure 12). However, the validated accelerated rise in liquid level remains to be a concern and strategies are continuously being developed to mitigate this issue as part of resource management.

2.2.3 Bulalo 96 (Bul-96)

Drilled in 1993, Bul-96 is a production well in the Mak-Ban field that has known production fluctuations similar to Bul-91. On December 4, 2013, a PTS survey was conducted and based on the FWHP data (Figure 13), the well appears to be stable during the conduct of the PTS survey. However, it was particularly interesting that there were two distinct repeatable profiles observed during the survey indicating the presence and absence of inflows.

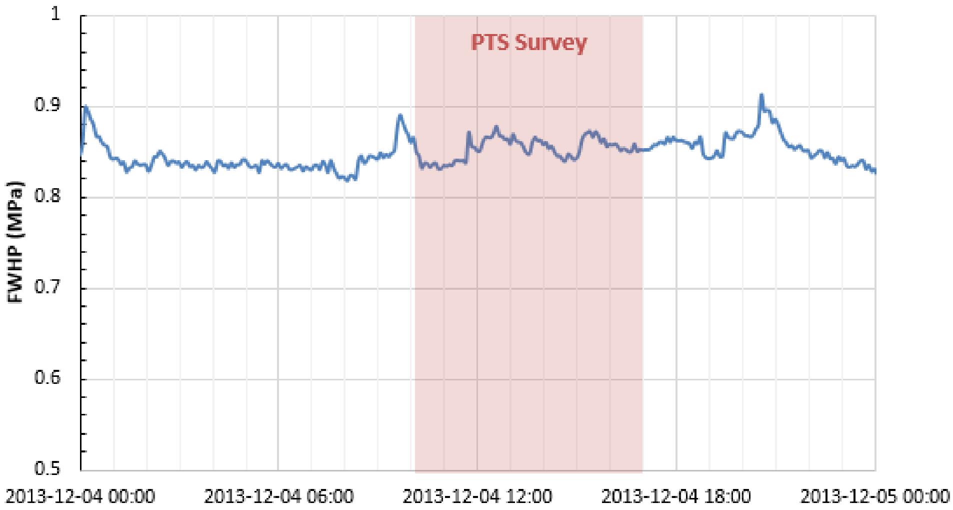

Figure 13. Hi-freq FWHP data of Bul-96 on Dec 4, 2013.

The first profiles (D1 and U1) showed five feedzones at 853 m MD, 1,341 m MD, 1,371 m MD, 1,524 m MD, and 1,828 m MD with enthalpies of 2,791 kJ/kg, 1,023 kJ/kg, 930 kJ/kg, 1,093 kJ/kg, and 1,104 kJ/kg, respectively. The second profiles (D2 and U2) only showed the shallowest feedzones from the first profiles at 853 m MD and 1,341 m MD with enthalpies of 2,791 kJ/kg and 1,023 kJ/kg, respectively. The deeper zones are suppressed during the second "condition" as the wellbore pressures are higher. The feedzones at 1,341 m MD – 1,524 m MD with relatively low enthalpy is causing the instability in the well performance.

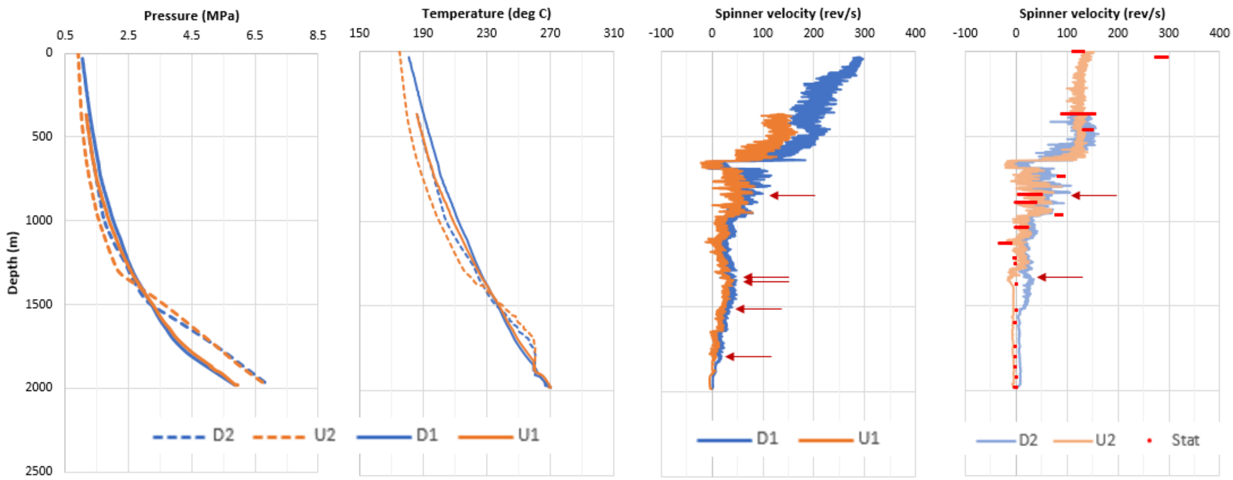

Figure 14. 2018 PTS survey of Bul-96.

2.2.4 Kapipihan 29 (Kap-29)

Drilled in 1985, Kap-29 is a "huff and puff" production well in the Tiwi field and characterized by being able to produce for a limited production time, followed by a recovery period prior to being re-stimulated to flow. A PTS survey was conducted on November 4, 2013 to try to determine the cause of the huff and puff behavior of the well. At the time of the survey, the well was only producing 4 kg/s of steam at a constant FWHP of 0.91 MPa and it was therefore expected that the survey results would be relatively simple to interpret. However, the results from the survey showed very different profiles for all the uplog and downlog runs, as shown in Figure 15.

The two downlogs showed quite different and unusual pressure gradients. Downlog 1 (D1) showed pressure discontinuity at 645 m MD where the pressure suddenly increased from 0.91 MPa to 1.96 MPa. Downlog 2 (D2) showed pressure reversal at 400 m MD and liquid gradient from 800 m MD to TD. The pressure reversal is obviously not a reservoir pressure condition but indicates dynamic changes are occurring in the wellbore while the survey is being conducted.

Similar with the downlogs, both uplogs also showed different profiles. Uplog 1 (U1) showed a steam gradient from the wellhead, followed by a two phase gradient starting at 463 m MD; liquid gradient starting at 673 m MD; and steam gradient from 892 m MD to total depth. Uplog 2 (U2) showed a steam gradient to what appears to be a "liquid" gradient until 600 m MD at 1.70 MPa and then changed to steam gradient at 0.9 MPa then a liquid gradient again from 800 m MD to 958 m MD total depth.

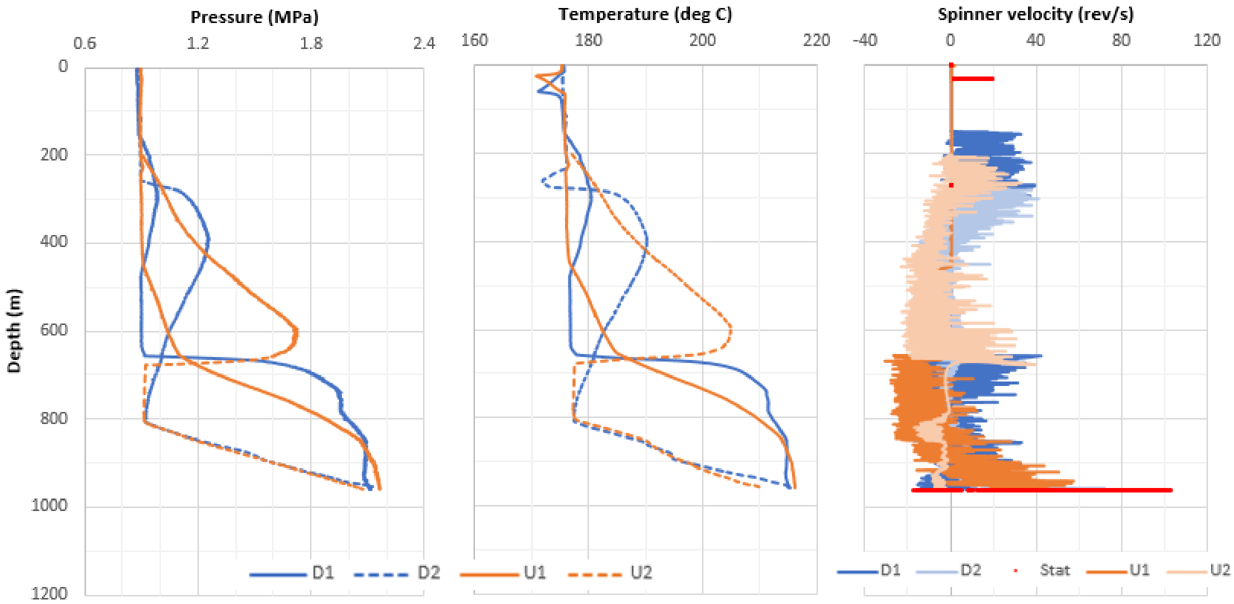

Figure 15. PTS survey of Kap-29 in 2013.

The results indicate that although the well was producing a relatively small but stable steam flow at the surface, with a steam column down to 150 m MD, the production actually appears to be from a 215 deg C liquid dominated zone at 958 m MD. However, the liquid water only has enough energy to flow up inside the casing, as suggested by the positive spinner response at the bottom of the well but then flows down again, as suggested by the negative spinner response during downlogs. The well is therefore acting like a "separator" and only the flashed steam is reaching the surface and the PTS survey was able to measure the transient responses associated with the dynamic behavior of the fluids.

3. CONCLUSIONS AND RECOMMENDATIONS

In the Tiwi and Mak-Ban geothermal fields, PTS surveys have proven to be very useful in characterizing downhole conditions and behavior of geothermal production wells which may be in either steady-state or transient conditions. As demonstrated by the case studies of Bar-11 and Bul-99, where both wells were at steady-state condition during the conduct of the surveys, PTS analyses could lead to identification of opportunities resulting to improved well productivity.

In interesting cases, PTS surveys may capture transient well behaviors characterized by changing profiles with time. For the case of Bul-91, very unstable spinner responses have been measured in regions of the well that suggest counterflow is occurring. In other wells, such as Mat-06 and Bul-96, there are significant changes in the PTS profiles from one survey to the next as the well transitions from one hydraulic state to another. Still others (e.g. Kap-29) have profiles that are in a complete transient state such that it is very difficult to interpret physically how the condition was achieved, given the thermodynamic properties of the fluid. In some of these surveys, quantitative analysis may not be possible but the surveys still provide qualitative information that helps in understanding the well's characteristics.

The wellbore simulation software which is normally used for mass and energy balance and pressure drop calculations to analyze PTS data assumes steady state conditions and this has limitations for unstable wells which exhibit transient state behaviors. PGPC has recently used a wellbore simulation software that can solve wellbore steady state and transient state solutions to analyze two production wells in Mak-Ban and obtained good results. Hence, it is recommended to explore other simulation software/tools that can solve transient state behaviors and provide additional insights into the dynamic conditions captured by the PTS surveys of the unstable wells.

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