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# Characteristics of the Matalibong Steam Zone, Tiwi Geothermal Field, Philippines

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## ABSTRACT

The Tiwi geothermal resource was initially liquid-dominated but pressure drawdown in the early years of production resulted in the formation or expansion of a shallow steam zone in Naglagbong and later in the Matalibong, Kapipihan and Bariis sectors to the west. The Naglagbong steam zone was quenched by the influx of groundwater in the 1980's but the steam zones to the west have persisted and continue to provide a significant percentage of the overall steam production at Tiwi.

Production from the steam zones was initially thought to be saturated steam but in the mid-1990's corrosion in the surface facilities was found to be associated with volatile chloride production, suggesting that superheated steam was being produced. Further investigation indicated that 15 of the Matalibong Steam Zone wells were producing steam with up to 35°C of superheat, and this had probably started to occur in the late 1980's.

Since the mid-1990's, the conditions in some of the Matalibong Steam Zone wells have changed due to a rising steam-water interface which has effectively reduced the volume of the steam zone by flooding some of the deeper production zones. This in turn has resulted in a reduction in enthalpy and steam production from four wells while two others have stopped producing due to enthalpy decline. However, 10 wells with shallow permeable zones continue to produce either saturated or superheated steam, with Mat-22 and -23 still producing >25kg/s steam (>11MW) each after 15 to 20 years of continuous superheated steam production.

The relatively low production declines seen in both the saturated and superheated steam wells in the Matalibong Steam Zone and the low pressure decline indicates that recharge must be occurring to the steam zone. This is considered unusual as superheated steam production is usually a sign of a declining resource where fluid reserves are being depleted. The recharge fluid appears to be a combination of boiled reservoir water, which originates close to the Bariis upflow, and influx of groundwater from the sides and possibly top of the reservoir, as indicated by the presence of Tritium in the produced steam. As this water and steam move through the hot rock above the steam-water interface, it boils and is superheated before being produced. This appears to be the most reasonable explanation for the sustainability of the superheated steam zone considering that the liquid level is now <120m below the production zones in the remaining superheated steam production wells.

The focus of reservoir management is now to stabilize the steam water interface so that the existing wells will continue to produce steam and possibly to induce the steam-water interface to move deeper, which could allow wells with deeper production zones to again produce saturated or superheated steam.

## 1. INTRODUCTION

The Tiwi Geothermal Field is located on the northeast flank of Mt. Malinao in Albay Province, Philippines, approximately 350km southeast of Manila (Figure 1). The field has a productive area of 12 square km (Figure 1) and is divided into four geographic sectors: Naglagbong (Nag), Kapipihan (Kap), Matalibong (Mat) and Bariis (Bar). The location of the Matalibong Steam Zone, which is the focus of this paper, is also included on Figure 1 as well as the approximate location of the Bariis Upflow Zone.

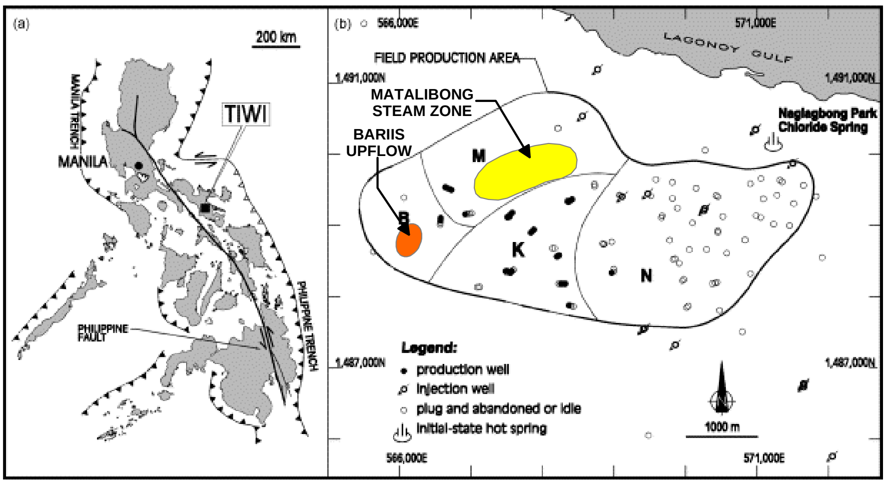


**Figure 1: Location of the Tiwi Geothermal Field and Main Production Sectors (N=Naglagbong; K=Kapipihan; B=Bariis; M=Matalibong)**

The history of the Tiwi development and analysis of the resource changes over time have been presented in a number of previous papers and reports (Alcaraz, et al, 1989; Barker, et al., 1990; Gambill and Beraquit, 1993; Sugiaman, et al., 2004; Sunio, et al., 2004 and 2005; Menzies, et al., 2009).

The first major step in the development of Tiwi was the successful completion of the deep discovery well, Naglagbong-1, by Philippine Geothermal, Inc (now Chevron Geothermal Philippines Holdings, Inc - CGPHI) in June 1972. This was followed by continued development and delineation drilling, leading to the start of commercial operation on May 15, 1979, when the first National Power Corporation (NPC) 55MWe unit was commissioned. By April 1982, the installed capacity had increased to 330MWe, with the installation of 6 x 55MWe units in three power plants (Plants A, B and C) located in the Nag sector. This was a very aggressive development schedule, even by today's standards, and was dictated by the need of the Philippine Government to reduce dependence on imported oil at a time when oil prices and power demand were rising significantly (Alcaraz, et al., 1989).

The steam production for the power plants was initially provided by wells drilled in the eastern Nag sector of the field (Figure 1) and by the time the final unit was commissioned, there was sufficient steam under wellhead to provide for a 25% buffer. However, as production increased with the commissioning of the six turbine-generator units, reservoir pressures declined by over 4MPa by 1983. With the decline in pressure and associated drop in water level, an extensive steam zone formed in the Nag sector and most of the wells started producing dry steam. However, the pressure decline also allowed the influx of cool, dilute groundwater into the reservoir, as indicated by a decrease in the chloride content of the produced brine (Gambill and Beraquit, 1993). The groundwater moved rapidly through the Nag sector and as early as 1982-83, it was affecting most of the Nag production wells, based on chloride dilution trends and enthalpy declines. It also contributed to calcite scaling both in the wellbore and formation as it mixed with reservoir fluid. With both cooling and scaling processes occurring, Nag steam production reduced significantly (Barker, et al., 1990) and it became necessary to drill new make-up production wells progressively to the west in the Kap, Mat and Bar sectors of the field (Figure 1).

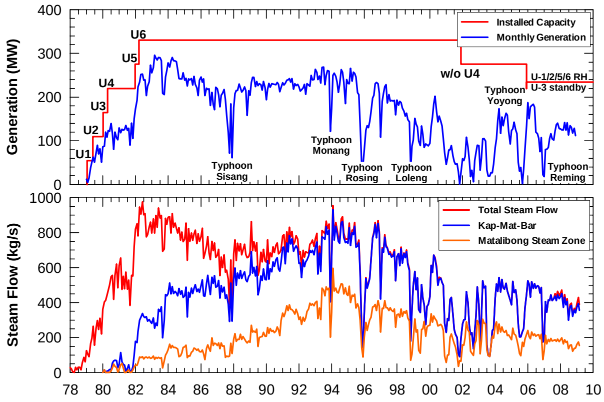


**Figure 2: Tiwi Generation and Steam Production History**

Drilling in the western sectors of the Tiwi field began in the Kap sector as early as 1979 as it was recognized that additional production area would be required to sustain steam production over the long term. Drilling in the areas to the west was more challenging than in the Nag area due to the terrain and it was therefore necessary to use multi-well pads and directional drilling techniques to reduce development costs. By 1984, over 50% of the total field production was coming from the Kap-Mat-Bar sectors of the field and this had increased to 100% by the mid-1990's (Figure 2).

Between 1979 and 1995, 76 wells were drilled in the western sectors of Tiwi, to depths ranging from 530m below sea level (bsl) to 2,375m bsl. The average depth was just over 1,220m bsl, which is about 1,525m total depth. Of the 76 wells drilled, 43 (56%) initially produced dry steam, indicating that an extensive steam cap was present in the western sectors, particularly in Kap and Mat.

Since 1995, only four additional production wells have been drilled in Tiwi; Bar-10 in 1997, which was affected by acid production, Bar-08 re-drill in 2006 and Bar-11/Kap-35 in 2008. These wells were all completed into the deeper, liquid dominated reservoir and produce both steam and brine.

The thermodynamic conditions at shallow reservoir depths in the western sectors were close to saturation (boiling-point-depth) conditions, indicating that there may have been pre-existing two-phase or steam zones in the western sectors prior to production although they were not believed to be extensive. However, the pressure drawdown that occurred in response to initial Nag production was sufficient to initiate boiling, leading to the formation or expansion of steam dominated conditions at shallow depths. Expansion of the steam zones continued, both laterally and with depth, as pressure drawdown increased in response to moving production further west. It is also apparent that the vertical permeability must be relatively high as the steam and water have segregated, resulting in steam dominated conditions at shallow depths, underlain by liquid water. Only in the Bariis upflow area does there appear to be an extensive two-phase zone.

The steam zones that formed in the western sectors in response to pressure drawdown provide a significant proportion of the overall steam production for the Tiwi power plants. The Matalibong Steam Zone, which is the focus of this paper, is the main steam production area and is of particular interest due to the number of wells that have been producing superheated steam for the past 15 to 20 years and continue to do so.

## 2. MATALIBONG STEAM ZONE

The Matalibong Steam Zone (Figure 3) covers a relatively small area of approximately 0.8 square km in the North and Central Matalibong sectors of the field and is located within the "outflow" region from the Bariis upflow, located further to the west (Figure 1). Although the production area is small, the 18 wells drilled in this zone have made a major contribution to the steam production requirements of the Tiwi power plants over the years, resulting in the formation of a low pressure "sink" in this area within the steam liquid zone.

The 18 production wells (Figure 3) were drilled between 1980 and 1993 and were assumed to be producing saturated steam. However, in the early to mid-1990's it was becoming apparent that some of the wells were producing superheated steam. This was first indicated by the chemistry data (Powell and Aquino, 1993; Sunio and Molling, 2005) as significant increases in chloride (from 4,800ppm to 16,000ppm) concentrations were occurring in discharge fluids from two-phase wells. The possibility that these high concentrations were due to mixing of produced liquid with superheated steam in the wellbore was proposed as a possible explanation (Powell and Aquino, 1993). It was also noted that some of the steam wells were producing volatile chlorides and boron and this was leading to corrosion in the wells and surface facilities.

Experience from The Geysers (California) indicated that volatile boron and chloride production was normally associated with superheated steam production (Molling and Villaseñor, 1999) and a review was therefore made of the production data from the Tiwi wells (Lim, 1997) to check if superheating was occurring.

Calorimeter measurements had been taken from the early 1990's to check discharge enthalpy but no significant analysis of the data was made until the mid-1990's when corrosion was becoming an issue. The review of the data indicated that 15 of the 18 Matalibong Steam Zone wells (Kap-5, -14, -34, Mat-3, -4, -5, -6, -7, -8, -9, -10, -22, -23, -27 and -28) as well as Kap-16, were producing steam with up to 35°C of superheat and this may have started in the late 1980's. As of early 2009, eight wells (Kap-12, -14, Mat-4, -6, -9, -10, -22 and -23) continue to produce superheated steam from the Matalibong Steam Zone.

## 2.1 Overall Production Characteristics and Recharge

Figure 2 presents the overall field generation and overall steam production history for Tiwi as well as the steam production from the Kap-Mat-Bar sectors and from the 18 Matalibong Steam Zone wells as a function of time. Matalibong Steam Zone production began in 1980 when Kap-5 was brought on-line and then increased as new wells were added; reaching a peak of 500kg/s in 1994, which was ≈55% of the total Tiwi steam production (880kg/s) at that time.

From 1994 through to 2004, there was a significant reduction in overall steam production and generation due to the following factors:

- "natural" decline in steam supply from the "base" wells drilled prior to 1995;
- lack of make-up well drilling after 1995. Only four make-up wells (one re-drill and three new wells) were drilled to provide "new" steam from 1997 to 2009;
- deterioration of the power plants, resulting in a significant increase in steam usage rates and therefore lower generation;
- plant shutdowns due to plant deterioration, typhoon damage from Typhoons Rosing (November, 1995) and Loleng (December, 1998) and rehabilitation activities (2000-2004).

Since 2004, production has generally stabilized as the rehabilitated plants have come back on-line with improved steam efficiency and generation dispatch has also improved. However, Typhoons Yoyong (December, 2004) and Reming (November, 2006) were responsible for extended shutdowns that were required to repair cooling towers and transmission lines.

The wells in the Matalibong Steam Zone have been affected by some of these issues, with four of the 18 wells no longer able to produce as of early-2009. Of the remaining 14, eight continue to produce superheated steam and two produce saturated steam. In 2009, the total production is 165kg/s of steam, which is still 40% of the total Tiwi production of 420kg/s (Figure 2). Hence, the Matalibong Steam Zone continues to be an important source of production for the Tiwi power plants.

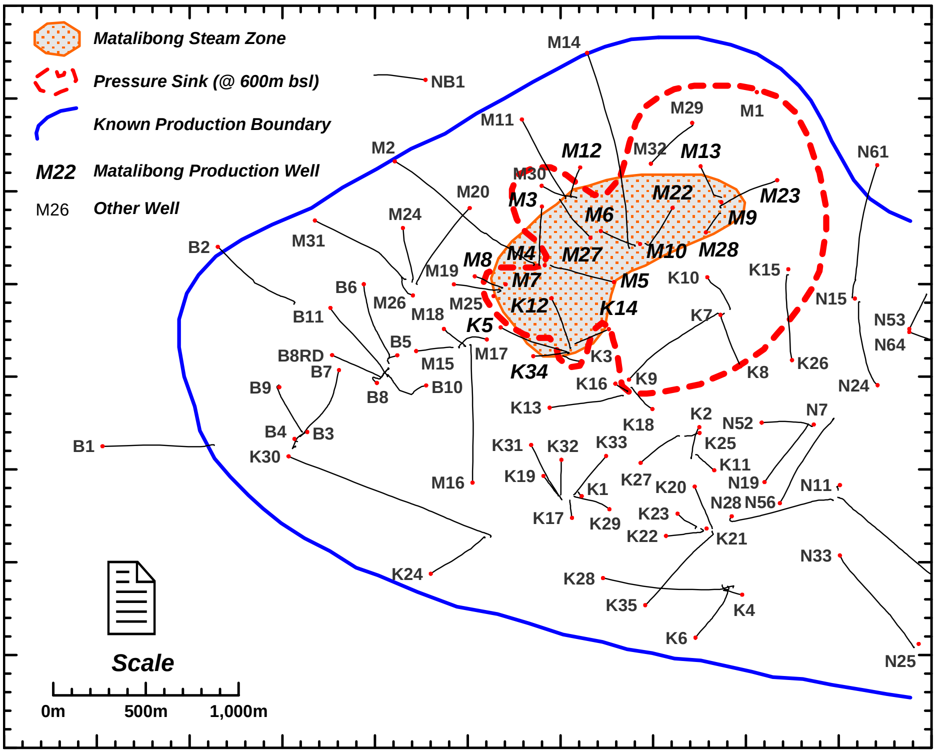


**Figure 3: Matalibong Steam Zone and Production Well Locations**

The decline in steam flow from the Matalibong wells since the mid-1990's is due to the following factors:

- Four of the production wells are no longer producing due to enthalpy decline (Mat-12 and Mat-28) or mechanical reasons (Mat-5 and Mat-7). This has resulted in a loss of production of 55kg/s;
- Four of the wells (Kap-5, Mat-3, -13 and -27) are still producing but with significant drops in steam production following enthalpy declines, which are believed to be associated with a rising steam-water interface (see next section). This has resulted in a loss of production of 35kg/s;
- The remaining loss of 250kg/s is due to decline in production from the remaining 10 wells that continue to produce saturated (Kap-34 and Mat-8) or superheated (Kap-12, -14, Mat-4, -6, -9, -10, -22 and -23) steam. This is equivalent to an average decline rate of 4.5% exponential since 1994, which is considered to be relatively low.

The moderate production decline and the low decline in steam zone pressure since 1995 (see next section) suggests that recharge must be occurring to the steam production wells, including the superheated steam wells. This runs counter to the conventional wisdom that superheated steam production either suggests "dry-out" has occurred due to a lack of fluid recharge or there is extreme boiling occurring in the vicinity of the wells due to very high pressure drops, which would suggest poor permeability. Neither of these conditions applies to the Matalibong Steam Zone.

There is evidence that at least some of the steam produced by the Matalibong Steam Zone wells originated as groundwater that has entered the reservoir, probably from the sides or the top. This is based on the results of repeat Tritium surveys conducted in Tiwi since the 1980's to monitor how groundwater is moving through the reservoir. Survey results indicate that Tritium was first observed in the North Mat area in the early 1990's (Powell and Aquino, 1993), which would coincide with the time of maximum pressure drawdown. The groundwater is believed to enter the hot rock above the steam-water interface, where it boils and is superheated before being produced. The other potential source of recharge is the deep liquid, which probably originates close to the Bariis upflow where boiling can occur at the steam-water interface. The resulting two-phase mixture or steam then migrates into the overlying steam zone where it is heated and produced.

### 2.2 Pressure, Temperature and Steam-Water Interface Changes

Shut-in pressure and temperature surveys have been conducted in the 18 production wells and in surrounding wells on a regular basis and the measured data are used to show how reservoir conditions have changed with time in the Matalibong Steam Zone. The downhole survey data were reviewed and the interpreted changes in pressure at 600m bsl and 1,000m bsl are plotted in Figure 4. The 600m bsl datum level was chosen as it is near the top of the reservoir and within the steam zone while the 1,000m bsl datum is within the underlying liquid reservoir.

Prior to production, the measured temperatures at the 600m bsl datum were close to 290°C while the reservoir pressure was 7.6MPa.g (Figure 4). These conditions are very close to saturation, which suggests there was probably an existing two-phase or steam zone at this level in the reservoir before significant production began. Note that in this area of the field, the reservoir top is also locally shallow, which would tend to aid convection and lead to higher localized heat flow, which would further increase the possibility of a steam zone forming under natural conditions.

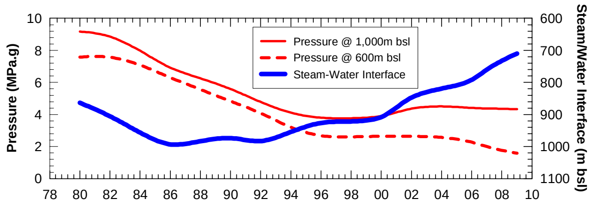


**Figure 4: Pressure Changes at 600m bsl and 1,000m bsl and Calculated Elevation (m bsl) of the Steam-Water Interface**

With the increase in production from the western sectors from the early 1980's to the mid-1990's, pressures in the Matalibong Steam Zone at 600m bsl declined at a relatively constant rate of 0.35 MPa/year, resulting in an overall drawdown of 4.8MPa (Figure 4) to a pressure of 2.75MPa.g. The corresponding saturation temperature of 230°C has been measured in the wells but is not believed to reflect the true rock temperatures. Away from the wellbore, the rock temperatures are likely to be higher, either because the rock is "dry" or the system acts like a two-porosity system, where the conditions in the matrix rock are quite different from the fractures that are in contact with and provide the fluid to the well. The matrix rock can then provide the heat source for superheating the steam prior to production. The data from Mat-23 presented in the next section show that there is significant differences in temperature between flowing and shut-in conditions in superheated steam wells, with the flowing temperature being significantly higher. It is therefore believed to better reflect the actual rock temperature.

In the deep liquid reservoir, as measured at 1,000m bsl, the overall drawdown over the same period of time was 5.5MPa (Figure 4). This difference in drawdown between the steam zone and the underlying liquid zone had the effect of lowering the elevation of the steam-water interface from 860m bsl to approximately 990m bsl (Figure 4) by 1986, where it remained reasonably stable until the early to mid-1990's. This effectively increased the volume of the Matalibong Steam Zone and allowed wells with deeper production zones to produce saturated or superheated steam rather than the underlying water.

With the significant reduction in production from 1994 through to 2004, deep liquid pressures initially stabilized and then increased over time while shallow steam zone pressures also stabilized (Figure 4).

Since 2004, overall steam production has increased and stabilized at 400 and 500kg/sand this has resulted in some further reduction in average steam zone pressure (Figure 4) to about 2.1MPa.g but the deep liquid pressures have remained relatively stable, possibly due to injection pressure support and/or recharge from groundwater.

The relative change in deep liquid and shallow steam zone pressures since the mid-1990's has resulted in a continuous rise in the steam-water interface (Figure 4) from 945m bsl in 1995 to 700m bsl in 2009. This is a significant change and downhole pressure/temperature logging data confirm that it has caused "flooding" of deeper production zones in some wells. These zones had previously produced dry or superheated steam but when the flooding occurred, they quickly changed from producing at steam enthalpies of 2,800+kJ/kg to liquid enthalpies of 1,160kJ/kg. As mentioned in the previous section, this has occurred in a number of the Matalibong Steam Zone production wells (Kap-5, Mat-3, -13 and -27) over the past few years, causing their steam production to decline, while Mat-12 and Mat-28 have ceased flowing altogether.

A similar situation has been reported to occur at The Geysers (Wright and Beall, 2007), where McKinley-13 was found to have a water level at 2,240m caused by pooling of water from surrounding injection wells. Cooling was also occurring in the area around McKinley-13 but the temperatures at and below the water level were still at saturation. The plan was therefore to re-direct injection to other areas of The Geysers, which would allow the water level to fall, resulting in boiling and possibly renewed steam production from a flooded deep zone in the well. Injection was reduced and it was found from subsequent PTS logs and production data that the liquid level had dropped and the drowned deep entries resumed production of saturated steam (Wright, 2009).

### 2.3 Well Mat-23, Production and Downhole Data

Mat-23 is one of the most successful production wells in the Tiwi field and is located on the northern edge of the Matalibong Steam Zone (Figure 3). Mat-22, which is located in the same area, has very similar characteristics and production history and between the two of them, they still supply sufficient steam for over 20MW power production.

Mat-23 was completed in 1992 to a total depth of 1,620m bsl but was found to only produce from the shallow steam zone. The production data from Mat-23 (Figure 5) show that the well initially produced over 76kg/s steam at a wellhead pressure of 1.8MPa.g in 1992 and is still capable of producing over 25kg/s steam at a wellhead pressure of 0.9MPa.g. The decline in production over time is consistent with an exponential decline rate of 5.1%, which is considered to be relatively low, considering that it has been producing superheated steam over most of its productive life. Both the flow from the well and the wellhead pressure have been reasonably constant since 2007.

The wellhead superheat data show there was an increase from 10 to 34°C from 1994 to 2004 and it has then remained reasonably constant since then, although recent data suggest it may have declined to 30°C over the past year.

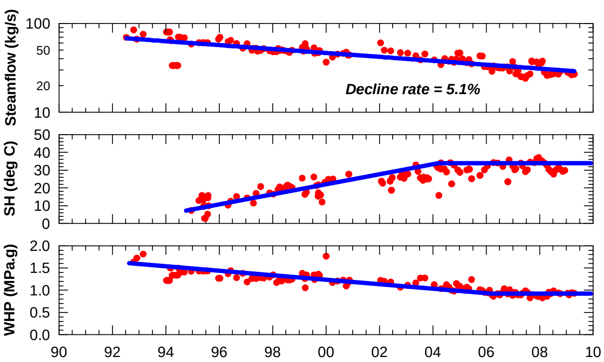


**Figure 5: Production History, Mat-23**

Downhole surveys were recently conducted in Mat-23 to provide additional information and insights into the well behavior under both flowing and shut-in conditions. The data are from a flowing Pressure-Temperature-Spinner (PTS) log conducted by Century Resources on 26 November, 2008 and a shut-in Pressure-Temperature (PT) log conducted using a Kuster "K10" downhole tool on 31 October, 2008.

The measured pressure and temperature data from the flowing and shut-in logs are plotted in Figure 6, along with the saturation temperatures calculated from the flowing and shut-in pressure data and the calculated superheat in the wellbore under flowing conditions.

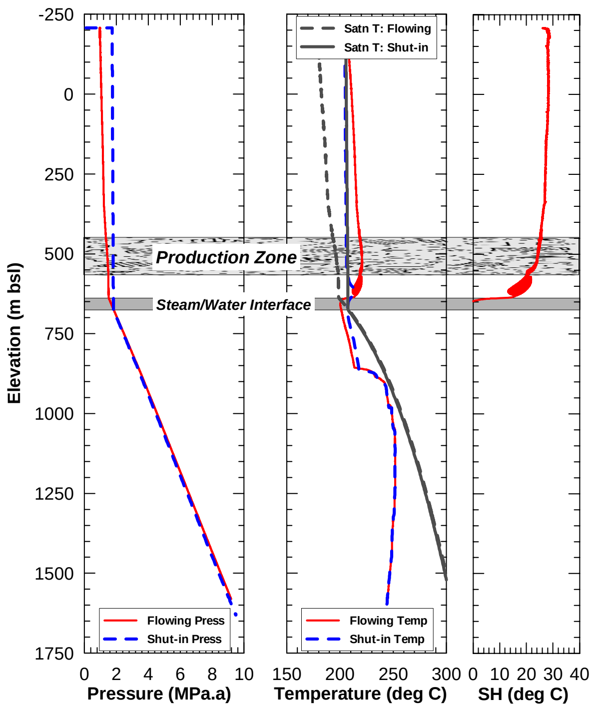


**Figure 6: Downhole Flowing and Shut-in Surveys from Mat-23, Including Calculated Superheat Profile**

Analysis of this data plus the spinner data under flowing conditions (not shown) indicates the following:

- The well produces from between 450 and 565m bsl, with the major zone located at 548m bsl. Below the production zones and above the steam-water interface, there appears to be a "stagnant" zone with no flow and there is also no flow from the underlying liquid reservoir;
- A maximum temperature of 221°C is measured from the flowing log at 533m bsl and the difference between the measured temperature and the calculated saturation temperature (197°C) indicates that the produced steam has 24°C of superheat in the wellbore (Figure 6), while at the wellhead, the superheat is 27°C;
- The steam-water interface under flowing conditions occurs at 650m bsl, indicating that the major production zone is 100m above the steam-water interface;
- The steam-water interface from the shut-in PT log is at 683m bsl, which is in reasonable agreement with the calculated interface location shown in Figure 4 under similar conditions;
- The temperature below the steam-water interface is less than the saturation temperature for both the flowing and shut-in logs, indicating that boiling is not occurring at the liquid surface and it is therefore not possible for the

liquid at this location to be recharging the overlying steam zone;

- Under shut-in conditions, the measured temperature opposite the production zone (206°C) is at saturation conditions and well below the temperature measured under flowing conditions (221°C). Hence, the shut-in temperature is being controlled by the local fluid pressure and is not measuring the true rock temperature, which is probably closer to the flowing temperature;

- There is some indication of superheating conditions above the steam-water interface under shut-in conditions as the measured temperatures are about 6°C hotter than the corresponding saturation temperatures.

## 3. CONCLUSIONS

The Matalibong Steam Zone has been producing steam for the Tiwi power plants since 1980, with peak production of 500kg/s in 1994 and it continues to provide approximately 40% of the overall steam production from the field in 2009.

An unusual feature of the Matalibong Steam Zone is the number of wells that have or are still producing superheated steam and the relatively stable performance of these wells. There is no indication that the superheated steam production is associated with a depleting resource or due to excessively high pressure drops in the vicinity of the wells. In fact, there is evidence that recharge has been occurring to the steam zone from groundwater sources since the early 1990's and it is also likely that boiling of the underlying liquid reservoir near the Bariis upflow is also providing recharge.

A number of wells that previously produced superheated steam have been affected by enthalpy declines caused by a rising steam-water interface. This has flooded deeper production zones that previously produced steam. In four of the 18 Matalibong Steam Zone wells, this has lead to reduced steam production, while two other wells have ceased flowing due to enthalpy decline. The overall loss in production due to these wells is estimated to be 75kg/s.

Downhole survey data from Mat-23 confirm that the steam-water interface is now relatively close to the production zones in the well. Hence the production from the superheated and saturated steam wells will be under threat if the steam-water interface continues to rise.

Understanding and stabilizing the steam-water interface is an important priority for reservoir management in the area of the Matalibong Steam Zone, considering the amount of steam production that is under threat if the steam-water interface continues to rise. If deep pressures can be reduced and/or steam pressures increased, this may deepen the steam-water interface and allow wells with deeper production zones to produce steam again, in a similar way to that reported for The Geysers. However, this may require shutting in of some of the steam wells to get the steam pressures to increase.

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