CORRELATION AND MODELING OF RESERVOIR PRESSURE CHANGES IN THE TIWI GEOTHERMAL FIELD, REPUBLIC OF THE PHILIPPINES

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ABSTRACT

Deep liquid reservoir pressure changes in the Matalibong sector of the Tiwi Geothermal Field have been monitored on a continuous basis since November 2005 by using capillary tubing systems installed in Mat-25, Mat-29 (March 2007 to April 2008) and Mat-30 (since July 2008). Monitoring of the Mat-25 and Mat-30 wellhead pressures provides similar information on the overlying steam reservoir.

With the precision provided by continuous pressure monitoring, the reservoir pressure trends in the deep liquid and shallow steam reservoir zones have been well defined. Analysis of the deep liquid response has indicated strong interaction between the production area and injection wells located approximately 2km to the north. This was not expected, considering the distances involved and the locations of the observation wells within the production area. However, the noted interaction is consistent with other evidence, such as changes in discharge characteristics, results from tracer tests and changes in micro-gravity, collected during the same time period.

Understanding the noted pressure responses is important to resource management in the Matalibong area as a rising liquid-steam interface has negatively affected the productivity of steam wells. This is expected to continue unless changes are made and knowing that injection is a factor in this process makes it possible to design a reservoir management strategy to mitigate this. To help with the development of this strategy, the deep reservoir, including both the production and injection areas, has been modeled using "Saphir©" well test software. After successfully matching the measured pressure responses, the resulting model is being used to provide forecasts of how the deep pressure trend will change in response to various production/injection scenarios.

1. INTRODUCTION

The Tiwi Geothermal Field is located on the northeast flank of Mt. Malinao in Albay Province, Philippines, approximately 350km southeast of Manila. The field has a known productive area of 12 km^2 (Figure 1) and is divided into four geographic sectors: Naglagbong (Nag), Kapipihan (Kap), Matalibong (Mat) and Bariis (Bar). The area of focus for this paper, as highlighted in Figure 1, includes the Matilibong production sector and the injection wells located to the north.

The history of the Tiwi development and analysis of resource changes over time have been well presented in a number of previous papers (Alcaraz, et al, 1989; Barker, et al., 1990; Gambill and Beraquit, 1993; Sugiaman, et al., 2004; Menzies, et al., 2010a; Menzies, et al., 2010b), including discussion of the many challenges that have been overcome or managed in producing this resource. Commercial operation began on May 15, 1979, when National Power Corporation (NPC) commissioned the first 55MWe turbine generator and over the next three years, generation capacity increased to 330MWe, with 6 x 55MWe units installed in three power plants (Plants A, B and C) located in the eastern Naglagbong sector of the field.

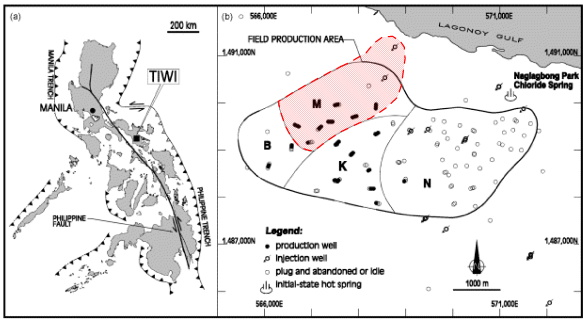

Figure 1: The Tiwi Geothermal Field and the Production Sectors (N=Naglagbong; K=Kapipihan; M=Matalibong; B=Bariis)

From 2002 to 2005, the units in Plants A and C were rehabilitated and generation capacities were increased from 55MWe to 60MWe in Plant A and from 55MWe to 57MWe in Plant C, while the units in Plant B have been essentially decommissioned. The present baseload capacity is therefore 234MWe although the expectation is that the field will be able to maintain generation at approximately 175MWe in the future, corresponding to full loading of three of the four units. Based on field performance during the past two to three years, this level of generation can be supported while maintaining a relatively low production decline rate of 3 to 6%.

1.1 Historical Reservoir Pressure Monitoring

The monitoring of reservoir pressure changes during production is an important part of the reservoir surveillance and management program. In Tiwi, as in many other geothermal fields developed in the 1970's and 1980's, the data have mainly been obtained by running periodic downhole pressure/temperature surveys in available wells using "Kuster" mechanical (KTG and KPG) survey tools, or more recently, electronic (K10) tools. For "idle" wells, these surveys can be conducted on a regular basis but for active production wells, the surveys can only be run when the wells are shut-in. Hence, the number of surveys conducted on many of these wells over the years has been relatively small. However, by combining data from wells having similar responses, it has been possible to define the general pressure trends in the various sectors of the Tiwi field in response to production.

Available pressure data from wells in the Matalibong sector of the field, which is the area of interest for this paper, are plotted in Figure 2 at an elevation of 1,000m bsl (below sea level), which is within the deep liquid reservoir. There is also an overlying, shallow steam zone that was formed by boiling as pressure declined in the early 1980's and the steam zone pressure history is similar to that shown for the deep liquid.

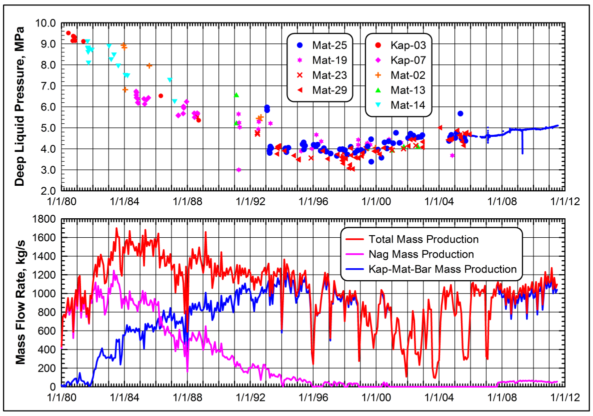

Figure 2: Correlation between Overall Production and Reservoir Pressure Changes

The total mass flow produced from the reservoir is also plotted in Figure 2, including separate plots for the eastern (Nag) and western (Kap-Mat-Bar) production sectors. Additional information on the production history is included in Menzies et al. (2010a). Production from the Naglagbong Sector, which was the initial area of production on the east side of the field, effectively stopped in the mid-1990's and this area is now mainly used for injection of both "hot" and "cold" brine (Figure 3). Therefore, the present total production of ≈1,100 kg/s comes from wells located on the western production sectors (Kap-Mat-Bar), with wells producing either saturated or superheated steam or two-phase flow (Figure 3).

The measured pressures from the individual wells are generally scattered but by combining this data from a number of wells, the overall pressure trends have been quite well defined and there is a good correlation with the overall production (Figure 2). There was initially a linear decline in pressure in both the steam and underlying liquid from 1980 to 1994 when production was high, with an overall decline from 9.65MPa to 3.80MPa (pressure change ≈5.85MPa). Pressure then stabilized until 1999, followed by a rebound from 1999 to 2004 from 3.80MPa to 4.50MPa (pressure change ≈0.70MPa) as production reached a low point due to plant issues, lack of make-up well drilling and rehabilitation activities. Since 2004, pressures have been relatively stable, although the individual well survey data is sparse.

1.2 Continuous Reservoir Pressure Monitoring

Although the data from downhole surveys has defined the overall pressure changes that have occurred in Tiwi over its 32 year production history, the lack of precision and continuity means that it is not possible to determine how wells are interacting with each other or to correlate responses of the reservoir to short term changes in production and/or injection. The monitoring therefore needed to be upgraded to better characterize the reservoir response to present production/injection and to provide more detailed data to help develop future resource management strategies. Two capillary tubing based pressure monitoring systems, including Incoloy tubing, 316SS chambers and surface transducer/data loggers, were therefore purchased in 2005 to start a program of continuous (every five minutes) long term reservoir pressure monitoring.

The improvement in the quality of the data that can be obtained by using capillary tubing systems is readily apparent in Figure 2 where the measured data from Mat-25 from 2005 to 2011 is compared with the earlier downhole survey data. It is clear that the continuous data has significantly better resolution than the individual survey data and the improved resolution is needed as the overall pressure change measured within the past six years is within the scatter of the earlier individual pressure measurements from Mat-25.

2. MATALIBONG PRESSURE MONITORING

The Matalibong sector of the Tiwi field (well names starting with "M" in Figure 3) presently provides about 40% of the steam production for the Tiwi power plants and is therefore very important to the present and future viability of the field. A majority of that production is from the Matalibong Steam Zone (Menzies, et al., 2010b), where a rising liquid-steam interface has caused productivity losses due to "flooding" of the deeper production zones. The loss of production due to this process has been estimated by Calibugan and Villaseñor (2010) to be ≈60kg/s (25MWe) between 2004 and 2010 and an additional 78kg/s (32MW) is at risk in the next ten years if the interface continues to rise at the presently estimated rate of 20m/year. Hence, understanding the reasons why the interface is rising and being able to control it has become a high priority for resource management.

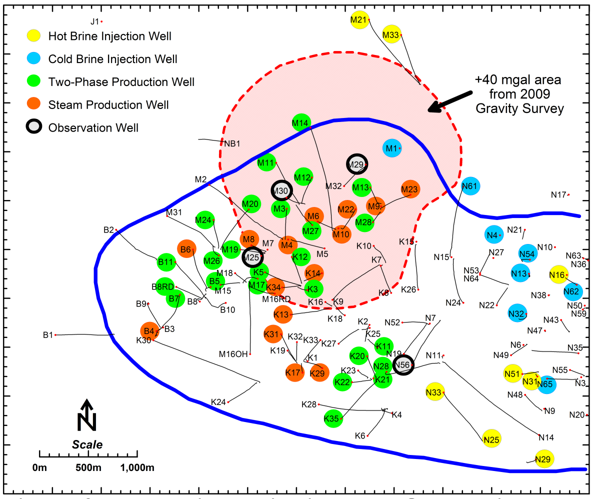

Figure 3: Production, Injection and Observation Well Locations

Although the extent of this issue was not fully understood in 2005, monitoring the deep liquid reservoir in this sector of the Tiwi reservoir was considered a priority and the first of the capillary tubing systems was installed in Mat-25 at 1,800m in November 2005. Mat-25 (Figure 3) is located at the south-west end of the Matalibong production sector, and was originally drilled as a deep corehole in 1993. It has generally had very stable downhole conditions and was therefore an ideal choice for an observation well. The second system was installed at Mat-29 in March 2007 at 1,200m to extend coverage of the pressure monitoring to the more northern Matalibong production area (Figure 3). However, in February / March 2008 a leak developed in the production casing at Mat-29, allowing groundwater to enter the well and flow down into the deep liquid reservoir. The well was therefore no longer a reliable observation well and was suspended with cement plugs in September 2008 to stop the downflow. The tubing was successfully recovered in April 2008 and transferred to Mat-30, a nearby well, in July 2008, where it was installed at 1,200m; also within the deep liquid reservoir. Monitoring of the deep reservoir has continued in both Mat-25 and Mat-30 to the present time.

At the time the capillary tubing was installed in Mat-30, continuous monitoring of wellhead pressures at both Mat-25 and Mat-30 was also started. Both wells are open to the shallow steam zone and the changes in wellhead pressure therefore reflect the pressure changes in this zone, provided there is no significant interaction between the deep liquid and shallow steam zone, such as inter-zonal flows, etc.

The locations of all the presently active production, injection and observation wells in the Tiwi geothermal field as of March 2011 are shown in Figure 3. The production wells are also identified as to whether they produce from the shallow steam zone (saturated or superheated steam), with discharge enthalpies of 2,790 kJ/kg or greater or if they have produced from the deep liquid zone at sometime during their production history. For injection, there are both "hot" and "cold" brine injection wells, with the fluid injected into the deep liquid reservoir. In the Matalibong area, Mat-21 and Mat-33 are the hot brine injection wells and Mat-01 has been used for cold brine injection. The casing leak in Mat-29 also meant that it was effectively a "cold" brine injector from February to September 2008.

2.1 Initial Analysis of Measured Pressure Trends

The measured deep liquid reservoir pressure data from the three observation wells (Mat-25, Mat-29 and Mat-30) are plotted in Figure 4. Note that the data are taken at different elevations and have not been corrected to a common datum; however, the plots have consistent scales so the changes in pressure can be directly compared.

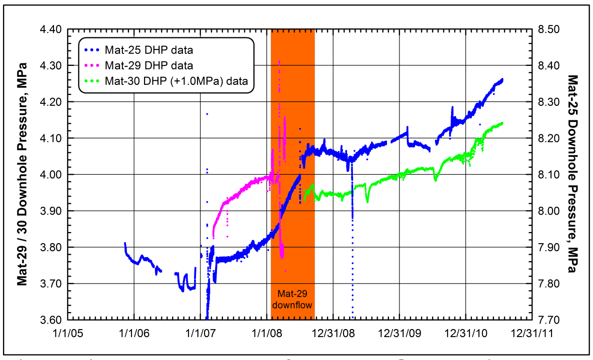

Figure 4: Pressure Data from the Observation Wells (Mat-25, 29 and 30)

During 2006, the pressures from Mat-25 were declining, which is consistent with depletion by production. There were also a number of short term events where the pressure trends changed and Alvarez (2006) was able to correlate the majority of these changes to production events; one such event was a shutdown in field activities in September 2006 when Typhoon *Milenyo* disrupted production for a few days, resulting in a 0.034MPa increase and then similar decrease in measured pressure.

In November 2006, Typhoon *Reming* also hit Tiwi and this resulted in a disruption in field production for about three months. Unfortunately, there was also some damage to the capillary tubing system and no meaningful data was collected during this forced shutdown. However, after everything was restored again, the pressure trend had reversed and in both Mat-25 and Mat-29, there were increasing pressure trends during 2007. This was initially difficult to explain, considering that both wells were surrounded by production wells, and this is discussed in more detail in a later section.

During 2008, the large increase in pressure noted in Mat-25 correlated very well with the period of time when the casing break in Mat-29 occurred, which allowed groundwater to enter the well and flow down into the deep reservoir. Hence, it indicated that the two wells were in very good hydrologic connection, even though they are about 1.5km apart (Figure 3). A Pressure-Temperature-Spinner (PTS) survey conducted in Mat-29 indicated that the downflow was ≈125kg/s, which is quite significant.

The suspension of Mat-29 in September 2008 caused a measurable pressure drop in both Mat-25 and Mat-30, providing further evidence of the continuity of the deep reservoir between the three wells. However, the pressure decline was significantly less than the increase in pressure that had occurred during 2008 and this is discussed further in a later section.

The data collected from Mat-25 and Mat-30 since July 2008 are plotted in Figure 5 and the overall pressure trends in both the shallow steam and the deep liquid are very similar for both wells, further indicating the good continuity within both reservoirs between the wells.

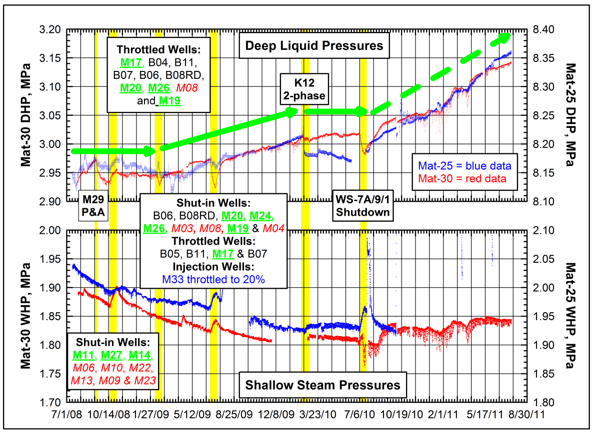

Figure 5: Deep Liquid and Shallow Steam Zone Pressure Data from Mat-25 and 30, Showing Correlations with Short Term Events

In addition to the longer term trends, there have been many "short" term events that either one or both of the observation wells have responded to and some of these are indicated on Figure 5. These events normally correspond to shut-in or throttling of a group of wells on one or more wellsites to allow surface facility work to be undertaken and the activity normally lasts for a few days. The bold, underlined well names shown in Figure 5 are those wells that are located in the vicinity of the observation wells and produce from the deep liquid reservoir while the well names in italic produce from the steam zone. The other wells, which are Bariis (B) producers, are not believed to affect the observation well responses, based on the results of the work by Alvarez

(2006). Santos (2009) also undertook a study of events that occurred between January 2008 and April 2009 and in many cases was able to determine which wells had an effect on the measured pressure in the observation wells. The results further indicated that some wells, particularly in the Bariis and South Kapipihan areas, did not appear to have any noticeable effect on the measured pressures. This type of analysis is on-going as more data are collected and is very helpful in developing a more complete picture of the reservoir continuity. However, it is complicated by the mix of production wells (steam and two-phase producers) and the fact that multiple wells are normally involved in shutdowns.

2.2 Effect of Injection on Pressure Responses

As early as 2006, there were indications that injection to Mat-21 and Mat-33 was affecting production wells in the Matalibong sector and the evidence, which was based on changes in production characteristics, well chemistry, results from tracer tests and repeat gravity surveys, has continued to grow over time. Although the tracer test and chemistry data provide positive evidence of mass returns to the production wells, the tracer first arrival times were longer than 27 days (Calibugan, et al., 2010) and there is no major evidence that thermal breakthrough is occurring, except possibly in one well. The more significant issue is pressure interference, as the combination of rising deep pressures and falling steam pressures is causing the liquid-steam interface to rise, as discussed earlier. Therefore, gaining an understanding and being able to reverse the rise in the interface is a very important aspect of the future management strategy for the Matalibong production sector.

The idea that injection to Mat-21 and Mat-33 could be responsible for the noted increases in deep pressure was initially difficult to appreciate, considering the injection wells are 2 to 3kms from the observation wells, are located outside the interpreted production area of the field and the observation wells are surrounded by production wells. However, as shown in Figure 5, there are a number of short term events highlighted where production wells had to be shut-in or throttled, which also resulted in a reduction in injection flow. Considering the locations of the observation wells, it was expected that the pressures would increase as production was reduced, which is what occurs with the steam zone pressures. However, the deep liquid pressures were found to decrease during most of the events, indicating that the deep reservoir was reacting to the reduction in injection rather than production. The responses in Mat-25 are also less pronounced than in Mat-30, which is consistent with the relative locations of the observation and injection wells.

With the increasing number of instances where the above responses occurred, it has became increasingly clear that there is very good hydrologic communication between the injection wells and the deep liquid reservoir in the Matalibong production sector.

3. NET "VOIDAGE" CONCEPT

After accepting that there is good communication between injection and production, the system was conceptualized as a simple tank model (Figure 6) to explain the longer term pressure changes that have occurred since 2005 in a more holistic way. If production from the shallow steam zone is assumed to be independent of the deep reservoir, the net "voidage" is calculated as the difference between total deep production and injection. If net voidage is positive (injection > production), pressures should increase and if net voidage is negative (injection < production), then pressures should decrease.

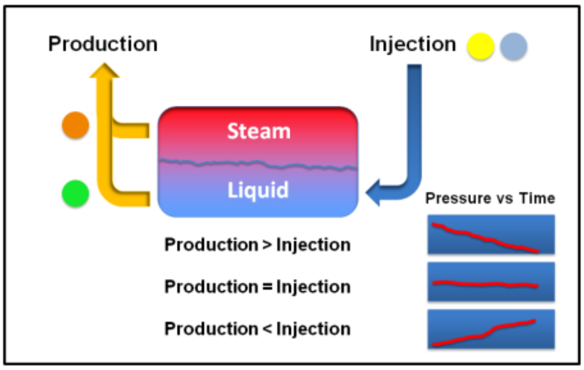

Figure 6: Simple "Tank" Model to Explain Measured Pressure Trends

To calculate the total deep production history, it is necessary to decide which wells are affecting the observation well responses and the following data have been reviewed to help determine which wells to include:

- **Micro-Gravity Data.** There has been a noted increase in gravity within the Matalibong area between 2004 and 2009, which is interpreted to be due to the rise in liquid-steam interface that has occurred in response to injection at Mat-01, Mat-21 and Mat-33 (Calayag, 2010). The area defined by a gravity change of greater than +40 mgal (Figure 3) is assumed to define the area of good hydrologic connection.

- **Pressure Data.** There have been indications from some of the short term responses in Mat-25 pressure data that the Bariis wells to the southwest can be excluded as there has been little or no response measured when these wells have been shut-in (Alvarez, 2006; Santos, 2009).

Based on this review, the wells used to calculate the deep production are the "two phase wells" located within the area defined by the gravity change of greater than +40 mgal (Figure 3) plus Mat-17 and Mat-19, which are located just to the south-west of this region.

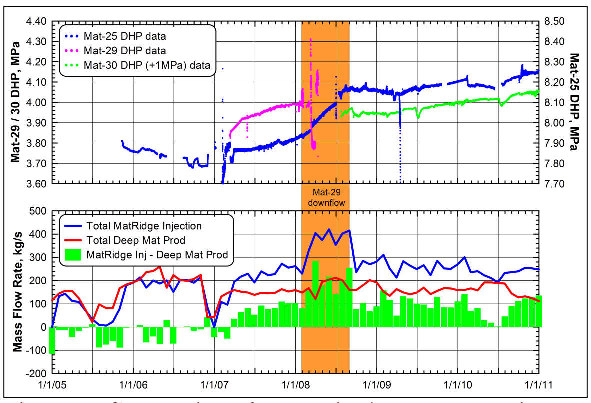

Figure 7: Correlation of Deep Liquid Pressures with Net "Voidage"

The total injection, total deep production and the net voidage are plotted in Figure 7, along with the measured deep pressure data from the three observation wells for the period 2005 to 2011. The results indicate that prior to 2007, the net voidage was negative and this was the time when pressures were declining. However, since early to mid 2007, the situation has reversed and there has generally been positive voidage, with either stable or rising pressures and a corresponding rise in the liquid-steam interface.

As injection does appear to be causing the rise in deep reservoir pressure, it should be possible to reduce the net voidage and hopefully make it negative (production > injection), by reducing injection to Mat-21 and Mat-33. Based on the data in Figure 7, reducing injection by ≈125kg/s should result in "neutral" voidage, which should at least stabilize the pressure. Work has therefore started on implementing projects in the field to address this issue and it is planned that injection will be reduced by this amount by mid-2012.

4. "SAPHIR©" MODELING

Although the analysis presented in the previous section does provide some ability to quantify the required reduction in injection rate, it is still essentially qualitative and does not provide the ability to forecast how deep pressures will change in response to different production/injection scenarios. As a first step, it was decided to develop a quantitative model using the "Saphir©" Well Test Analysis software (KAPPA Engineering, 1990) as it has the ability to include multiple wells and can calculate the pressure responses using both analytical and numerical models. However, it was also recognized that it has limitations as it can only handle isothermal conditions.

4.1 Matching the Observation Well Pressure Responses

The initial modeling (Solunde, 2011) concentrated on matching of the Mat-25 pressure data and confirmed that Saphir© had the capability to model the system using simple analytical and numerical models. Reasonable matches were obtained to the measured pressure data and forecast runs indicated that the proposed reduction in injection flow rate of 125kg/s would result in stabilization of the downhole pressures.

The initial models were then reviewed (Co, 2011) and matching was extended to include the data from all three observation wells (Mat-25, 29 and 30) using both analytical and numerical models. Although the Saphir© software includes the ability to do automatic matching, it was necessary to use a trial and error process for some of the matching due to the number of active wells being considered. It was also necessary to vary the wells that were included until the best match was obtained.

The final parameters that were used in both the analytical and numerical models to obtain the matches are shown in Table 1. These parameters were maintained constant for matching of all three observation well data sets.

Table 1: General Input and Properties Data

Average Porosity	10%
Total Compressibility	2.45×10^{-9} Pa^{-1}
Layer Temperature	260°C
Water Saturation	100%
Fluid Viscosity	1.0×10^{-4} N.s/m^2
Reservoir Transmissivity	33.5 Darcy.metres (homogeneous / isotropic)
Reservoir Size	230km^2

The locations of the production and injection wells that were included in the final model are shown in Figure 8.

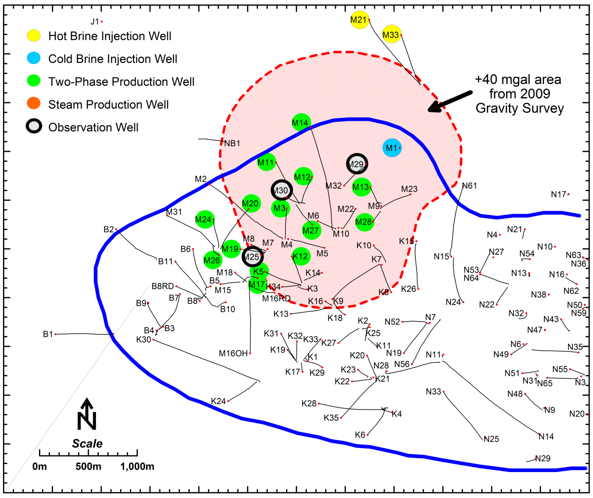

Figure 8: Production and Injection Wells Used for Matching of Observation Well Data Using Saphir©

During the matching process it was found necessary to impose a closed boundary to improve the matches, although the enclosed area (area = 230km^2) is significantly larger than the known area of the reservoir. From a modeling perspective, this basically means that re-charge is occurring, as is normally seen in geothermal reservoirs, but it is less than would occur if "infinite acting" boundary conditions applied. Note that in one of the cases considered by Sotunde (2011), the boundaries were positioned based on the actual production area but it was then necessary to allow some re-charge from a constant pressure source across a segment of the boundary in order to match the data.

The total reservoir volume required is also a function of the total system compressibility. In these models the total compressibility was assumed to be 2.45×10^{-9} Pa^{-1}, which corresponds to a single phase liquid in a confined reservoir. As there is an overlying steam zone and two-phase conditions exist in some areas of the field, the actual total compressibility is probably between one to three orders of magnitude larger than the single phase liquid compressibility assumed here (Brock, 1986) and this would then result in a reduced area for the model.

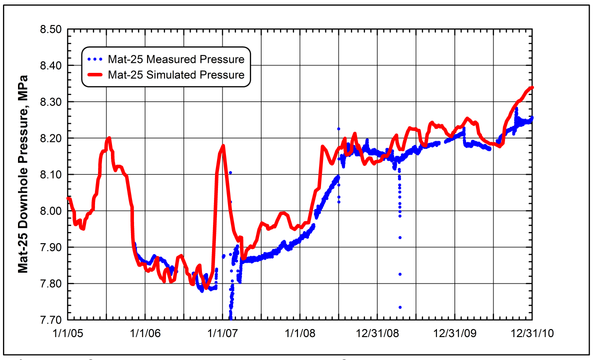

Figure 9: Match to the Mat-25 Measured Pressure Response Using the Saphir© Numerical Model

The calculated response using the numerical model is compared with the measured pressure data from Mat-25 in Figure 9. The match is reasonable, considering the simplicity of the models, as discussed above, particularly the assumption that the permeability is homogeneous and isotropic. The transmissivity of 33.5 Darcy.metres is also a reasonable value for a productive geothermal reservoir. Note that the match using the analytical model is almost identical.

4.2 Forecast of Future Pressure Changes

Following the success of matching the measured data, the models were then used to forecast how the pressure would response to changes in the injection rate, with three scenarios considered:

- Maintaining the present injection conditions in Mat-21 and 33 (injection rate ≈250kg/s);
- Reducing injection to 50% of its present rate (injection rate ≈125kg/s, and;
- Stopping injection to Mat-21 and 33.

In all three scenarios, it was assumed that the injection rate remains constant at the above values while the overall production rate from the production wells shown in Figure 8 declines by 6%.

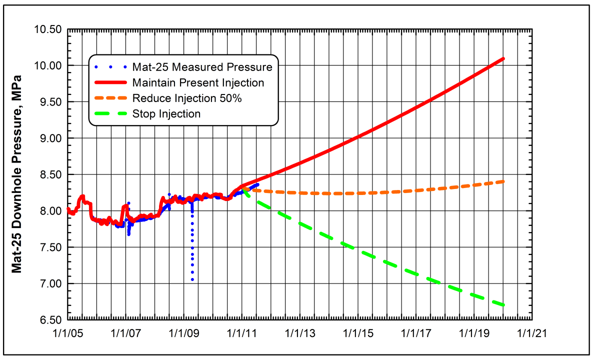

Figure 10: Numerical Model Forecast of Reservoir Pressure Changes in Response to Different Injection Scenarios

The results for the three scenarios calculated using the numerical model are shown in Figure 10. It is apparent that reducing injection to ≈125kg/s should at least stabilize the deep reservoir pressure as the net voidage will be close to zero. The slight rise in deep pressures after 2015 is due to the net voidage ratio becoming positive when the decline in production means that injection exceeds production. Hence, it will be necessary to continue to monitor the changes and make further adjustments as necessary.

The stabilization in deep pressures will not necessarily stabilize the liquid-steam interface as this also depends on how the pressure changes in the overlying steam; if the steam zone pressure continues to decline then the interface will continue to rise. Hence it will probably be necessary to reduce injection further in the future to maintain a negative net voidage in the deep reservoir and get the liquid-steam interface to fall. This may then uncover previously flooded production zones, allowing them to start producing steam again.

5. CONCLUSIONS

- Monitoring reservoir pressure by repeat downhole surveys in a number of wells provides sufficient data to show how the reservoir is reacting to production and/or injection over the long term but is not generally adequate for correlating short term responses or for analysis of interwell connections.
- Continuous pressure monitoring using capillary tubing systems is proving to be very successful in the Matalibong Sector at Tiwi and is providing data with sufficient precision to clearly show interactions between the production, injection and observation wells.
- The measured reservoir pressure responses clearly show strong interaction between the injection and production areas, as shown by the short term pressure responses and the correlation between the pressure changes and net voidage. This has added to growing evidence from other data of a strong connection, such as changes in well discharge characteristics, tracer test results and micro-gravity survey results.
- The pressure increases caused by injection in the deep reservoir have caused the liquid-steam interface to rise and negatively affect the productivity of steam wells. Having the ability to measure the changes in pressure with time has improved our knowledge of the process and has helped in designing a long term reservoir management strategy to reduce deep pressures.
- Based on the net voidage analysis, reducing deep pressures will require diversion of at least 125kg/s of injection flow to another area of the field and projects are now under way to accomplish that by mid-2012.
- The "Saphir©" modeling was successful in matching the measured data and the results from the forecast runs suggest that reducing the injection to 50% of its present level (≈125kg/s) will reduce the net voidage to zero and this should at least stabilize the deep pressures.
- The actual effect on the liquid-steam interface will also depend on the pressure changes in the overlying steam zone and it will probably be necessary to maintain a negative voidage in order to get the liquid-steam interface to descend. If this does occur, then it may allow previously flooded production zones to flow again.

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