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Tiwi Geothermal Brine Injection Surface Facility Development as Response to Changing Subsurface Conditions

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ABSTRACT

The Tiwi steam field has been in operation for the past 35 years and over the last 15 years it has witnessed changes in operating system and reservoir conditions which have ultimately affected the brine injection systems and brine disposal strategies. The influx of cool meteoric waters and injected fluids, production of acidic fluids, decline of reservoir pressures, increase in non-condensable gas concentration and enthalpy changes are some of the major challenges that have affected Tiwi and the major challenge for the injection system has been the increasing brine production in most of its producing sectors. This has been managed by instituting a number of technical and operational changes of the Tiwi surface facilities, both tactical and strategic in nature, which have included conversion of the original cold brine injection system to hot brine injection, installation of bypass and parallel lines for additional capacity and flexibility, drilling and hook-up of new injectors, conversion of idle wells as injectors and interconnection of two independent hot brine injection systems. Instituting these changes has helped the Tiwi field in maintaining a major geothermal resource, even in the face of these major operational and reservoir challenges.

1. INTRODUCTION

The Tiwi geothermal field, one of the fields operated by Philippine Geothermal Production Company, Inc. (PGPC), is located at approximately 350km southeast of Manila and situated at the northeast section of Mt. Malinao, an extinct Quaternary stratovolcano in the East Philippine Volcanic Arc (Figure 1) (Gambill and Beraquit, 1993).

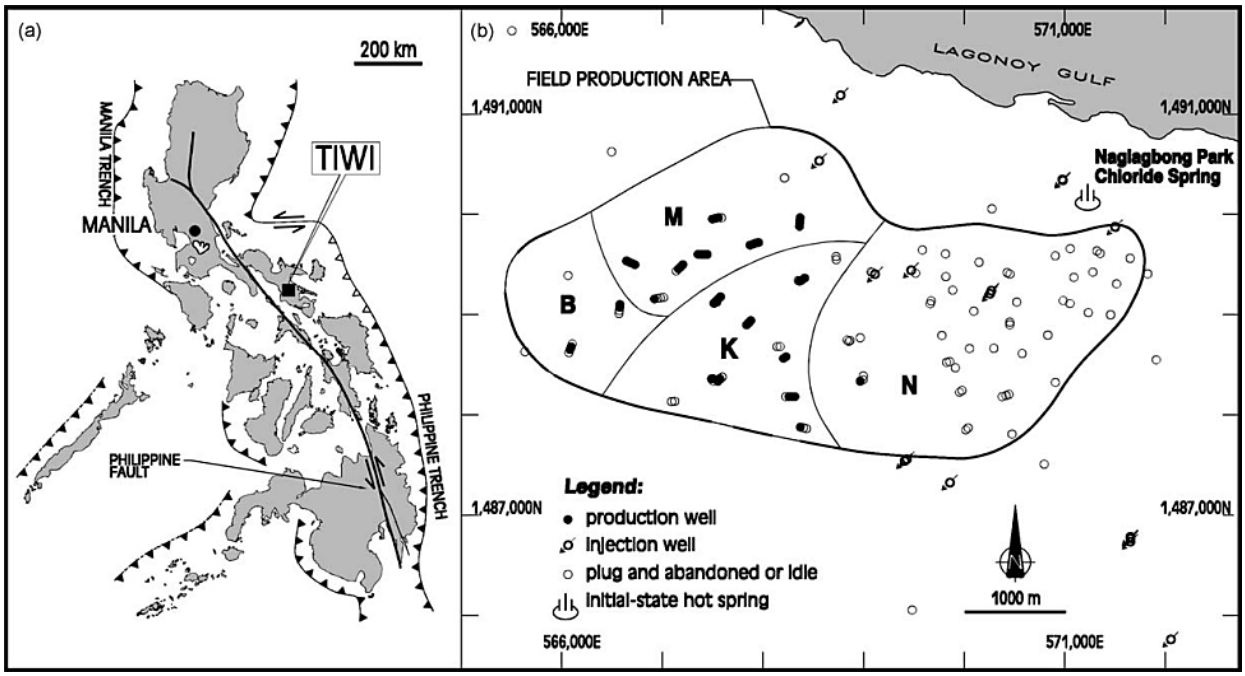

Figure 1. Geographical location of the Tiwi Geothermal Field *(N – Naglagbong; K – Kapipihan; M – Matalibong; B – Bariis)*

The production field is divided into four major geographic sectors, with the Naglagbong (Nag) sector generally having single well locations while the remaining three sectors; Kapipihan (Kap), Matalibong (Mat) and Bariis (Bar), have a number of multi-well pads. Since Tiwi is a generally wet steam field, a typical multi-well pad consists of: two-phase flow piping from each well to a header which collects the fluid from several wellheads and connects to the separator; the separator vessel; steam pipelines which take the steam from the separator to the power plant; and the brine disposal pipelines which take the separated brine to the re-injection wells. This configuration requires minimal two-phase cross country lines but needs lengthy cross country steam lines and brine disposal lines across the field.

Initially, waste water (i.e. separated brine and cooling tower condensate) from the Tiwi production system was disposed of into the Lagonoy Gulf through the Nag brine canal but brine reinjection was soon started in 1983 to provide mass and pressure support as pressure draw-down became significant at Nag from 1979 to 1982 due to the increasing mass extraction as the power plants were

commissioned. The brine disposal system then continued to evolve and 100% brine injection was reached by 1993 and 100% brine and condensate injection by 2000. Brine reinjection is now the sole method used for waste water disposal.

The first brine injectors were the idle, corrosive production wells within the Nag area, located inside the production area. However, due to the adverse impact on production that occurred, injection was moved out from "infield" to "edgefield" and eventually to the "outfield" area located to the southeast of the field (Figure 2). The Southeast Hot Brine Injection System (SEHBIS) is the main disposal system for brine produced in Nag and Kap areas to the present and includes both edgefield and outfield injectors. (Sunio, *et.al.*, 2005)

When production began in the Nag area in 1979, reservoir pressures declined significantly and this allowed cooler, dilute ground water to enter the reservoir, which caused a significant reduction in steam production from the Nag area. New make-up wells therefore had to be drilled progressively to the south and west to maintain generation, so that by the mid-1980's, the majority of the steam produced came from the Kap-Mat-Bar sectors (Menzies, *et al.*, 2010a).

When production shifted further to the west, a separate brine disposal system was set-up in West Tiwi, referred to as the MatRidge Brine Disposal System (MRBDS). The injection wells for this system are located to the north of the Mat production area as shown in Figure 2.

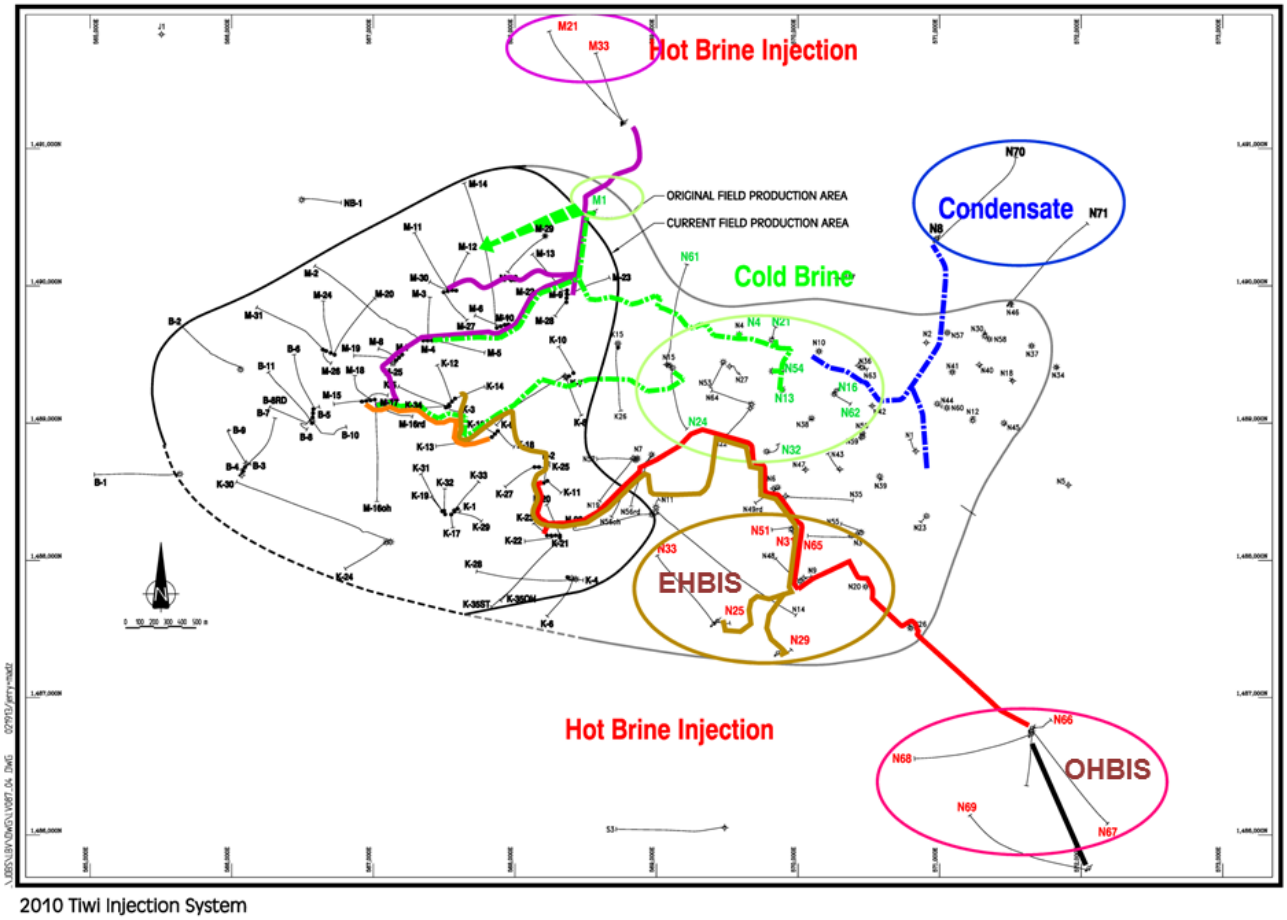

Figure 2. Tiwi Injection System

2. MAT RIDGE BRINE DISPOSAL SYSTEM

The wells in Mat and Bar produce either dry steam, with varying degrees of super-heat, or two-phase fluids. Where the majority of the wells in a well pad are two-phase wells, they are mixed with the steam-producing wells and eventually separated in a separation vessel. For well pads where the majority of the wells are steam wells, a smaller test separator was utilized to separate the brine. The produced steam was then mixed downstream with the super-heated steam wells as shown in Figure 3. Separated brine from the vessels flowed into a series of cascading holding ponds (sumps) down the hill, before finally flowing by gravity to Mat-01 and Mat-21 injection wells and being injected as "cold" brine.

2.1 Challenges of the Initial Surface Facility Configuration

The increased extraction from the Mat and Bar sectors in the 1980's and 1990's caused extensive boiling to occur as the pressures declined, and within the steam zone, the increase in extraction also caused the production of "superheated" steam. Some wells that produced superheated steam, also produced volatile Cl, which formed very high, localized concentrations of HCl where condensation occurred in the carbon steel pipelines, resulting in accelerated corrosion. For well pads with only one two-phase well

with low brine content, mixing with one or more superheated wells resulted to evaporation/flashing of the brine and the deposition of salts and silica inside the pipeline (Menzies, *et al*., 2010b).

Brine in the MatRidge sumps (holding ponds) indicated oversaturation with respect to amorphous silica at temperatures of 50 to 100°C, with SSI ranging from 2 to 4.5. Due to oversaturation and low retention time of brine in sumps, silica precipitates in the pipelines which inadvertently lead to deposition of silica in lower elevation sumps, interconnecting pipelines and the injection wells as a result of the flashing and cooling of the brine. This eventually resulted to high maintenance efforts and cost in the scale cleanout and injection well capacity maintenance.

2.2 Modifications to the Initial Configuration

Three basic process principles were employed in the redesign of the Matalibong steam and brine gathering system. The first concept involved the mixing of available brine with all the dry steam wells for de-superheating and acid scrubbing. The superheat is generally removed without causing brine to become supersaturated with respect to silica content. The brine is also unchanged in terms of its corrosivity due to the presence of typical geothermal ions which act as buffers to the absorption of HCl. The second concept was to pay close attention to the mixing order to avoid scaling and corrosion issues, particularly where it was not cost-effective to tie individual superheated wells into the entire bulk flow. For example, in one of the wellsites, a slip stream of brine from the separator is recirculated upstream of the first superheated well in the well pad. The third process principle utilized the elevation differences among well pads to transfer separated brine from one portion of the two-phase system to the next by gravity (Kitz and Toreja, 2002).

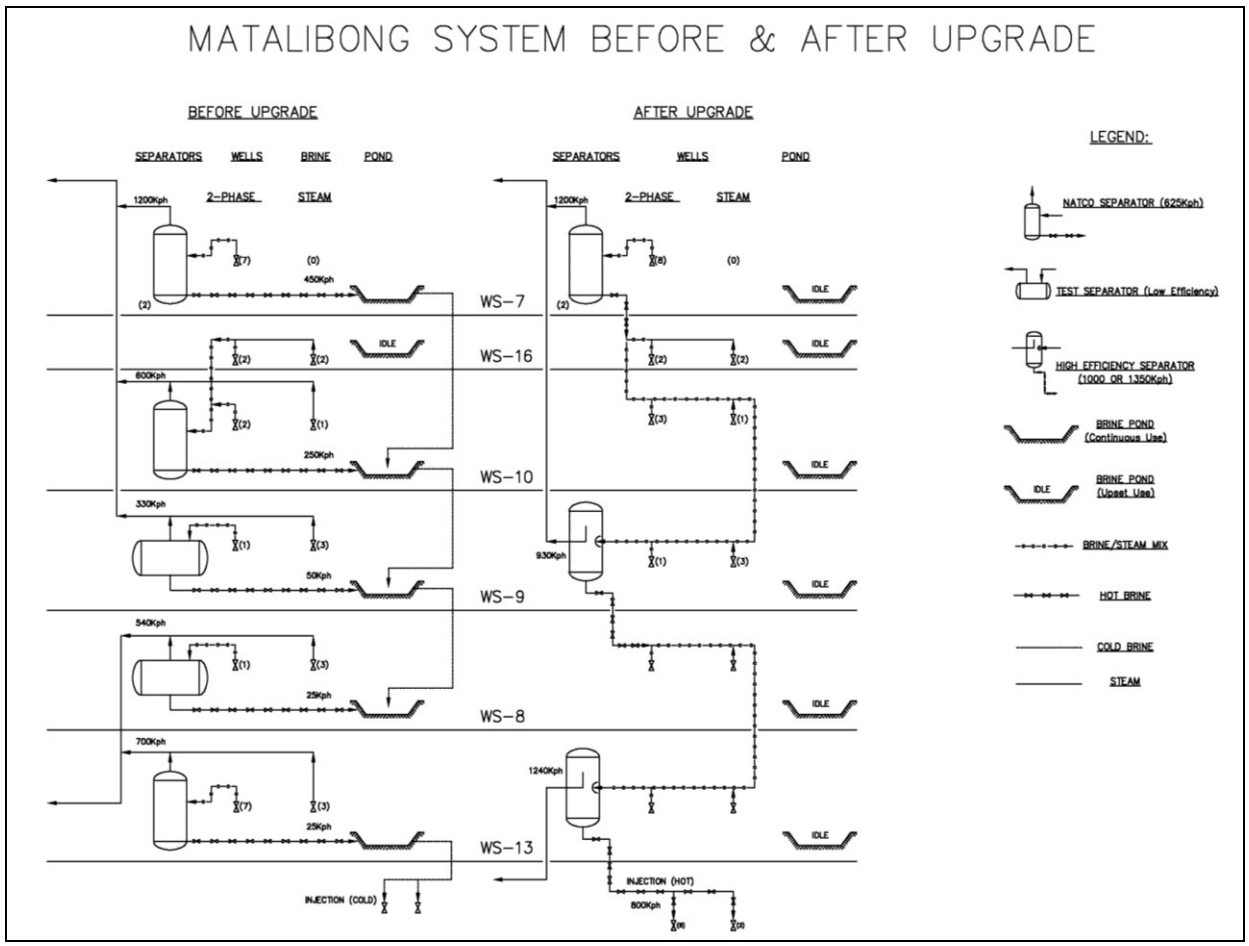

Figure 3. Configuration of Matalibong System Before and After the First Upgrade

The process principles described resulted to reduced corrosion and scaling in both the brine and steam lines and eliminated the use of the cascading holding pond (sump) system. The new system also brought all the brine to the Wellsite 13 (WS-13) separator. A new hot brine disposal line was also constructed from WS-13 to the MatRidge injector, Mat-21. The brine holding ponds however, were not totally abandoned but are occasionally used for well start-ups after turnarounds and high-level upsets of the separators.

With this new configuration, brine produced from the Wellsite 07 (WS-7) separator, the highest separation vessel in terms of elevation, is directly mixed with the bulk flow in the WS-16 to WS-10 flowline (right side of Figure 3). The superheated wells in WS-10 are de-superheated and washed from the WS-7 brine stream and the entire combined flow goes downhill to the lower well pad of WS-9. The total flow from WS-16, 10 and 9 and the brine flow from WS-7 is separated in the WS-9 separator and the brine produced from the process goes further downstream to the wells in WS-8, wherein four wells are mixed into the separated brine. The two-phase fluid is then combined with the wells of WS-13, where brine is separated and eventually injected to the MatRidge injector, Mat-21.

2.3 Challenges of the Upgraded Configuration

The first MatRidge upgrade was completed by early 2000 and the injector, Mat-21 started operating as a hot brine injector and the system was renamed the MatRidge Hot Brine Injection System (MRHBIS). However, the well had limited capacity and the system could not be fully utilized until it was worked over and re-drilled in 2005. Mat-1 was therefore used as a temporary cold brine injector.

Upon the completion of the rehabilitation of the four power plant units in 2004, production and injection in the Matalibong sector increased. The most significant change in the production wells at MatRidge during this period was the change of some dry wells to two-phase production caused by the continuous rise in the steam-water interface (Figure 4) from 900m bsl in 2000 to 820m bsl in 2004 within the sector (Menzies, *et al*., 2010b) and this caused a significant increase in brine production, which required more capacity in the brine injection system (Figure 5).

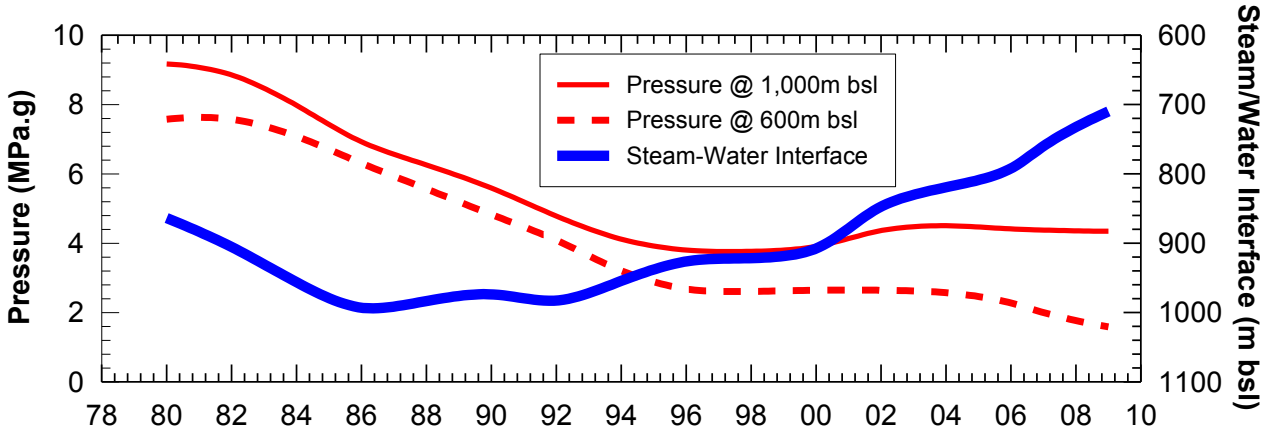

Figure 4. Historical deep reservoir pressure trends, 1978 to 2010

Measurements of brine production in 2005 showed that Matalibong was producing 176 kg/s to 227 kg/s, which is ~72kg/s to 122kg/s above the surface facility capacity limitation. Furthermore based on the observed 3% annual enthalpy decline, the forecasted brine production showed that 403kg/s additional injection capacity would be needed in ten years. Mat-33 was therefore drilled in early 2005 to provide additional injection capacity and the existing surface facility also needed to be further upgraded to cater for the current and forecasted brine production.

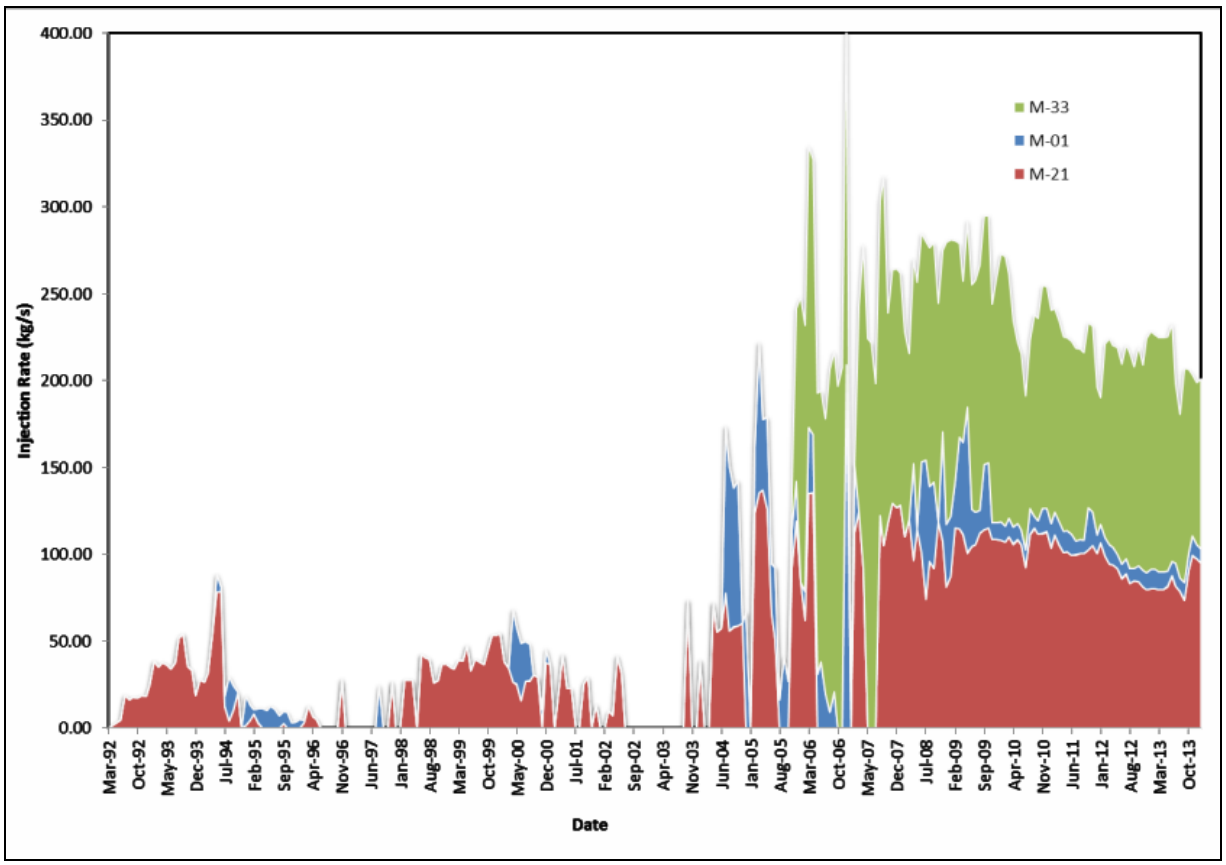

Figure 5. Historical Matalibong Brine Injection Rates, 1992 - 2013

The first upgrade of the MRHBIS also introduced an operational problem. The configuration required WS-13 to be on continuous operation to be able to transport brine from the higher elevation separators and well sites to Mat-21. This lack of flexibility required the utilization of the cold brine injection system in cases wherein WS13 was not operational. This then introduced the problem of rapid silica scaling of the cold brine disposal system facilities and led to generation curtailment (Vizon, *et.al*., 2005).

2.4 Modification of the Upgraded Configuration

To address the challenges of short and long term system capacities, flexibility, production, and cold brine injection system reliability, a second major upgrade of the MRHBIS was implemented. Among the various upgrade included are (1.) the installation of a 760m-bypass hot brine line from WS-08 to WS-13, ensuring continuous operation during WS-08 and WS-13 shutdown scenarios, and (2.) the installation of a 1.8km-parallel line from downstream of WS-13 to the well pads of Mat-21 and Mat-33, providing a system capacity of 415kg/s. Figure 6 shows the installations, indicated by the green lines lines, included in the second upgrade of the MRHBIS.

The second upgrade provided for additional capacity to the piping system by adding parallel lines and installing level control valves along the cross country lines. It also provided for the injection of WS-15 wells into the MRHBIS without entering the WS-13 separation system. The new piping upgrade incorporated a new level control valve, whose controller utilizes pressure data as process value to correctly maintain the liquid level in the upstream piping of the injection system.

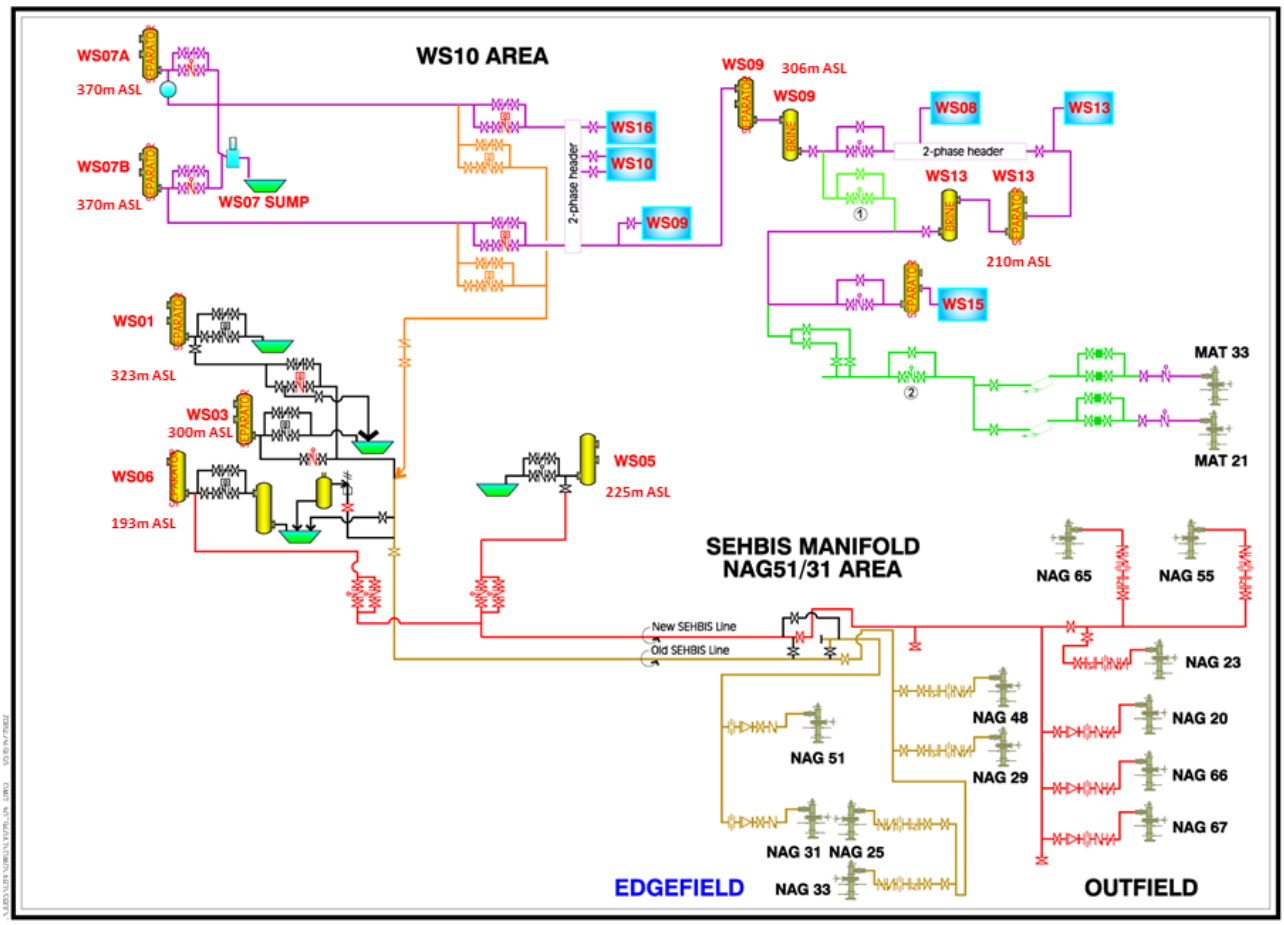

Figure 6. Schematic of the Current Tiwi Hot Brine Injection System

2.5 Post Second-Upgrade Challenges

After the commissioning of the upgrade project in 2006, the MRHBIS generally injected at stable injection rates into Mat-21 and Mat-33, with minimal or only intermittent dumping in the four MatRidge well pad separators. The injecting wellhead pressures of Mat-21 and Mat-33, however, were way below the saturation pressure of 895kPa and this was primarily due to the large injection capacity of the wells (Figure 7).

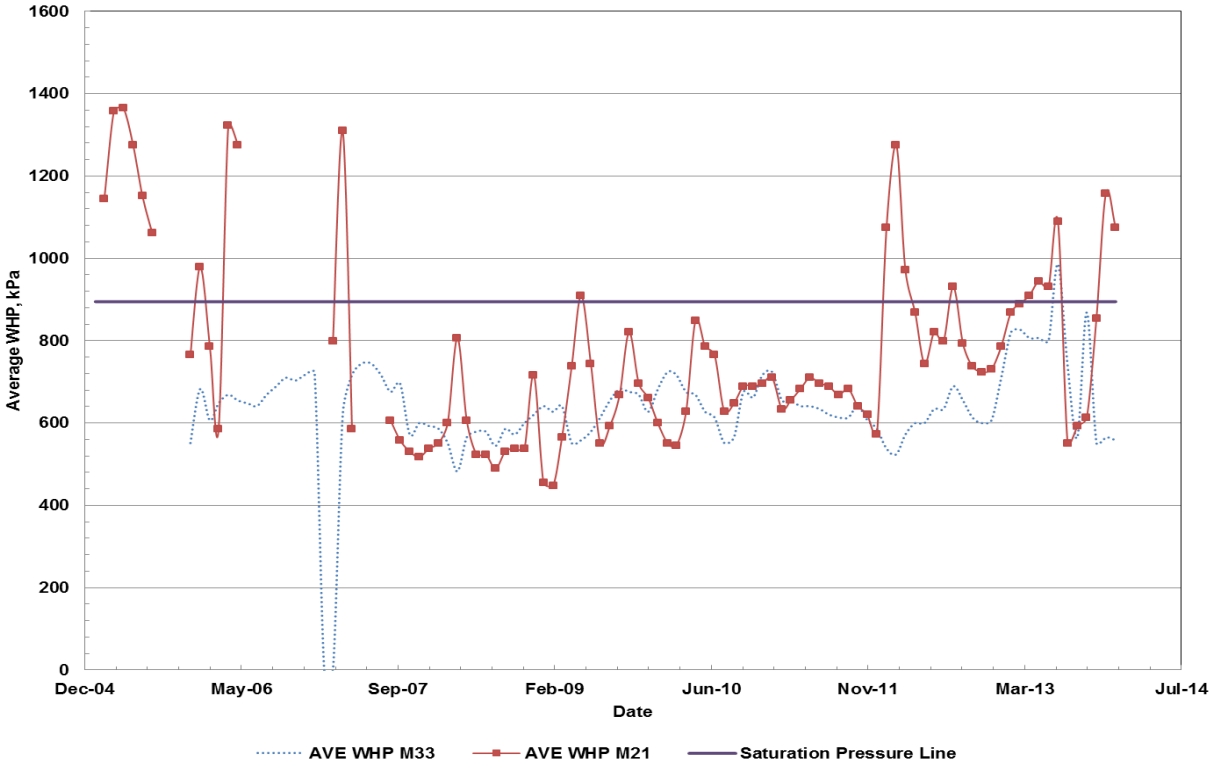

Figure 7. Historical Average Wellhead Pressures (WHP) of Mat-21 and Mat-33

Hence, the MRHBIS experienced intermittent flashing and associated "vapor lock" along the injection lines, which reduced their capacity and required the intermittent use of Mat-01 well to dispose of the dumped cold brine from the WS-13 separator. A process review conducted in 2009 to evaluate the possible causes of dumping led to the upgrade of control valves the following year. Since MRHBIS is operated through gravity, the control valve system, upon commissioning, was operated at manual mode to maintain head from WS-13 to Mat-21 and Mat-33 and mitigate the previously experienced intermittent dumping at the separators due to flashing in the line. Additionally, the WS-08 to WS-13 parallel line had been commissioned in 2010, discontinuing the de-superheating through brine washing of steam at WS-08 pad and the brine from the higher elevation separators can now bypass the WS-13 separator.

Tracer tests conducted in 2008, confirmed that the MRHBIS injectors were communicating with the Matalibong production reservoir with the tracer returns mainly governed by pressure, feedzone depths and distance of host injectors to the producers (Calibugan, *et. al*., 2010a). Early tracer returns from Mat-01, the nearest injector, were observed in nearby shallow wells while Mat-21 and Mat-33 first arrivals were seen in the western peripheral wells that have deep entries and along the path to low pressure.

The WS-07 to Southeast Hot Brine Injection System (SEHBIS) hot brine line was constructed to mitigate the impact of MatRidge injection on the Matalibong production area by interconnecting the MRHBIS and the SEHBIS, and providing for the diversion of 126kg/s brine from WS-07 separators. The details of this line are discussed in Section 4.

3. SOUTH EAST HOT BRINE INJECTION SYSTEM (SEHBIS)

As detailed in Section 1, the initial injectors of Tiwi were the corrosive production wells at the central Nag area. However, it was quickly found that these wells had adverse impacts to the Nag production wells as they were located within the then productive area. To mitigate both chemical and thermal breakthrough effects, injection into these wells was discontinued in 1986 and injection was moved out to a group of wells located at the southeastern edge of the Nag area ("edgefield" injectors). However, due to the insufficient capacity of the edgefield injectors to dispose all of the produced brine from the Nag and Kap wells, outfield injection started in October 1987 using Nag-66 and Nag-67. Two more outfield injector wells, Nag-68 and Nag-69, were commissioned in January 1988 and February 1990, respectively. These "outfield" and "edgefield" injectors comprise the Southeast Hot Brine Injection System (SEHBIS), which disposes of the hot brine from the Nag and Kap areas (Figure 2).

3.1 SEHBIS Initial Configuration

The SEHBIS was initially constructed to inject brine produced from WS-05, WS-06, WS-01, WS-03 and SS-04 through a common line from WS-03 separator brine outlet to the SEHBIS hot brine injectors. Brine from these well sites, except SS-04, was injected through static head or gravity to the injection wells while SS-04, due to its lower elevation, utilized pumps to inject separated brine to SEHBIS. The brine injection was separated into two sectors: the Edgefield Hot Brine Injection System (EHBIS) composed of Nag-25, 29, and 33; and the Outfield Hot Brine Injection System (OHBIS) system composed of Nag-65, 66, 67, 68 and 69. The OHBIS contained the Southern Brine Injection Pump Station (SBIPS) which was intended to pump brine to the outfield injection wells. During upset conditions, SS-04 cold brine, after collection in the dropout chamber, was dumped together with the WS-05 and WS-06 cold brine to the cold brine injectors, Nag-16, Nag-32, and Nag-62 (Vizon, *et al*., 2002).

Pipeline capacity simulation modelling conducted in 2001 (Toreja, 2001) and 2002 confirmed that the SEHBIS capacity at that time was 304kg/s only, which is about 63 to 88kg/s less than the brine produced from the well pads. SEHBIS injection capacity was primarily limited by the line pressure drops resulting to low injection system pressure, the elevation of WS-06 separator, which restricted the maximum pressure available for injection, and the increasing brine production. The low injection pressure along the injection system introduced potential for sludge formation and silica scaling of pipeline and wellbore, which reduced facility capacity and eventually resulted in dumping to the cold brine system in WS-05 and WS-06.

The low injection pressure of SEHBIS was primarily due to excessive pressure drop in the injection system brought about by undersized piping sections along the injection line and this also affected the ability to operate the outfield injection pumps, which were ultimately bypassed, which then limited the capacity of the system to the available static head from WS-06 (Kingston Morrison, 1997). These problems were further exacerbated by the fact that the brine injection requirement for the Nag and Kap wells was increasing (Figure 8).

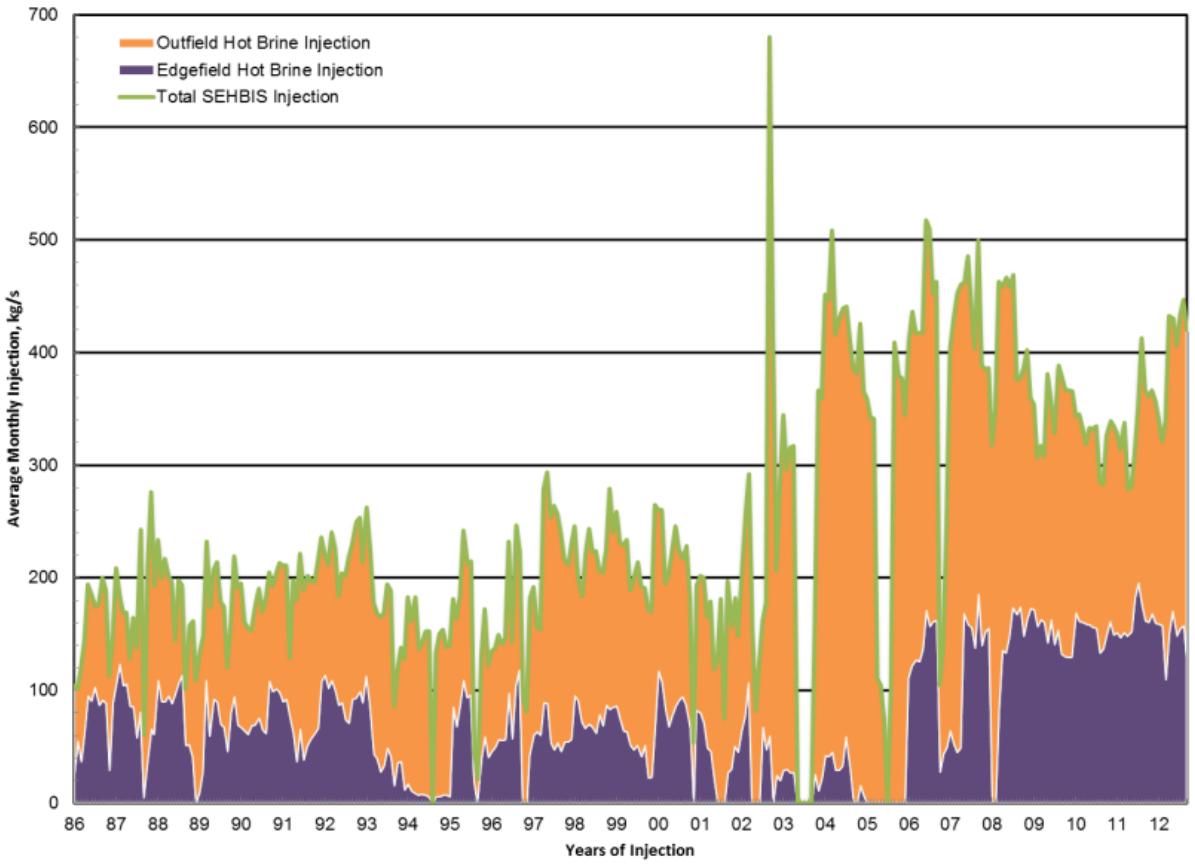

Figure 8. SEHBIS Brine Injection Trend from 1986 to 2012

3.2 SEHBIS Major Upgrade (2004 – 2010)

Proposal to upgrade SEHBIS was introduced and endorsed as early as 1997. The main themes of the upgrade proposals were the elimination of the excessive pressure drop from WS-06 down to the southeast hot brine injectors, elimination of edgefield injection, and injection of all SEHBIS hot brine. Two major strategies were laid down to achieve these: A. Upgrade the existing injection pipeline by adding a larger diameter companion pipeline along several sections of the injection line or B. Relocate the SBIPS and construct and construct larger diameter companion pipeline along several sections of SEHBIS.

The large pressure drop in the SEHBIS injection system was tackled in a proposal by the Tiwi Injection Team in 2002 (Vizon and Barcelon, 2002) by introducing the concept of providing two dedicated pipelines to the outfield and edgefield injectors. The edgefield injection pipeline aimed to utilize the head available from WS-03 to the EHBIS while the outfield injection pipeline would utilize the available head from WS-06 to the OHBIS. Meanwhile, SS-04 would have Nag-16 and Nag-62 as dedicated hot brine and cold brine injectors, respectively. Operation of Nag-16 and Nag-62 as dedicated injectors for SS-04 started in 2007 upon commissioning the Nag-28 production well to SS-04.

A concept design review of the proposed upgrade was conducted (Taylor, 2003) and the upgrade project was completed between 2003 and 2005. With the new upgraded condition, SEHBIS had been split into two interconnected piping systems dedicated to EHBIS and OHBIS wells. A valve manifold which served as the interconnection of both lines had been installed upstream of the Nag-31/51 well pad. The upgraded SEHBIS allowed operation at higher injecting wellhead pressures (IWHP), thereby, increasing the injection capacity of the system and at the same time reducing the chance for flashing along the line and at near-wellhead to occur. The IWHP's after the upgrade were between 1034 and 1379kPa while the typical IWHP before the upgrade was usually below the saturation pressure of 894kPa (Regulacion, *et.al*., 2005).

3.3 Challenges of the Upgraded SEHBIS

The deep well drilling of Kap-35 (2008) introduced a large amount of additional brine production to SEHBIS (~ 189kg/s) for disposal. Exacerbating this problem was the declining capacities of the major injectors of SEHBIS, which prompted the well work-over program for Tiwi in 2006. The work-over program included both scale drill-out (SDO) and acidizing operations and was intended to restore the injection capacities of the wells, which had declined over time due to silica scaling (Regulacion and Pazziuagan, 2006).

By 2011, injection capacity of most injectors had declined again and a root cause analysis on the injection decline concluded that the well capacity declines could be attributed to the underutilization of some large capacity injectors, inconsistency of Operations control procedure, short term upsets and lack of strainers in the injection well head configuration (Calibugan and Alvarez, 2011). Two parallel projects, namely the 2011 Work-over Program and the Tiwi Idle Well Hook-up Project, were carried out with the goal to increase the overall injection capacity of SEHBIS. The work-over program aimed to recover the capacities of a number of injection wells while the Tiwi Idle Well Hook-up Project involved re-commissioning three idle wells (Nag-23, Nag-55, and Nag-48) as hot brine injectors. The net gain from the two programs totaled 189kg/s of brine injection capacity.

A second batch of idle wells was identified in 2013 to supplement the required capacity for the WS-07 to SEHBIS brine diversion project, which is designed to divert MatRidge brine to SEHBIS. The first well to be hooked up, Nag-14, provided an additional capacity of 107kg/s upon its commissioning in mid-2013. This then allowed the re-commissioning of the WS-07 to SEHBIS line, which had been delayed due to the lack of injection capacity in SEHBIS in 2012, the diversion of 76kg/s brine from MatRidge and the shutting in of Nag-33, an edgefield injector. Nag-64, an additional idle well shall also be hooked up to SEHBIS by the end of 2014 or the first quarter of 2015 to provide additional injection capacity.

Aside from the hook-ups of idle wells, another round of work-overs of injection wells are being proposed to provide additional capacity in the outfield and further reduce edgefield injection.

4.0 INTEGRATING THE TIWI HOT BRINE INJECTION SYSTEMS

Field surveillance data consisting of geochemistry, tracer test results, geophysics, downhole pressure and production data collected from 2005 to 2010 indicated that the MatRidge injection wells (Mat-21 and 33) were having a negative impact on the Matalibong production area. It was projected that maintaining the status quo with respect to the existing injection setup and strategy would likely increase steam loss due to a rising steam-liquid level, which was assumed to be due to a rise in deep reservoir pressures associated with high injection rates at Mat-21 and Mat-33 (Calibugan, *et al.*, 2010b).

Evaluation of the impact of MatRidge injection to Matalibong production showed that actual steam losses, as of 2010, attributed to the increasing steam-liquid level were 60kg/s or an equivalent lost generation of 24MWe. The future projected steam loss was determined by assuming that no changes are made to the injection system and the steam-liquid level rise continues at the same rate for the next 10 years. Based on these assumptions, the steam loss projections were 42kg/s (16MWe) by 2015 and an additional 36kg/s (14MWe) in the following 5 years (2016 – 2020) (Calibugan and Villasenor, 2010). It was also shown that reducing injection by at least 50% should result in stabilization of the steam-liquid level.

Based on these analyses, a project to mitigate the injection influence in North Mat production was initiated in the same year, through the construction of the WS-07 to SEHBIS pipeline to provide for brine diversion away from MatRidge. The objective is to reduce injection to allow deep reservoir pressures to stabilize or start to decline as they were in 2006. The steam-liquid level is then expected to descend, if sufficient brine can be diverted, and this will then reduce the projected steam losses in the Matalibong area and possibly lead to the eventual recovery of some of the steam flow already lost.

The WS-07 to SEHBIS Project, which aims to achieve 126kg/s diversion of Matridge brine to SEHBIS, started construction in 2011 and was commissioned in 2013. The 1.5km pipeline serves as an interconnection between Matridge and SEHBIS, through a tie-in at WS-10 well pad to the EHBIS. The brine diversion that had been successfully transferred to date is approximately 75kg/s and work is on-going to increase this.

The elevation differences between MatRidge and SEHBIS well pads and the large injection capacity of Mat-33 are the two operational challenges that the WS-07 to SEHBIS has to overcome before the new cross country brine line could be completely commissioned and diversion of the MatRidge brine successfully completed. The former introduced challenges in ensuring that cold brine dumping at the lower-elevation well pad was minimized while the latter the challenge of maintaining above saturation IWHP for Mat-33 during high brine diversion. These had been addressed operationally by simultaneous valve manipulations in the diversion line and the Mat-33 isolation valve during increase/decrease of brine diversion.

5.0 CONCLUSIONS

Tactical and strategic surface facility developments have been implemented in the Tiwi field over the last 15 years in response to the changing subsurface conditions. The challenges from these changes include both surface facility and sub-surface issues but the major challenge for the injection system has been to provide the necessary capacity where and when it is required. Major facility developments started in the early 2000s to address these challenges, starting with the conversion of the MatRidge disposal system from a cold brine cascading holding pond system to a gravity-induced hot brine injection system, installation and upgrades of major hot brine lines, conversion of cold brine injectors to hot brine injectors, hook-up of idle wells and the diversion of MatRidge brine to SEHBIS. At present, PGPCs strategy with regard to Tiwi injection still focuses on 100% brine reinjection while optimizing steam generation capability and focusing on providing sufficient flexibility in the injection system to be able to react to future resource changes that are certain to occur. Hence the current focus on providing and maintaining brine injection capacity in all the existing injection areas.

The various developments of the Tiwi surface facilities, as a response to the ever-changing subsurface conditions, have helped ensure the economic success of the Tiwi field's steam production for the last several years. It is understood that there will continue to be surface and subsurface challenges in the future, but PGPC is confident that the tactical and strategic surface facility developments can and will address these and the Tiwi geothermal field will remain a reliable source of geothermal energy in the Philippines.

6.0 ACKNOWLEDGEMENT

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REFERENCES

Calibugan, A.A. and Alvarez, R.R.: Root Cause Analysis of SEHBIS Injection Capacity Decline in 2010, *CGPHI Internal Report*, MK, 11-483, (2011).

Calibugan, A.A., Sunio, E.G., and Villaseñor, L.B.: Mat-Ridge Tracer Injection Tests Results, *CGPHI Internal Repor*t, MK, 11-377, (2010a).

Calibugan, A.A, and Villaseñor, L.B.: An Evaluation of the Impact of Mat-Ridge Injection to North Mat Production, *CGPHI Internal Report*, MK-11,392, (2010b).

Gambill, D.T. and Beraquit, D.B.: Development History of the Tiwi Geothermal Field, Philippines, *Geothermics*, **22**, (1993), 403-416 (1993).

Kingston Morrison: Disposal System Upgrade: Injection Systems Preliminary Engineering, *PGI Internal Document*, RPT-3855-MP-008, (1997).

Kitz, K., and Toreja, J.: Maintaining Steam Purity in Response to Changing Reservoir Conditions in Tiwi, Philippines, *Proceedings*, Geothermal Resources Council Transactions, Vol.26, (2002), 763-768.

Menzies, A.J., Villaseñor, L.B., and Sunio,E.G.: Tiwi Geothermal Field, Philippines: 30 Years of Commercial Operation, *Proceedings*, World Geothermal Congress, Bali, Indonesia (2010a).

Menzies, A., Villaseñor, L., Sunio, E., and Lim, W.: Characteristics of the Matalibong Steam Zone, Tiwi Geothermal Field, Philippines, *Proceedings*, World Geothermal Congress, Bali, Indonesia (2010b).

Regulacion, R.E. and Pazziuagan, D.G.: Well Testing Results: Workover of Injection Wells Nag-67, -68, -62 & -16, *CGPHI Internal Report*, MK, 10-825, (2006).

Regulacion, R.E., Villaseñor, L.B., Vizon, J.A., Corral, A.U. and Cerdeño, R.C.: 2005 Tiwi Injection Team Summary Report, *UPI Internal Report*, MK, 10-796, (2005).

Sunio, E.G., Villaseñor, L.B., Protacio, J.P., Regulacion, R.E., and Batayola, G.J.: 2004 Tiwi Conceptual Model Update, Part 2: Exploitation-state, *CGPHI Internal Report*, MK, 10-751, (2005).

Taylor, C.: SEHBIS Upgrade Proposal Concept Design Review, *PB Power Report*, 150202-REPT-001, (2003).

Toreja, J.S.: SEHBIS Simulation Results, *PGI Internal Report*, DOC-9932, (2001).

Vizon, J.A. and Barcelon, E.A.: Southeast Hot Brine Injection System Upgrade Proposal, *UPI Internal Report*, (2002).

Vizon, J.A., Barcelon, E.A., Cirujales, E.C., Sunio, E.G., and Ontoy, Y.C.: Infield Hot Brine Injection System Upgrade Proposal, *UPI Internal Report*, (2002).

Vizon, J.A., Villaseñor, L.B., and Regulacion, R.: Mat-ridge Hot Brine Injection System Upgrade Proposal, *UPI Internal Report*, Philippines (2005).