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Evaluation and integration of reservoir tracer results in optimizing reinjection strategies

Kenneth Jireh G. Taboco, Jennifer Espartero-Dales, Mary Ann B. Torres

Energy Development Corporation, 6th Floor Rockwell Business Center Tower 3, Ortigas Avenue, Pasig City, Philippines

taboco.kg@energy.com.ph, espartero.jc@energy.com.ph, torres.mab@energy.com.ph

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ABSTRACT

Reinjection (RI) returns or the inflow of injected brine is one of the dominant reservoir processes inherent in the Southern Negros Geothermal Production Field (SNGPF) in the Philippines. Previous studies have already shown that RI returns, when optimized, can provide artificial recharge and act as pressure support to sustain field production. Conversely, when uncontrolled, RI returns can cause severe cooling, resulting in well output decline or worse, non-commercial wellhead pressures in affected production wells. Reservoir tracer tests using Naphthalene Disulfonate (NDS) have been conducted to understand the impact of RI returns. This paper will present updates on the several tracer tests done in SNGPF and how the data was used to evaluate RI impact by simulating cooling predictions at different RI loadings for optimized reservoir management. The outcome is a well-understood connection between the reinjection and production sectors amidst a dynamic reservoir environment and effective reinjection strategy.

1. INTRODUCTION

The Southern Negros Geothermal Production Field (SNGPF) is located in the municipality of Valencia, Negros Oriental, Philippines (Fig 1). It is one of the five geothermal sites operated by the Energy Development Corporation. The field supports the operation of four (4) power plants namely: 112.5MWe Palinpinon Geothermal Power Plant (PGPP1), 20MWe OK5 Modular Power plant (OK5MPP), 48.3MWe Nasulo Geothermal Power Plant (NGPP), and 40MWe Sogongon Modular Power plant (SGMPP). PGPP1 began commercially operating in 1983—and recently celebrated its 40th year of operation—while OK5MPP and SGMPP started operating in the 1990s. NGPP, the newest power plant, was commissioned in 2014, to accommodate an additional 28.3MWe of extraction. Wells cut-in to this power plant were previously used to supply steam to 20MWe Nasuji Modular Power plant, which is currently in deactivated shutdown. The total current operating capacity of SNGPF is 220.8MWe.

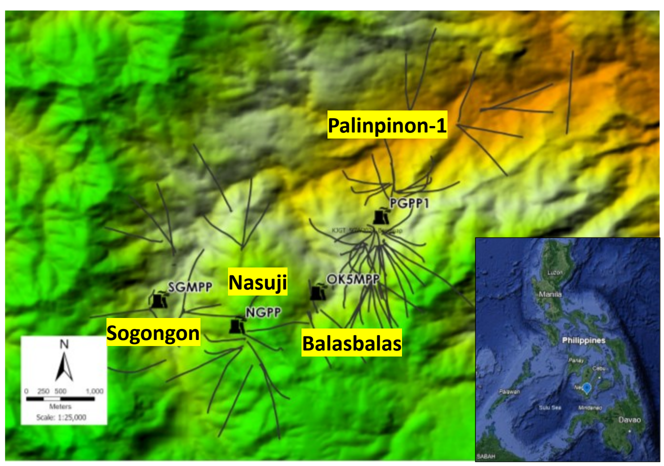

Figure 1. SNGPF location

The field is divided into two sectors: Palinpinon 1 (Pal-1) where PGPP1 is located; and Palinpinon 2 (Pal-2) which is further divided into sub-sectors: Balasbalas, Nasuji, and Sogongon. This paper will present updates of reservoir tracing conducted in Pal-1, Nasuji, and Sogongon. Wells in Balasbalas are all discharging dry wells, thus the only sector without a reinjection (RI) well.

2. REINJECTION RETURN

The majority of drilled production wells in SNGPF are liquid dominated, where water fraction is about 50-70% of the total mass flow of the well. This implies that reinjection (RI) returns is one of the dominant reservoir processes in the fields. RI returns is simply the re-entry of injected brine or condensate back to the production area through common or shared structures and/or geologic formations from the RI wells. This re-entry is driven by the high pressure of the RI sink and relatively lower pressure of the production area. Pal-1 started its operation with full reinjection of separated brine in 1983. Given the effects of RI returns at that time, the learnings from Pal-1 were applied to the development of Pal-2 (Vidal et al., 1999), such as the sufficient distance of reinjection wells from the production area and the monitoring of geochemical signatures as indication of RI returns as illustrated in Figure 2. Continued or prolonged RI return will result in an increase in water flow and/or steam flow or output decline of affected production wells. Thus, the need for effective reinjection management to ensure sustainable steam supply to the power plant is crucial and necessary.

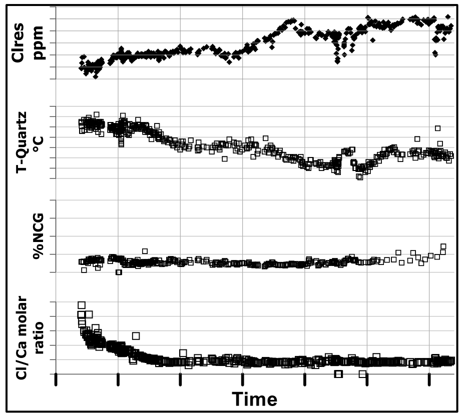

Figure 2. RI return geochemical trends

Several studies have documented the SNGPF experience for this process (Harper & Jordan, 1985; Seastres et al., 1995, Bayon & Ogena, 2005; Malate & Aqui, 2010). One of the findings is that RI returns can be a good source of artificial recharge as well as mass and pressure support (Orizonte et al., 2000), given that the reinjection brine or condensate has sufficient reheating time as it travels from the reinjection sink to the production area. In SNGPF, separated brine has a temperature of about 160°C while condensate is injected at 25-35°C. Conversely, if the RI returns fast (insufficient reheating time) and in large volumes, it will result in the cooling of affected production wells and in the worst case, decline in wellhead pressures (WHP) below commercial levels (Malate & Sullivan, 1991).

3. RESERVOIR TRACING

Monitoring of RI geochemical signatures and physical parameters (e.g., discharge enthalpy, water flow, steam flow) will determine if a well is affected by RI returns. However, monitoring of these parameters alone will not answer to what extent a production well is affected, or identify which specific reinjection well(s) are contributing to the problem. This is how reservoir tracing becomes useful, as it is used to quantify the amount of brine or condensate affecting particular production wells and determine the connections from reinjection well(s). The data acquired can then be further evaluated using cooling simulation software (i.e., TRCOOL, part of ICEBOX software package) to generate cooling scenarios at different RI loading. These scenarios will become the basis for optimum loading (the recommended amount of fluids that can be loaded to an RI well), considering the net effect on affected wells in a production sector. The cooling simulations will then be tested in the field to validate the actual responses. With the information gathered and analyzed in a robust reservoir tracing study, the reinjection strategy of an entire field can be refined.

The tracer study discussed in this paper was conducted using different isomers of Naphthalene Disulfonate (NDS), an established reservoir tracer that has been used in geothermal fields worldwide (Mella et al., 2006; Sambrano et al., 2010; Kristjánsson et al., 2016). The frequently used isomers were 2,6-NDS, 2,7-NDS, and 1,6-NDS due to their thermal stability below 330°C while 1,5-NDS was used until 2009 only and was discontinued after studies have shown that its thermal stability starts to degrade at 280°C (Dashkevich et al., 2015). These NDS tracers were utilized in different sectors and in different periods of time. Since NDS is a liquid tracer, the data gathered was limited to wells with 2-phase discharge (i.e., with water flow).

3.1 Palinpinon-1

NDS Tracer Injection in Palinpinon 1 (Pal-1) sector was first conducted in November 2009 to quantitatively evaluate the effect of the RI loading of three major injectors, RI5, RI2, and RI3 using 2,7-NDS, 1,5-NDS, and 2,6-NDS, respectively (Fig 3). The main objectives of the tracer program were to 1) validate geochemical evidence regarding the effect of RI to production, 2) confirm suspected flow paths, and 3) determine optimum RI loading in Pal-1.

The monitoring program of tracer returns was completed after a year since tracer injection. Tracer data analysis was done using ICEBOX software package. Results then showed that out of 26 production wells in Pal-1, 17 were positive of tracer returns. The tracer injected at RI5 had 100% mass recovery, while 48% was recovered for RI3, and only 22% recovered for RI2. Various RI loading scenarios for cooling model runs were conducted. To ensure accuracy of the cooling prediction, tracer models (from TRINV) were calibrated from each historical well utilization and its corresponding effect to the individual well's reservoir temperature (TQuartz). Once matched, parameters used in the model were used to determine the cooling effect of different RI loadings. The following optimum load for the three RI wells was established based on the result of the cooling simulations: 54 kg/s for RI5, 110kg/s for RI3, and >100 kg/s for RI2.

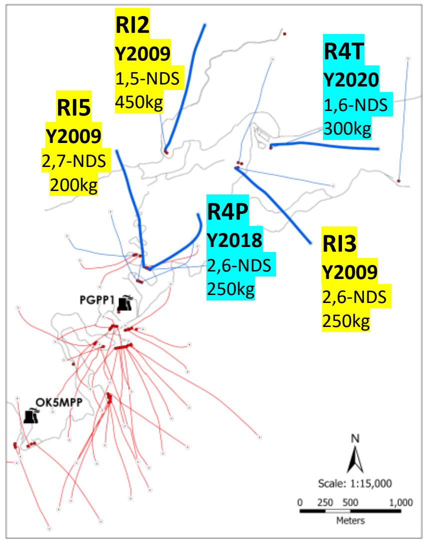

Figure 3. Pal-1 location of RI wells with tracer

Starting 2010, there was a higher extraction rate in Pal-1, brought about by the drilling and utilization of new high capacity wells (>10 MWe), particularly at the southeast area (referred to as SE wells hereinafter) of the sector. This led to pressure drawdown initially, and higher rate of reinjection returns thereafter. With the changes in mass extraction and well utilization, the second tracer program was conducted to update the optimum loading for all Pal-1 RI wells.

Tracer tests in R4P and R4T were conducted in 2018 and 2020, respectively, to determine the effect of increased cold injection at R4P and cut-in of R4T which contributed to observed TQuartz decline in SE wells. For R4P, 200 kg of 2,6-NDS were injected, while for R4T, 300 kg of 1,6-NDS were injected. Tracer data analysis using ICEBOX software package yielded that almost the same number and similar wells that had positive returns from RI5, RI3, and RI2 back in 2009 also registered positive returns with R4P and R4T. Moreover, the tracer injected at R4P had 100% mass recovery within only six months (compared to one year during the first tracer program) of monitoring. For R4T, 42% was recovered within the same period. With the fast returns observed from R4P and cooling scenarios conducted, it was determined that the well's optimum load is only 20 kg/s. R4T, on the other hand, was recommended to be shut, due to its direct connection with SE wells, causing rapid cooling.

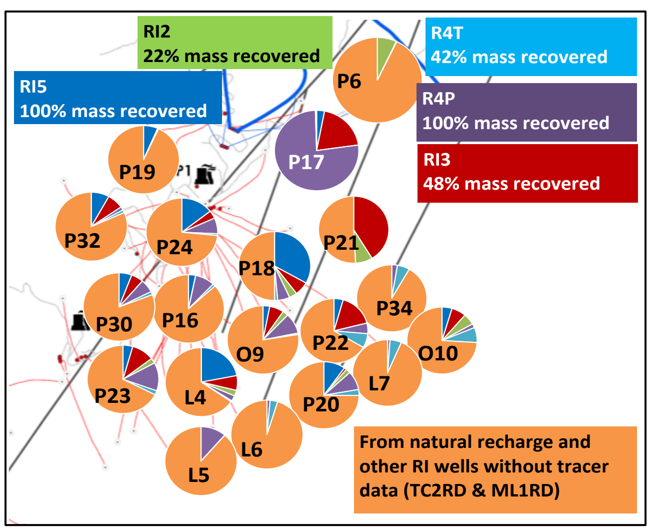

Figure 4. Palinpinon-1 RI fraction *(text inside the pie chart denotes well name)*

The results of the tracer tests conducted from 2009 to 2020 were integrated and are illustrated in Figure 4. The circles or pies represent the RI fraction of each production well at the approximate location of their bottom hole. RI fraction is a calculated value that factors in the amount of RI load and the water flow of the production well with the tracer recovery. Currently, there are 19 known production wells to have confirmed connections with the five tested reinjection wells (represented as rectangles with their respective % mass recovery). These wells intersect four common NE-SW trending structures (represented as black lines) that are identified as primary conduits conveying fluids from the RI sector to the production sector. Faults intersecting with these structures serve as a secondary flow path which would explain the well-dispersed tracer returns across the sector. The wells closest to the RI sink were expected to have higher RI fraction (i.e., P17), but was not the case for P6, which had low water flow. Some wells further from the RI sink (i.e., L5) also registered brine recovery due to common structures.

Since the implementation of these recommendations as early as 2009, the decline rate in RI-affected production wells was observed to stabilize. In the instances that power plant operations were forced to deviate from the recommended optimal loadings of wells, negative effects were quick to be felt. One such example was in 2017 when R4T was used temporarily as cold injection to accept PGPP1 condensate while a downhole survey was conducted in R5T (not show in Fig 3), the dedicated condensate RI well of said power plant. The cut-in of the well was further delayed due to the leaking along its HDPE line. It was only after six months that R5T was put back online and R4T was shut. In that span of time, a total of 10MWe drop in affected production wells was observed due to RI returns, based on physical and geochemical signatures. When cold injection was terminated in R4T, only 7–8MWe was recovered after two months. Steam recovery was later observed but at a gradual rate.

3.2 Palinpinon-2

The first NDS tracer program in Pal-2 was conducted in 2005 for two major injectors, R2J (Nasuji sector) and R2S (Sogongon sector), in order to assess the reservoir response to the increased mass extraction with corresponding higher injection rates from a planned additional power plant. R2J was injected with 200 kg/s of 1,5-NDS while R2S was injected with 200 kg/s of 1,6-NDS (Fig 5). The results of the tracer program were discussed by Maturgo et al. (2005) and concluded that the current load of both RI wells were close to optimal, that is, 80 kg/s for R2J and 60 kg/s for R2S. They also recommended that for operating an additional power plant, a new reinjection well must be drilled and should be located farther from the production sector.

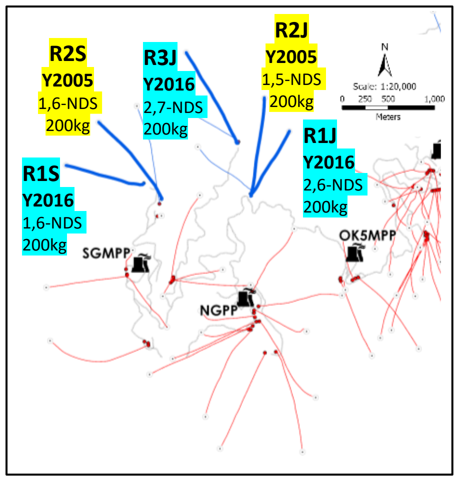

Figure 5. Pal-2 RI location with tracer test

A simultaneous discharge test (SDT) was conducted in 2011–2012 to determine the ability of the Nasuji sector to support the planned increased extraction during the operation of NGPP (Solis & Taboco, 2015). From the results of the SDT and following the recommendations from Maturgo et al., (2005), a new reinjection well, R3J, was drilled in 2014 to accept additional brine. To determine the best reinjection strategy, a tracer study was conducted in 2016 on R3J and the two remaining RI wells without tracer data: R1J and R1S. About 200 kg of 2,7-NDS, 2,6-NDS, and 1,6-NDS, respectively, were used for each RI well (Fig 5). The monitoring program of tracer returns lasted for one year.

Out of 14 production wells monitored, 11 showed positive connection with both R3J and R1J while eight wells showed positive connection with R1S. The total mass recovered was 72% from R3J, 65% from R1J, and 10% from R1S. It showed that, R3J, despite being drilled farther, still contributed a significant amount of brine going to the production sector. It goes to show that the structures intersected by R3J forms part of the network of structures that connect the RI sink to the production area. From the study, there were four major structures identified to be RI conduits.

Given the results of the cooling simulations, R3J was recommended to be operated at 100 kg/s, despite its 180 kg/s capacity. R1J was recommended to be shut due to the fast arrival of tracers (1–3 days). Lastly, R1S, which had the lowest tracer recovery, was recommended for an optimal loading of 35 kg/s out of its capacity of 100 kg/s. Its optimal loading was considered for further testing once there was a need for more brine. With the addition of two production wells starting 2016, R1S is currently accepting 89 kg/s with no significant RI return observed in the production wells of Pal-2.

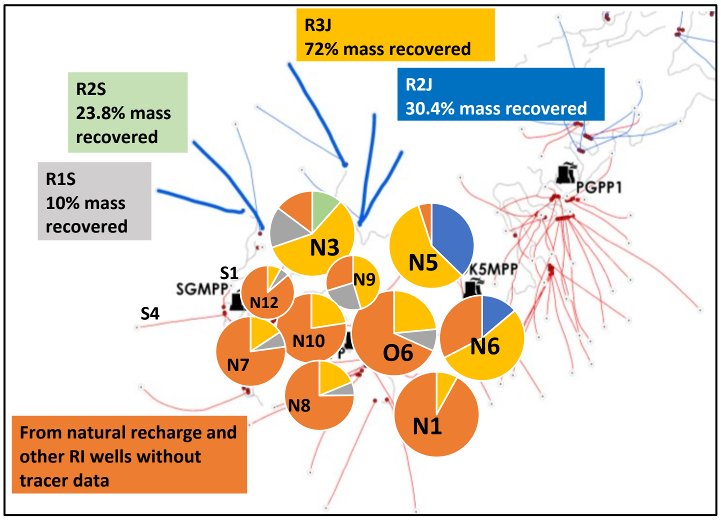

Figure 6. Palinpinon-2 RI fraction *(text inside the pie chart denotes well name, fraction from R1J not included as well was shut)*

Integrating the 2005 and 2016 tracer results, Figure 6 illustrates the RI fraction of each production well. Similar to PAL-1, wells that are nearest to the RI sink had higher RI fraction (i.e., N3 and N5). N6, although farther, also showed a significant RI fraction, likely because of its location. It is the only well in the southeast area drawing in from the deeper liquid feed while its neighboring Balasbalas wells are drawing from the shallower region (not in map). For R2S, only one well has a confirmed tracer recovery. Other wells also registered positive returns but tracer recovery was too low (<2.5 ppp) (Maturgo et al., 2005). It is believed that currently more production wells have a connection to this RI. A new tracer test is planned to be executed in 2024 to 1) confirm connections with R2S, 2) update the optimal loading of R1S, and 3) test the new RI well, R4J. In addition to NDS tracer, injection of gas tracer will also be conducted to confirm suspected connections of Nasuji RI wells to the high enthalpy (i.e., dry discharge) wells of Balasbalas. Since 2016, an addition of four production wells have been drilled and utilized, thus, the need to further refine the reinjection strategy of Pal-2 to ensure sustainable steam supply to the three power plants in the sector.

4. CONCLUSION

Effective reinjection strategies are crucial to resource management in the Southern Negros Geothermal Project Field, where majority of the production wells are liquid dominated and where reinjection returns is a dominant reservoir process. The experience of SNGPF in reservoir tracing in the span of almost two decades has shown benefits in improving decline rate management (through RI optimum loading), proper planning and design of future production and reinjection wells (identification of RI conduits), and overall, a better appreciation of the impact of RI returns in an exploited geothermal system. Moving forward, testing other tracers (i.e., gas tracers) to determine the impact of RI returns to dry wells will be incorporated to improve overall resource management.

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