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Reservoir Tracer Testing in Maibarara Geothermal Field: Evolution of Maibarara's Field Management Strategy

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INTRODUCTION

The Maibarara Geothermal Field, located about 70 km southeast of Manila, is one of the two active geothermal systems associated with Mt. Makiling, alongside the Makiling-Banahaw (Mak-Ban) Field. Covering a 9-hectare development area northwest of Mt. Makiling, Maibarara has a total installed capacity of 32 MW from its two power plant units. The 20-MW Maibarara-1 Geothermal Power Plant (M1GPP) began operations in February 2014, while the 12-MW Maibarara-2 Geothermal Power Plant (M2GPP) was commissioned in April 2018.

The Maibarara Geothermal Power Facility (MGPF) was developed within a compact 9-hectare zone, integrating the steam field, power plant, and switchyard to maximize land use. Limited space required the separator vessels to share pads with production and reinjection wells, leading to the adoption of an infield hot reinjection scheme in 2013. Hot separated brine was then reinjected into MAI-9D and MAI-11D (Esberto et al., 2021). Although hot reinjection offers advantages such as minimizing reservoir cooling and reducing operational costs by eliminating pumping systems, MGPF experienced a gradual decline in reinjection capacity during hot reinjection operations. This decrease in injectivity is attributed to hot reservoir conditions in which elevated formation temperatures limit the acceptance of reinjected hot fluids. In 2014, MGPF transitioned to a cold reinjection strategy following a series of cold injection tests that demonstrated improved well injectivity at lower brine temperatures, resulting in higher reinjection acceptance (Maturgo et al., 2015). Since then, MGPF has maintained this cold infield reinjection (IRI) scheme, with tracer tests in 2016 and 2022 evaluating operational performance and subsurface connectivity.

1 RESERVOIR RESPONSE TO INFIELD REINJECTION (IRI) STRATEGY

In 2014, when the only operational unit was the 20-MW Maibarara-1 Geothermal Power Plant (M1GPP), the production wells in use were MAI-6D and MB-12D. The reinjection wells at the time included MAI-9D and MAI-11D for the injection of separated brine, and MB-14RD for the power plant condensates. That same year, wells MB-15D and MB-16RD were drilled as production and reinjection wells, respectively, for the planned 12-MW M2GPP expansion.

During this period, all wells are located within the compact Maibarara field, where reinjection follows a cold infield reinjection (IRI) system. Separated brine is discharged via an atmospheric silencer, cooled through thermal ponds and brine canals, and reinjected into the reservoir through designated wells.

Continuous monitoring of physical and geochemical parameters revealed the reservoir's response to the IRI system. Between early 2015 and 2016, production well MB-12D began showing signs of reinjection returns (Fernandez et al., 2021). Over more than 10 months, brine production increased six times its baseline value, while the enthalpy declined from ~2200 kJ/kg to ~1790 kJ/kg. Chloride concentration at reservoir conditions rose by ~4000 ppm, accompanied by a decline in the non-condensable gases (NCG) carbon dioxide (CO_2) and hydrogen sulphide (H_2S). The reservoir temperature, estimated via Na/K geothermometer, decreased by around 33°C within ~10 months. These changes indicated the influx of low-enthalpy, high-chloride, low-gas fluid, which is consistent with reinjection fluid breakthrough. The steam flow from MB-12D initially increased by approximately 7 kg/s, possibly due to the heating of the injection fluids. However, this increase was only temporary, and the steam flow eventually returned to its baseline level. The reinjection wells active during this period were MB-14RD and MB-16RD. To mitigate breakthrough and boost reinjection capacity, especially as MB-16RD's capacity has begun to decline, MB-17RD was drilled in 2016.

From mid-2021 until 2023, a similar reinjection breakthrough was observed in MB-12D's reservoir. However, the changes in brine production, enthalpy, chemistry, and temperature during this period were more gradual and

less prominent. At this time, the reinjection wells in use were MB-14RD and MB-17RD, while MB-16RD had already been isolated from the system and placed on standby.

2 RESERVOIR TRACER TEST

Maibarara has conducted two reservoir tracer studies—one in 2016 and another in 2022. These studies aimed to identify subsurface fluid pathways and assess the degree of interconnectivity between reinjection and production wells. The method involves injecting distinct chemical tracers into reinjection wells and monitoring their breakthrough in production wells to track fluid movement and connectivity.

2.1 Methodology

The 2016 tracer study utilized MB-14RD and MB-16RD as reinjection wells, with MAI-6D and MB-12D serving as monitoring wells. Two tracer chemicals—1,5-Naphthalenedisulfonic acid (1,5-NDS) and 2,6-NDS—were injected into MB-14RD and MB-16RD, respectively, at a quantity of 300 kg each. In the 2022 study, MB-14RD and MB-17RD were used as reinjection wells, with the same monitoring wells as in 2016 (MAI-6D and MB-12D), along with the addition of production well MB-15D. The tracers used in 2022 were 2,7-NDS and 1,6-NDS, injected into MB-14RD and MB-17RD, respectively, at 100 kg each.

The difference in tracer mass used between the 2016 and 2022 reservoir tracer tests reflects the differing objectives and levels of reservoir understanding at the time of each study. The 2016 test represented the first reservoir tracer test conducted in the Maibarara field; therefore, a conservative approach was adopted, and a relatively larger tracer quantity was injected to ensure adequate tracer recovery and reliable detection. In contrast, by 2022, subsurface flow paths had been better constrained based on earlier tracer responses, allowing for a more optimized tracer dosage while still achieving test objectives. For this paper, only the results from monitoring well MB-12D are presented and discussed.

At the beginning of each tracer study (2016 and 2022), baseline concentrations of the tracer chemicals were established to accurately monitor tracer breakthrough in the production wells. For MB-12D, the baseline concentration for all tracer chemicals used in both studies was 0.04 parts per billion (ppb). During the monitoring phase, samples were collected via a ¼-inch cooling coil connected to the bottom sampling point along MB-12D's branchline (Figure 1). The coil was submerged in a cooling bucket to maintain sample temperatures below 35 °C. Sampling was conducted twice daily during the first week of each study, then reduced to once daily from the second week onward, continuing until a decline in tracer concentration was observed. The sampling methodology and frequency were consistent across both the 2016 and 2022 tracer studies.

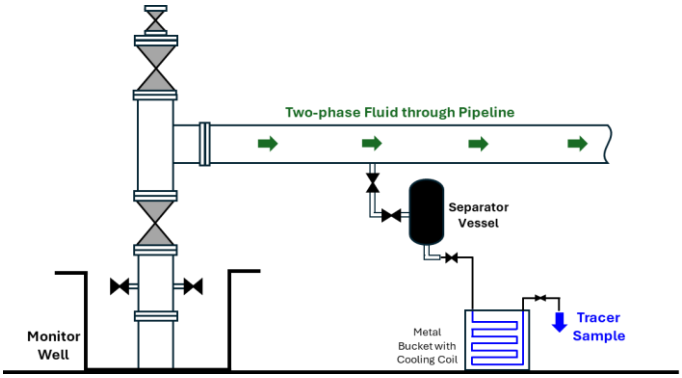


Figure 1. Tracer sample collection from the monitor well.

The tracer samples collected from the monitoring wells were analyzed for the presence of the tracer chemicals. Subsequently, the resulting tracer concentration data were plotted against time to identify key parameters such as breakthrough time and peak concentration. The breakthrough time refers to the day when the tracer chemical is first detected in the monitoring well.

The monitoring of MB-12D continued until the tracer concentrations returned to baseline levels, which marked the completion of the tracer monitoring phase.

2.2 Data Processing and Analysis

Following the completion of the tracer monitoring phase, the concentration data were processed using the ICEBOX software (Arason et al., 2004). This analysis provided estimates of tracer recovery and enabled simulation of the cooling influence of reinjection wells on the production sector. The same principles and

equations for tracer recovery and thermal breakthrough prediction outlined by Axelsson et al. (2005) were applied. Equations 1 and 2 were used as the basis for the tracer recovery calculation and cooling predictions, respectively, for MB-12D:

$$m_i(t) = \int_0^t C_i(s)Q_i(s)ds \tag{1}$$

$$T(t) = T_0 - \frac{q}{Q}(T_0 - T_i)\left[1 - \text{erf}\left\{\frac{kxh}{c_w q\sqrt{\kappa(1-x|\beta)}}\right\}\right] \tag{2}$$

where in Equation 1, $m_i(t)$ indicates the cumulative mass recovered in production well number i (kg), as a function of time, C_i indicates the tracer concentration (kg/L or kg/kg) and Q_i the production rate of the well in question (L/s or kg/s, respectively). Meanwhile, for Equation 2, $T(t)$ represents the production fluid temperature, T_0 the undisturbed reservoir temperature, T_i the injection temperature, q and Q the rates of injection and production, respectively, erf the error-function, k the thermal conductivity of the reservoir rock, κ its thermal diffusivity, x the distance between the injection and production well.

Tracer data from both the 2016 and 2022 studies were processed using the ICEBOX software. In 2016, the data were initially analyzed using the DOS-based version of ICEBOX, as shown in the paper of Marzan et al. (2021), but were later reprocessed using the web-based version for consistency and improved functionality. In contrast, the 2022 tracer data were processed directly using the web-based version of the software.

Table 1. Tracer chemical breakthrough and recovery in MB-12D from each reinjection well.

Year	Tracer	Reinjection Well	Tracer Breakthrough in MB-12D (days)	Tracer Recovery (%)
2016	1,5-NDS	MB-14RD	30	0.09
	2,6-NDS	MB-16RD	1	87
2022	2,7-NDS	MB-14RD	4	60
	1,6-NDS	MB-17RD	5	23

Table 1 shows the summary of the tracer breakthrough time as well as the tracer recovery in MB-12D from each reinjection well, and the results show contrasting flow paths. In the 2016 reservoir tracer study, MB-12D recovered only 0.09% of the tracer from MB-14RD, indicating weak hydraulic connectivity. In contrast, the tracer injected into MB-16RD exhibited rapid breakthrough to MB-12D and a high tracer recovery of 87%, confirming a strong, direct connection between these two wells. In the 2022 tracer study, the connectivity between MB-14RD and MB-12D significantly increased, with tracer recovery reaching 60%. For MB-17RD, despite a fast breakthrough in MB-12D, tracer recovery was lower at 23%.

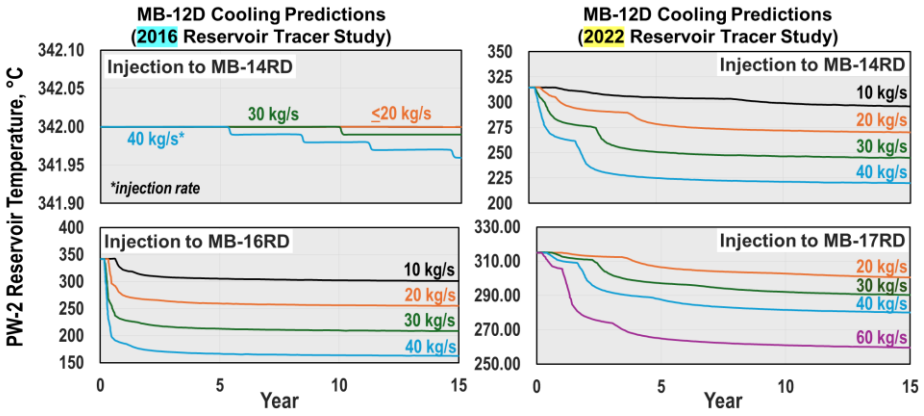


Figure 2. Cooling predictions of the MB-12D reservoir using the 2016 and 2022 tracer models, incorporating multiple injection rate scenarios.

After calculating the tracer recovery, the MB-12D model was used to simulate reservoir cooling under different reinjection flow rates over set time periods (Figure 2). The goal was to predict how MB-12D's reservoir would respond to continuous injection based on well connections identified in the tracer study.

Results from the 2016 tracer data showed rapid cooling in MB-12D's reservoir with injection into MB-16RD, even at a low flow rate of 10 kg/s, while injection into MB-14RD showed negligible cooling. In contrast to MB-14RD's negligible cooling effect based on the 2016 trace simulation results, the 2022 MB-14RD to MB-12D simulation indicated significant cooling (>10°C) within 1–2 years at flow rates above 10 kg/s. Meanwhile, for MB-17RD, cooling in MB-12D's reservoir could occur within a year if injection exceeds 30 kg/s.

3 DISCUSSION

As discussed in the previous sections, Maibarara experienced two episodes of reinjection returns in MB-12D's reservoir. Given the proximity of production and reinjection wells, reinjection fluid breakthrough to MB-12D was anticipated under both hot and cold infield reinjection schemes. This expectation is primarily due to the shared fault, Siam-siam Fault, between MB-12D and MB-14RD, which could serve as a potential pathway for reinjection fluids to migrate back into the production sector. However, the rapid cooling observed during the first breakthrough (2015–2016) was unexpected, as MB-14RD was then used only for plant condensates, and MB-16RD—also in use—was not known to share any fault with MB-12D.

The 2016 tracer study clarified these dynamics. It confirmed weak connectivity between MB-12D and MB-14RD (0.09% recovery) and revealed a strong, direct connection with MB-16RD (87% recovery), indicating an unmapped fault (Figure 3), later named as Tago or "Buried" Fault. This led to operational adjustments, shifting reinjection from MB-16RD to a newly drilled injection well in 2016, which was MB-17RD. This allowed MB-12D to recover from the first reinjection breakthrough.

The second reinjection breakthrough (2021–2023) involved the infield reinjection wells MB-14RD and MB-17RD. The changes observed in MB-12D's physical and geochemical parameters during this period were more gradual than in the first episode (2015-2016). MB-14RD was identified as the primary contributor for this RI breakthrough, as its role evolved from handling small condensate volumes in 2015 to accepting larger reinjection loads by 2016. The 2022 reservoir tracer study indicated a possible enhanced connectivity between MB-14RD and MB-12D based on the higher tracer recovery in the 2022 tracer study compared to the 2016 study (~0.09%). The possible enhanced connectivity might have been likely influenced by a chemical workover on MB-14RD in June 2021, which might have increased hydraulic connectivity and reinjection returns.

The same tracer study also confirmed a connection between MB-17RD and MB-12D with a tracer recovery of around 23%, possibly via the Kapos and Siam-Siam Faults (Figure 3). Although MB-17RD does not share a direct fault with MB-12D, reinjection fluids may migrate through the Kapos Fault and reach MB-12D via the Siam-Siam Fault.

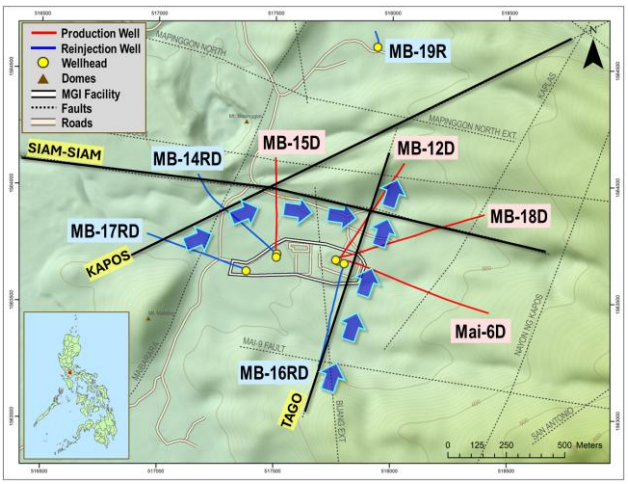


Figure 3. Map showing the discovered "Tago" (or Buried) Fault through the 2016 Reservoir Tracer Study, including the Siam-Siam and Kapos Faults, which connect MB-14RD and MB-17RD to MB-12D.

Cooling prediction simulations based on the 2016 and 2022 tracer studies provided critical insights into the potential thermal response of MB-12D's reservoir under continued high-volume reinjection into MB-14RD, MB-16RD, and MB-17RD. The results indicated a significant risk of reservoir cooling, prompting the need for a revised field management strategy to safeguard resource sustainability for the Maibarara field.

Building on these findings, along with other reservoir assessments, MGI implemented an Outfield Reinjection (ORI) strategy. In July 2024, an ORI well, MB-19R, was drilled in a pad north of the existing MGPF and has been

operational since then (Figure 3). The ORI system enabled MB-12D to recover from the second reinjection breakthrough (2021–2023), increased overall reinjection capacity, and introduced operational flexibility. The ORI system now allows a balanced approach—maintaining infield reinjection for reservoir recharge when necessary, while diverting excess fluids outfield to minimize thermal interference and ensure long-term field stability.

4 CONCLUSION

The 2016 and 2022 reservoir tracer studies provided critical insights into reservoir connectivity and thermal behavior in the Maibarara field, shaping the evolution of its field management strategy.

The key findings of the 2016 and 2022 reservoir tracer studies include:

- The 2016 reservoir tracer study showed that tracer chemicals traveled to MB-12D's reservoir within 30 days from MB-14RD and just 1 day from MB-16RD. Meanwhile, the 2022 study indicated that tracers injected into MB-14RD and MB-17RD reached MB-12D in 4 and 5 days, respectively.
- The first injection breakthrough, observed between 2015 and 2016, was attributed to an unmapped fault—the Tago Fault—between MB-12D and MB-16RD, which caused rapid cooling in MB-12D's reservoir.
- The second injection breakthrough, occurring from 2021 to 2023, originated from MB-14RD and MB-17RD through intersecting faults. The 2022 tracer study revealed a possible enhanced connectivity between MB-14RD and MB-12D, likely influenced by a chemical workover on MB-14RD.
- Cooling simulations confirmed that a continued infield reinjection (IRI) strategy posed a significant risk of reservoir temperature decline due to the wells' subsurface connectivity through faults.

In response to the findings from these studies, Maibarara adopted an Outfield Reinjection (ORI) strategy to safeguard reservoir integrity. ORI not only mitigated thermal interference from reinjection fluid breakthrough but also increased reinjection capacity and operational flexibility, enabling a balanced approach between infield recharge and outfield diversion. This case demonstrates the value of tracer testing and predictive modeling in guiding adaptive geothermal field management for long-term sustainability.

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