Geochemical Parameters for Evaluating Brine Outfield Injection Impact at Salak, Indonesia

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ABSTRACT

Salak Geothermal Field has implemented brine infield injection since it began commercial production in 1994. While infield injection provides pressure support to sustain production, it can also lead to reservoir cooling, negatively impacting the production wells if the injected brine does not heat up before reaching the producers. This cooling process has caused a significant decline in production in several two-phase production wells at Salak. To address this issue and ensure long-term reservoir performance, brine injection was relocated to the outfield and edge-field area. Integrated reservoir analyses, including reservoir, geochemistry, and geophysics data, are being conducted to monitor the impact of brine outfield injection on the production wells. Various geochemical parameters and methods, such as chloride, enthalpy, non-condensable gas (NCG), and the 7-component Geochemistry Mixing Models, are being used to evaluate the marginal recharge influx and steam cap development following the implementation of outfield injection. Three years after the implementation, two-phase production wells at Salak show a decreasing chloride trend, indicating a reduced impact of brine injection breakthrough. The 7-component Geochemistry Mixing Model also suggests more contribution from the Mass-In-Place (basal upflow) and less contribution from brine injectate, with no increase in marginal recharge influx despite the continuous drop in reservoir pressure and increasing voidage. Enthalpy and total NCG data have increased, implying steam cap development. This is further confirmed by reservoir data, which shows a decreasing liquid level and improved production performance. Overall, brine outfield injection at Salak appears to have a positive impact by accelerating steam cap development and has effectively halted further cooling in the reservoir.

1. INTRODUCTION

Salak geothermal field (also known as Awibengkok) is the largest geothermal producer in Indonesia with an installed capacity of 381 Mwe and is situated approximately 70 km south of Jakarta in West Java. The first commercial production at Salak commenced in 1994 with the commissioning of the 55 MW Unit 1 and Unit 2. In 1997, Units 3, 4, 5, and 6 were commissioned with a capacity of 55 MW from each unit. In 2004, Unit 4/5/6 were uprated to generate 65.6 MW and re-uprated in early 2022 to 67 MW, while Unit 1/2/3 were uprated to 60 MW (Kurniawan et al., 2023). Under the JOC with Pertamina (now PT. Pertamina Geothermal Energy, or PGE), Star Energy Geothermal Salak (SEGS) supplies the steam to Units 1, 2, and 3. Units 1,2,3 are owned by the Indonesia State Electricity Company or PT. PLN, and operated by its subsidiary, PT Indonesia Power. SEGS supplies steam, operates, and generates electricity from Units 4, 5, 6, and is the owner of these facilites.

1.2 Injection Breakthrough

In 1994, the produced brine was injected infield into the hottest portion of the reservoir, which is at AWI I (**Figure 1**), to economically develop units 1 and 2 (Golla et al., 2020). At that time, it was also viewed that the brine produced from generating 110MW would not significantly harm the high-temperature reservoir. However, after several years of infield injection, most production was experiencing cooling due to injection breakthrough, shown by the changing chloride trend through time (**Figure 2**). To maintain reservoir performance for successful long-term management of the Salak Field, a proper balance between pressure support and thermal breakthrough was a crucial part (Acuna et al., 2008). This led to a plan for relocating brine injection to deeper and more distal locations along the field margin and outside the field production boundary. This strategy is expected to result in steam cap expansion and mitigate high production decline rates.

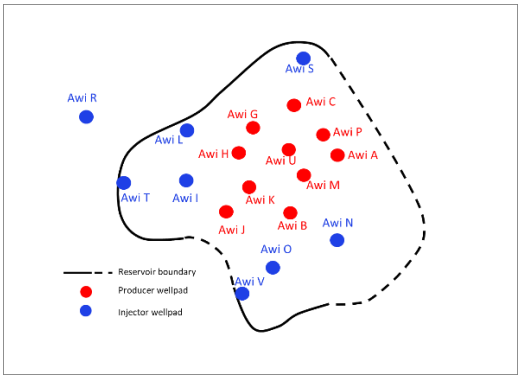


Figure 1. Location of producers and injectors at Salak.

1.3 Salak Injection Realignment Program

Salak Injection Realignment Program (SIRP) is intended to accelerate steam cap expansion and mitigate cooling issues due to injection breakthrough at western production wells by moving the brine and condensate injectate to a more distal location. The program consists of Condensate Out Injection (COI), Proximal Southeast (PSE), and Brine Outfield Injection (BOI). The COI was completed in mid-2013 and could move all condensate injection outfield or at the edge of the field, to AWI S-3, AWI V-1ST, and AWI R (Kurniawan et al., 2023). Based on the geochemistry monitoring, there is no condensate injection breakthrough to the main reservoir after the COI implementation.

The PSE was started to partially implement by the end of 2020, by moving 1,300 kph of brine from AWI I to AWI N and O injectors. The full implementation of moving 2,600 kph was completed in early 2022. The BOI was fully implemented in early 2022 by moving the 1,800 kph brine from infield injection at AWI I to the outfield at AWI R. AWI R was previously used as condensate injectors. For the BOI implementation, the condensate was diverted to AWI T-1 and AWI V-1.

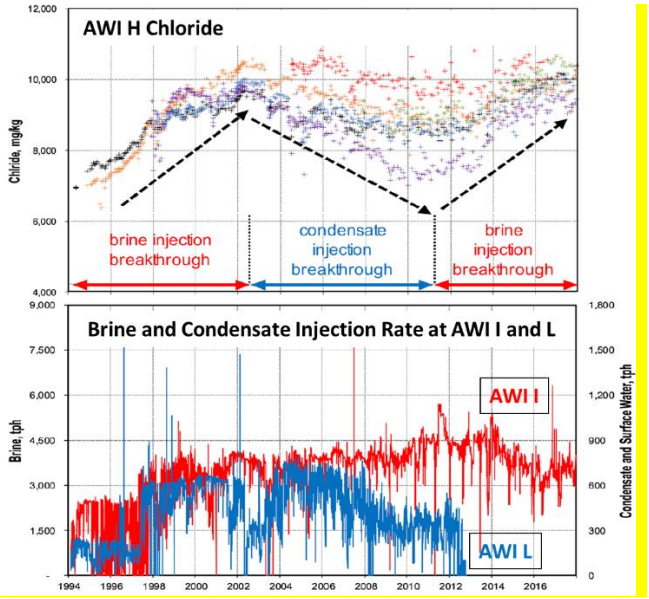


Figure 2. Historical chloride concentration showing the impact of brine and condensate injection breakthrough as observed in AWI H wells, with total brine and condensate rate injected at AWI I and AWI L (modified from Golla et al., 2020).

2. GEOCHEMICAL PARAMETERS

Surveillance activities are conducted to monitor reservoir performance, such as well's production performance, reservoir pressure response, liquid level monitoring, liquid reservoir temperature evolution, and geochemistry monitoring after the SIRP implementation. Routine geochemical monitoring includes chloride, Non-Condensing Gas (NCG), enthalpy, and comprehensive liquid chemistry analysis. The data are analyzed using a time series plot, ternary diagram, and the 7-component geochemistry mixing model.

2.1 Chloride, NCG, and Enthalpy

Chloride is a conservative element and is present in the liquid phase. When the two-phase fluid is separated into steam and brine on the surface, the chloride will partition into the brine, resulting in a higher chloride concentration in the brine. Then the brine is reinjected into the re-injection well. If there is connectivity between the producers and injectors, the reservoir chloride trend of the producers will increase through time due to a mix between the mass-in-place fluid and the high-chloride content brine injectate. And vice versa, if there is a decreasing chloride trend over time, then it can indicate less brine injection breakthrough or dilution with low-chloride concentration fluid (e.g. condensate injectate, marginal recharge). Therefore, chloride can be an indicator of brine injection breakthrough occurring in the reservoir. In Salak geothermal field, Chloride analysis is conducted monthly from all two-phase wells using titration. The surface chloride concentration is returned to the reservoir chloride concentration by a flash-corrected process. The chloride trend analysis is conducted using reservoir chloride concentration.

NCG are gas species that cannot condense to the liquid phase. The NCG content in the steam cap tends to be greater compared to the NCG content produced from the flashing of reservoir brine (Rohrs et al., 2010). Consequently, production from the steam cap influences the total NCG production of a well. In two-phase wells, total NCG content will increase over time if there is a boiling or steam cap development process because the entries of the steam cap contain more gas than steam flashed from the brine reservoir. In Salak, the total NCG content is measured monthly using a wet-test meter (WTM), and comprehensive analysis for each gas species in NCG is analyzed using a gas chromatograph semi-annually.

Enthalpy is necessary for geochemical data interpretation because it determines steam fraction at sampling conditions and allows correction of chemical concentration back to reservoir condition (flash-correct process) (Hirtz et al., 2001). Enthalpy data is used to understand the reservoir process. If there is increasing enthalpy over time, then it indicates boiling and steam cap development. And vice versa, if there is a decreasing enthalpy trend, it indicates cooling due to injection breakthrough or marginal recharge/groundwater influx. In Salak, enthalpy data is obtained quarterly from the Tracer Flow Testing (TFT) sampling.

2.2 The 7-Component Geochemistry Mixing Model

The 7-component geochemistry mixing model is developed by Sunio and Molling (2009) to assess the historical influx of marginal recharge (MR) into the Salak reservoir to support the improvement of the field numerical model and field management activities for selected wells. Other aims of this mixing model are to assess the composition changes of the Salak production liquids, evaluate the proportions of brine/condensate injectate, estimate the amount of original mass-in-place (MIP) composition, and identify the injectors that may be impacting a particular producer in a given year (Julinawati et al., 2011). It quantifies the liquid composition of a production well using 7 chemical species: Cl, B, SO_4, HCO_3, NH_4, Ca, and Mg. The end-member compositions are Mass-In-Place (MIP), Brine Injectate (BI), Condensate Injectate (CI), and Marginal Recharge (MR). The MIP composition is taken from the baseline chemistry data, representing the initial reservoir condition. Brine and condensate injection data are taken from the injection wells in the same year where the production liquid chemistry is sampled. MR data is taken from historical downhole samples or surface samples. The complexity of the matching technique led to the development of a "matching score" from 1-10. The score of each chemical species is listed in **Table 1**. Several assumptions are used for this method:

- Matching technique requires a match with Cl, and then B as a second priority, then with the rest of the species SO4, HCO3, NH4, Ca, and Mg as the last priority.
- Cl is the first element matched, and then B because these species are hydrophilic (i.e., conserved in the liquid). A "best" match always assumes that Cl and B are matched before any other species.

- Full score is given if the value is within the range for a given chemical species.
- Half score is given if the matched value is within 10% of the measured range of values for a given chemical species.
- Brine injectate is always part of the mix.

Table 1. Score of each chemical species used for 7-component geochemical mixing model.

Constituent	Score	Assumption
Cl	3	Conservative
B	2	
SO_4	1	Affected by boiling
HCO_3	1	
Mg	1	Affected by carbonate precipitation
Ca	1	
NH_4	1	Enriched during boiling

The analysis of 7-component mixing models is conducted for all two-phase production wells annually, using the reservoir composition of the liquid, taken from the semi-annual comprehensive sampling. The result of each year is compared over time to determine changes in liquid composition. An example of the 7-component mixing model is shown in **Table 2**. With a proportion of 28% MIP, 70% brine injectate, and 2% marginal recharge, a score of 8.5 is obtained with 5 elements matched between the mixing model results and the actual data, and 1 element is within the 10% range.

Table 2. An example of the 7-element geochemistry mixing model using MIP, brine injectate, and marginal recharge as the endmembers.

Data	Proportion/ Total	Cl (ppm)	B (ppm)	SO_4 (ppm)	HCO_3 (ppm)	Mg (ppm)	Ca (ppm)	NH4 (ppm)
Basal Upflow (MIP)	28%	6267	214	7	29	0.07	146	2.2
Brine Injectate	70%	11233	414	21	37	0.27	572	5.6
Marginal Recharge	2%	186	9	550	103	18.00	56	3
Mixing model result		9658	351	25	36	0.49	443	4.6
Actual data from well		9551 - 9942	347 - 358	24 - 27	35 - 39	0.44 - 0.49	464 - 552	3.0 - 3.2
Score	8.5	3	2	1	1	1	0.5	0

3. GEOCHEMICAL MONITORING RESULTS

3.1 Chloride Trend

The monthly chloride trend from the two-phase production wells shows a decreasing trend after the SIRP implementation (**Figure 3**). This decreasing chloride trend might indicate less brine injection breakthrough impact from the previous brine injection wells, AWI I wells. However, another hypothesis related to the decreasing chloride trend might be related to dilution with Marginal Recharge influx. The 7-Component Geochemistry Mixing Model is used to validate the hypothesis, whether the decreasing trend is due to less brine injection breakthrough, or due to mixing of a dilute marginal recharge liquid.

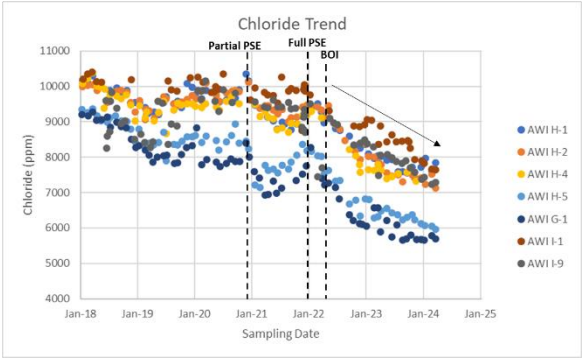


Figure 3. Chloride trend of western two-phase production wells.

3.2 The 7-Component Geochemistry Mixing Model

Numerical modeling result indicates that Salak Injection Realignment Program (SIRP) is crucial in improving long-term reservoir performance (Kurniawan et al., 2023). Such massive and rapid voidage may allow marginal recharge fluid entering the reservoir, preventing steam cap development and cooling it. The reservoir process can be determined by quantifying the composition of MIP, brine injectate, and marginal recharge of the wells and analyzing the changes over time using the 7-component geochemistry mixing model. Results of the 7-component geochemistry mixing model of some wells are shown in **Table 3** and **Figure 4**. The results show that those wells have a decreasing brine injectate composition after implementing the SIRP. The net voidage due to decreasing brine injection is replenished by the basal upflow, which is shown by increasing MIP proportion over time. There is no increasing marginal recharge influx, confirmed by no increase in MR proportion over time.

Table 3. Results of the 7-Component Geochemistry Mixing Models.

Well	Year	Mass-In-Place	Brine Injectate	Marginal Recharge	Score
AWI G-1	2019	46.8%	45.7%	7.5%	6
	2020	54.1%	38.4%	7.5%	6.5
	2021	61.4%	29.6%	9.0%	7.5
	2022	75.3%	17.7%	7.1%	7.5
	2023	89.1%	1.0%	9.8%	5
AWI H-1	2019	27.6%	71.9%	0.5%	6
	2020	32.1%	66.9%	1.0%	5
	2021	41.9%	56.7%	1.3%	6
	2022	46.9%	51.7%	1.4%	6.5
	2023	60.3%	37.5%	2.2%	5
AWI H-2	2019	30.8%	68.6%	0.5%	6.5
	2020	33.1%	66.7%	0.3%	6
	2021	38.4%	59.7%	1.9%	6
	2022	42.2%	55.9%	1.9%	6
	2023	66.2%	32.0%	1.9%	7
AWI H-5	2019	40.2%	54.5%	5.3%	5
	2020	57.7%	40.0%	2.2%	6.5
	2021	70.2%	27.2%	2.7%	7
	2022	77.8%	19.3%	2.9%	6
	2023	94.0%	2.0%	4.0%	6.5
AWI I-1	2019	45.6%	53.7%	0.7%	9
	2020	20.7%	77.7%	1.6%	8
	2021	28.3%	70.1%	1.5%	8.5
	2022	35.4%	62.7%	2.0%	8.5
	2023	45.6%	53.0%	1.4%	6
AWI I-9	2018	28.2%	65.3%	6.5%	5
	2020	17.8%	76.4%	5.7%	5
	2021	24.9%	69.6%	5.5%	6
	2022	27.9%	67.9%	4.2%	6
	2023	60.9%	38.0%	1.1%	6.5

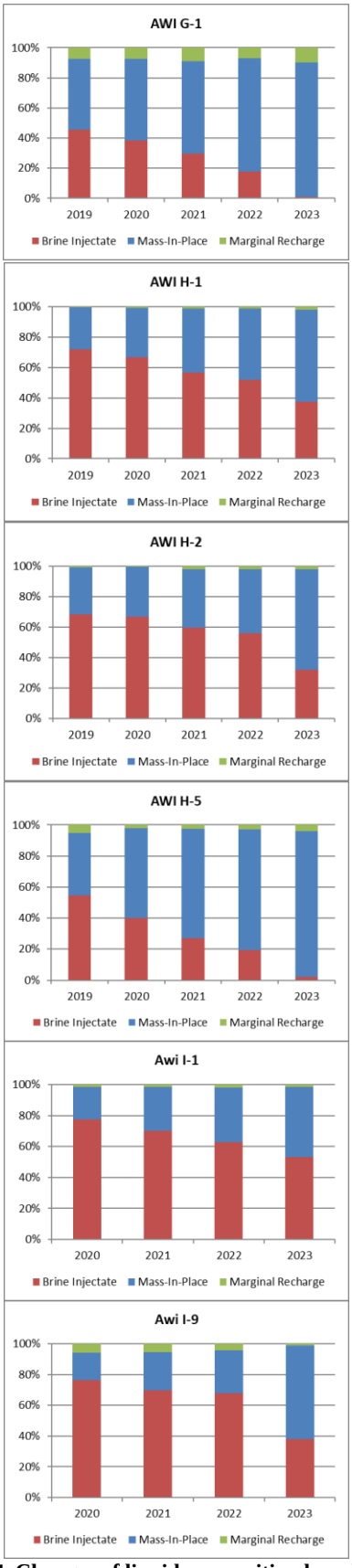


Figure 4. Changes of liquid composition based on the 7-Component Geochemistry Mixing Models of several two-phase production wells.

3.3 NCG and Enthalpy Trend

Some production wells experience better performance as a beneficial effect due to SIRP implementation. One of the wells is AWI H-5, which shows steam cap development caused by reservoir pressure drop after brine infield injection was reallocated to the outfield and edge field. The steam cap development is shown by an increasing NCG and enthalpy trend, accompanied by a decreasing brine rate (**Figure 5**).

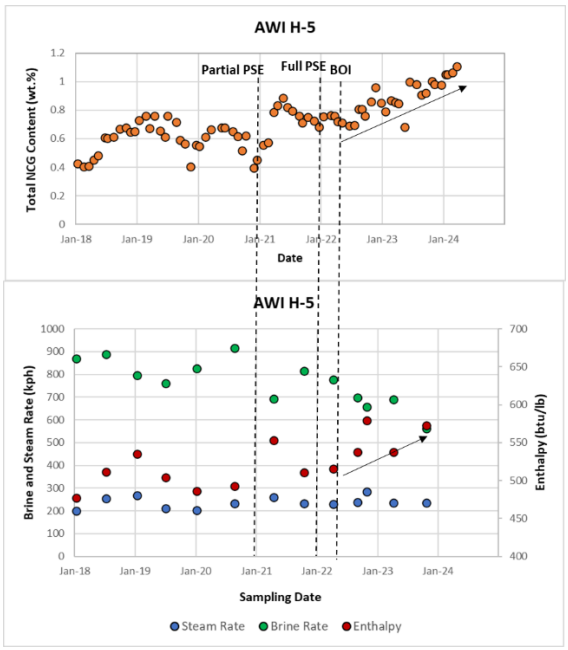


Figure 5. Increasing NCG and enthalpy trend at AWI H-5 after full implementation of SIRP.

A decrease in the liquid level further confirms the establishment of steam cap. Initially, the steam cap is produced by the shallowest feed zone that is located above the liquid level (**Figure 6**). Following the SIRP implementation, a decrease in reservoir pressure resulted in a subsequent reduction in liquid level. Currently, the top two feed zones are above the liquid level. This evidence validates the benefits of shifing brine injection from the infield to the outfield and edge field, and supports the boiling process that takes place in this well.

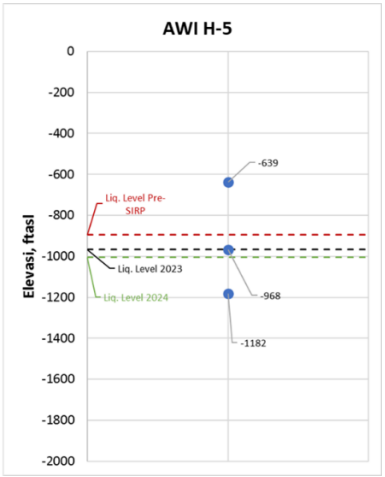


Figure 6. Evolution of liquid level at AWI H-5.

Aside from total NCG content, gas geochemistry interpretation using N_2-CO_2-Ar ternary diagram can also be used to determine the existence of marginal recharge in a well. Enrichment of N_2 and Ar might indicate a source of groundwater influxthat enriches N_2 and Ar from the atmosphere before entering the reservoir. An example of wells with marginal recharge influx with high content of N_2 and Ar is AWI I-8 well, which is oriented toward the margin of the field. In the N_2-CO_2-Ar ternary diagram, AWI I-8 is consistently plotted at the N_2-Ar side, far from the typical geothermal reservoir that is usually plotted near the CO_2 apex (**Figure 7**). After SIRP implementation, AWI H-5 data are remained plotted at the historical time point, and there is no N_2-Ar enrichment or shift towards AWI I-8 values. This plot suggests no increasing marginal recharge influx to AWI H-5 due to decreased pressure support following the brine infield injection move-out.

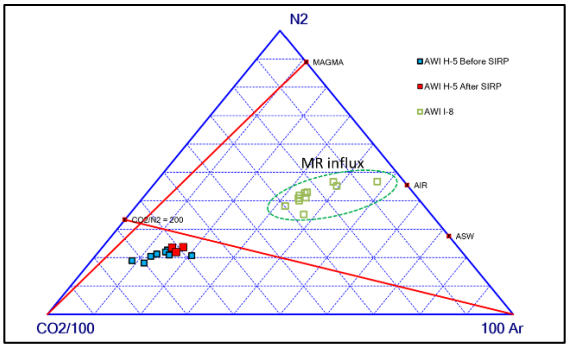


Figure 7. N_2-CO_2-Ar gas ternary diagram showing AWI H-5 is still plotted near the CO2 apex and no N_2-Ar enrichment after SIRP implementation.

3. CONCLUSION

After moving infield brine injection to the outfield and edge field, Salak production wells experience a positive impact by halting reservoir cooling due to brine injection breakthrough and promoting steam cap development. Geochemistry monitoring shows that the two-phase production wells in the western area have a decreasing chloride trend, which indicates less brine injection breakthrough impact. This hypothesis is also confirmed by the 7-component geochemistry mixing model results, which shows less brine injectate composition and more mass-in-place contribution in the reservoir over time. The increasing total NCG content and enthalpy data indicate steam cap development in the two-phase wells. This is also confirmed by evidence showing that liquid level data dropped after the SIRP implementation. Furthermore, based on the concentration of N_2 and Ar gas, there is no N_2 and Ar enrichment, which indicates that there is no significant marginal recharge influx due to the less pressure support. Overall, routine geochemistry monitoring is critical for evaluating changes in the reservoir process due injection strategy modifications, and it must be integrated with other data (e.g., reservoir, geophysics, geology) to construct an updated conceptual model for further field development.

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