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Monitoring System for Measuring Reservoir Response After Salak Injection Realignment Program

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ABSTRACT

Salak Injection Realignment Program (SIRP) intends to mitigate the cooling issues from infield condensate and brine injection by moving condensate injection to the outfield reservoir area and diverting brine injectate from AWI I to proximal southeast and outfield reservoir area. The condensate injection out has been implemented since 2013, while the brine has been diverted from AWI I to proximal southeast area (PSE) since the 4th quarter of 2020. The modeling effort indicates that after the injection cooling is mitigated, it could sustain or even improve the production performance of Salak field.

Numerical modeling result indicates that Salak Injection Realignment Program (SIRP) has a vital role in improving long-term reservoir performance. Hence, it is critical to understand how the reservoir behaves after injection realignment started. Such massive and rapid voidage may invite marginal recharge (MR) entering the reservoir to prevent steam cap development and/or cools off the reservoir. Therefore, a fast and reliable early warning system is required to enable the asset management team to act accordingly.

SIRP Monitoring System (SMS) was then developed to enable quick analysis and interpretation of well behavior that can be further processed and correlated to understand reservoir behavior. SMS derived from numerical model forecast that is post-processed using WellHist (Star Energy in-house wellbore modeling tool) to provide higher resolution of data for individual well basis interpretation. SMS compares numerical model forecasted liquid pressure response with actual down-hole pressure monitoring data, as well as WellHist forecasted individual well production performance with actual production data. After six months of partial PSE implementation, the monitoring data responding positively according to the forecast. The actual responses of SIRP will be continuously monitored, evaluated, and considered to determine most suitable future plan.

1. INTRODUCTION

The Salak Geothermal Field (also known as Awibengkok) is the largest operating geothermal field in Indonesia with an installed capacity of 381 MWe located about 70 km south of Jakarta in West Java. The commercial production at Salak commenced in 1994 with the commissioning of the 55 MW Unit 1 and Unit 2 followed by Unit 3, 4, 5, and 6 were commissioned in 1997 with 55 MW for each unit. Since 2004, Unit 4/5/6 were uprated to 65.6 MW and re-uprated in early 2022 to 67 MW while Unit 1/2/3 were uprated to 60 MW. Under the JOC with PERTAMINA (now PT Pertamina Geothermal Energy (or "PGE"), Star Energy Geothermal Salak Ltd. ("SEGS") supplies steam to Units 1, 2 & 3 (owned by the Government of Indonesia's Perusahaan Listrik Negara or "PLN" and operated by its subsidiary PT Indonesia Power). SEGS supplies the steam to, operates, and produces electricity from Units 4, 5 & 6.

In response to long-term commercial production, as common issues of mature fields, the Salak Geothermal Field has also encountered several reservoir management challenges, such as injection breakthrough, influx of marginal recharge, wellbore scaling, and production of significant amounts of non-condensable gas. Salak injection strategy has always been recognized as the key to the successful long-term reservoir management of the Salak field. In the early state of Salak field development, the produced brine was injected infield to economically develop Units 1 and 2. However a plan to relocate brine injection to deeper or more distal locations field production boundary was designed in order to properly manage both the pressure support and thermal breakthrough from injection and natural recharge (Acuna et al., 2008).

An exceptional project namely The Salak Optimization Project was then initiated in March 2005 with a goal of redesigning the production and injection well configuration in a way that mitigated cooling by injection, reduced the production decline rate in the field, and maximized the production potential of the Salak field going forward. The project evaluated several cases through numerical modelling, the best resource performance is expected to be obtained by implementing:

1. Condensate Out Injection by moving all the plant condensate (1,500 kph) injection to outfield locations
2. Proximal Southeast Injection (PSE) by moving 3,000-6,000 kph from AWI I to AWI N & O injectors
3. Brine Outfield Injection (BOI) by moving approximately 10-15% of the total brine and to achieve a "net 3000 kph" of total injection outside the proven reservoir
4. Keep injecting at AWI I-6 and convert AWI B and AWI I wells to production (when possible)

Based on preliminary project economics, it was confirmed that the production potential of the field could be increased through expansion of the production area and moving injection outside the proven reservoir boundary (Ganefianto et al. 2010).

2. SALAK INJECTION REALIGNMENT PROGRAM (SIRP)

To realize the best resource performance modeling, the Salak Geothermal Field initiated the Salak Injection Realignment Program (SIRP) which the main intentions are to accelerate the steam cap expansion and to mitigate the cooling issues in West Salak by moving the condensate and brine injectate to the distal locations. Several new injector wells and new surface facilities (pipeline and pump) were prepared to relocate the brine and condensate injection in Salak. SIRP has been gradually implemented since then.

2.1 Condensate Out Injection

The condensate from Unit 1-6 was initially injected to AWI L since commercial production in 1994. However, the monitoring indicated condensate injection in these wells has impacted nearby AWI G and H wells producers. The condensate injection in AWI L wells then were fully terminated in 2013. The delineation drilling in 2005-2009 completed seven new injectors wells drilled towards edge the reservoir (AWI Q-1, R-1, R-2, S-2, S-3, T-1, V-1) allowing full condensate injection in new distal locations. The Condensate Out Injection was completed in mid-2013 and was able to move all condensate injection either outfield or at the edge of the field. The start of condensate injection from Unit 4-6 to AWI S-3 in the north in 2009, AWI V-1ST1 in the south in 2011, and condensate from Unit 1-3 to AWI R at Cianten Caldera in 2013 has not shown any chemical impact to the producer wells.

2.2 Proximal Southeast (PSE) and Brine Outfield Injection (BOI)

At the beginning of production in 1994, the produced brine from AWI G, H, and K was injected to infield area in AWI I and AWI J as it was believed that the brine produced from generating 110 MWe (Unit1&2) would not significantly harm the high-temperature reservoir. Salak Unit 3-6 (4 x 55 MW) come online in 1997; hence, the volume of produced brine that was injected infield increase significantly. The chemical breakthrough was observed in AWI K wells within four months after injection started at AWI J; brine injection in AWI J was terminated and converted into production wells in 1997 (Abdurachman et al., 2015). Infield injection at AWI I also resulted in chemical breakthrough at AWI G and H wells within nine months after injection started. The thermal breakthrough indicated by slight temperature reversals were noticed in AWI G and H wells in 1997, but at low enough rates that some of these production wells have continued producing (Golla, et al, 2020).

Since then, AWI I wells have been utilized as brine injectors for West Salak producer wells while AWI N and O brine injectors have been continuously used to inject produced brine from East Salak. The 2002 tracer test results indicated that AWI I-4OH was the most connected brine injector with the AWI G and H wells (Rohrs et al., 2005). Therefore, this well was redrilled away towards the west in 2005 to minimize its negative impact to nearby production wells. The 2006 tracer test results showed the connectivity of AWI I-4RD to nearby wells had decreased while AWI I-6 is still the least connected injector. With the success in drilling AWI I-4RD, the same strategy was also implemented at Proximal Southeast injectors AWI N and O which were considered to be directly connected to the East Salak wells. Some AWI N and O wells were deepened and drilled away toward the edge of the field. The 2006 tracer test results showed that the redrilled AWI N and O injectors recovered a lower % of the tracers compared with the original wells (Abdurachman et al., 2015).

New surface facilities were also designed and built to allow brine moving from AWI G and H that previously injected to AWI I to the proximal southeast and outfield area. By the end of 2020, the surface facilities have been ready for partially implementing Proximal Southeast Injection. The PSE was started by moving 1,300 kph brine from AWI I to AWI N and O injectors. The full implementation of moving 2,600 kph is expected in the near future.

AWI R at Cianten Caldera that since 2013 was used as condensate injectors for Unit 1-3 has been prepared as the brine outfield injectors. The hydraulic fracturing using high pressure condensate injection in AWI R was performed in 2019 to increase its capacity to accept more injection rate for brine injection realignment. Brine Outfield Injection is planned to move 1,800 kph from AWI I to AWI R. The condensate from Unit 1-3 which previously injected to AWI R will then be diverted to AWI T-1 and AWI V-1. Meanwhile, AWI S-3 will remain as the condensate injectors for Unit 4-6. The location of Salak production and injection well pad mentioned above are depicted in figure 1.

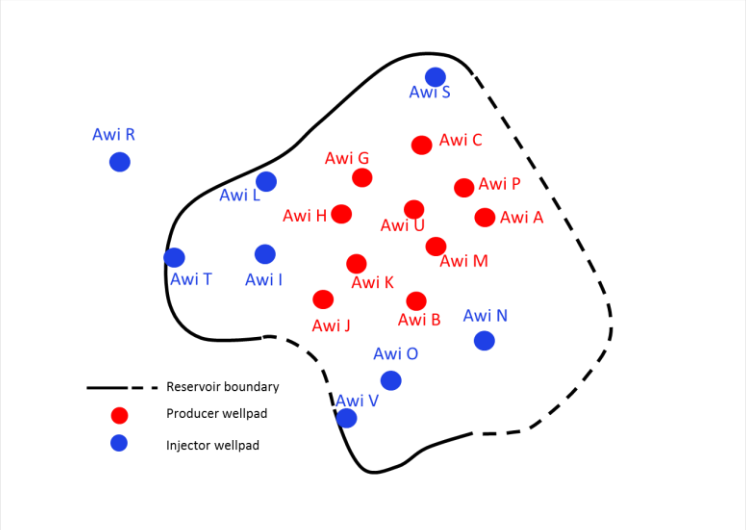

Figure 1: Production and injection well pad location in Salak Field.

Numerical simulation result indicates that SIRP can improve long-term reservoir performance such as (1) Improve existing wells production performance - prevent steam loss in cooling wells; (2) Fasten steam cap development in West Salak - resulting in higher steam rate when feedzone evolved, and (3) Reduce decline rate - lead to steam plateau extension. On the other hand, since SIRP also means that Salak reservoir will lose its pressure support from infield injection in AWI I, it can also lead to some detrimental effects such as less pressure support in liquid reservoir and consequently invite more marginal recharge (MR) to enter the Salak reservoir. Considering the upside potential and downside risk of SIRP, it is necessary to develop a reliable monitoring tool to forecast and monitor wells and reservoir behavior after SIRP implementation in effort to determine the success measures of the program and to provide early warning if the reservoir does not respond as expected.

3. SALAK INJECTION REALIGNMENT PROGRAM (SIRP) MONITORING

Once SIRP implemented, a robust monitoring system must be in place to quantify the reservoir reaction to sudden increase in net voidage. The asset management team needs to quickly mitigate and respond to unwanted effect of SIRP.

3.1 Well and Reservoir Monitoring through Surveillance Program

Several surveillance activities are defined to monitor the parameters that represent reservoir and well performance response after SIRP implementation (figure 3). The parameters consist of (1) Production performance of the wells (steam rate and enthalpy); (2) Reservoir pressure response (steam cap pressure and liquid pressure) and liquid level monitoring; (3) Liquid reservoir temperature evolution; (4) The geochemistry surveys such as routine chloride, NCG, and downhole sampling (DHS) are also needed as additional data to understand the changes in reservoir behavior. All monitoring data will be compared to forecast result to measure the success of SIRP implementation.

Key Resource Parameters	Data / Information Required	Surveys Required	Response After SIRP Implementation	
			Upside signpost	Downside signpost
Well production performance	Steam rate & flowing enthalpy	Daily production data acquisition	Production improvement: increase steam rate and enthalpy in the West and Central cells wells	Production drop / well died
		Quarterly TFT survey		
Deep Liquid Reservoir Pressure Response and Steam Cap Expansion	Liquid pressure evolution	Continuous downhole pressure monitoring	Liquid level drops allowing the steam cap development and feedzone evolution in West area	No steam cap development and feedzone evolution
		Shut-in PT survey		
	Steam cap pressure evolution	Stable shut-in WHP at well with steam cap feedzone		
		Shut-in PT survey		
	Liquid level evolution	Compare liquid and steam cap pressure to determine liquid level		
		Shut-in PT survey		
Deep Liquid Reservoir Temperature Evolution	Liquid temperature evolution	Shut-in PT survey	Normal temperature decline or temperature increaes after less injection breakthrough	Temperature drops faster than normal due to marginal recharge
Geochemistry	Surface chloride concentration	Routine Cl monitoring	Steam cap development (NCG increase); Reduction in injection breakthrough (chloride content decrease)	MR cooling (chloride content decrease confirmed by geochemistry mixing model result)
	NCG concentration	Routine NCG monitoring		
	Fluid composition at depth	DHS survey		

Figure 2: Well and reservoir monitoring to capture SIRP response

As the reservoir liquid pressure is very sensitive to increase in the reservoir voidage, five continuous down-hole pressure monitoring systems were installed to monitor liquid pressure change in the main production area of Awibengkok reservoir. Awibengkok reservoir is compartmentalized into 4 sectors that are divided based on distinctive temperatures, fluid chemical signatures and tracer test pattern (Stimac et al, 2008). Currently most of the extraction comes from the Central and Eeastern sectors. Therefore, to continuously monitor the evolution of deep liquid pressure, three down-hole pressure monitoring were installed in Central Cell (AWI C-1, G-2, K-6) and the remaining monitoring wells were placed in Eastern Cell (AWI M-4, AWI B-2) as shown in figure 2.

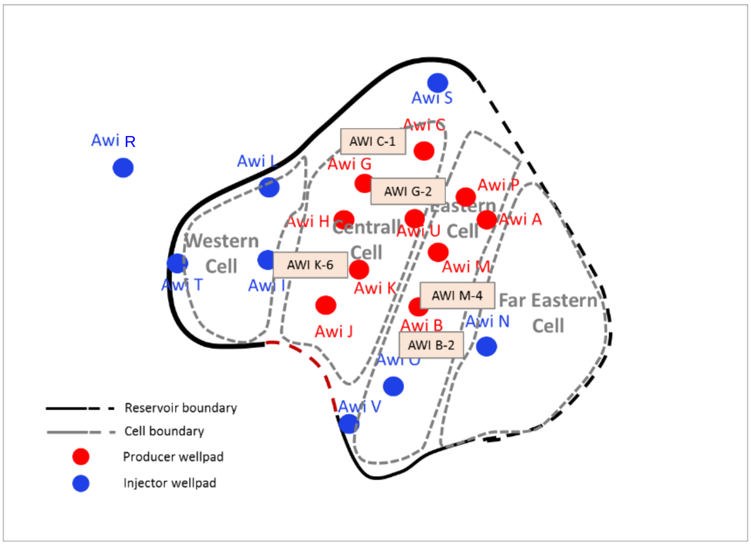

Figure 3: The Salak Geothermal Reservoir Compartmentalization based on distinctive temperature, chemical characteristics and tracer test result. Five liquid monitoring wells were installed in the main production area of Salak field.

3.2 Production Performance Forecast after SIRP Implementation

To quantify the success measure of SIRP implementation, a reliable forecast need to be developed as a comparison to actual monitoring data. Previous practice in forecasting well performance after SIRP implementation was only based on numerical simulation results. However, the recent numerical model has limited resolution due to large gridblock size making many feedzones are lumped and have the same properties (elevation, pressure, and enthalpy). Consequently, phase evolution, enthalpy change, and liquid level change in each feedzone cannot be clearly seen.

The ultimate solution to overcome the resolution limitation is to refine the gridblocks. However, the efforts would be time-consuming making the forecasting well performance after SIRP implementation cannot be carried out immediately. Another way to overcome the resolution limitation is to use WellHist as the main forecasting tool since it can provide pressure and enthalpy on an entry-by-entry basis. Wellhist is a program that runs a wellbore simulator in a series of times that can be used to calculate well deliverability response to changes in reservoir pressure and enthalpy conditions. WellHist methodology relies on deriving feedzone pressure and enthalpy trends with time for the individual feedzones. Additionally, a wellbore model of each well is constructed using data of well geometry, elevation, and productivity index (PI) of the individual feed zones. Current WellHist model has a good representation of actual condition as the calibration has been carried out up to the recent actual data. However, WellHist cannot capture reservoir physics change after SIRP implementation since WellHist forecast only uses normal trend (no trend changes due to production/injection strategy adjustment). Therefore, the determination of future pressure and enthalpy will use both current data from WellHist and future trend from numerical simulation.

Figure 4 shows the difference between the liquid level and enthalpy forecast in AWI X using the reservoir simulation (left figure) and using WellHist (right figure). In the left figure, the simulation block resolution limits the liquid level forecast where the bottommost brine feed zone (with 60% contribution) will evolve after the entire block (-1000 to -1300 ftASL) completely turns to dry steam which is yet to be reached in 2026. Meanwhile, WellHist's forecast can capture the progressive changes in liquid level and provide a better resolution of forecast result compared to the reservoir simulation. In fourth quarter of 2023, the liquid level is expected to fall below the bottommost feedzone and the well will completely evolve to dry steam producer with 1200 Btu/lb enthalpy as shown in WellHist's forecast.

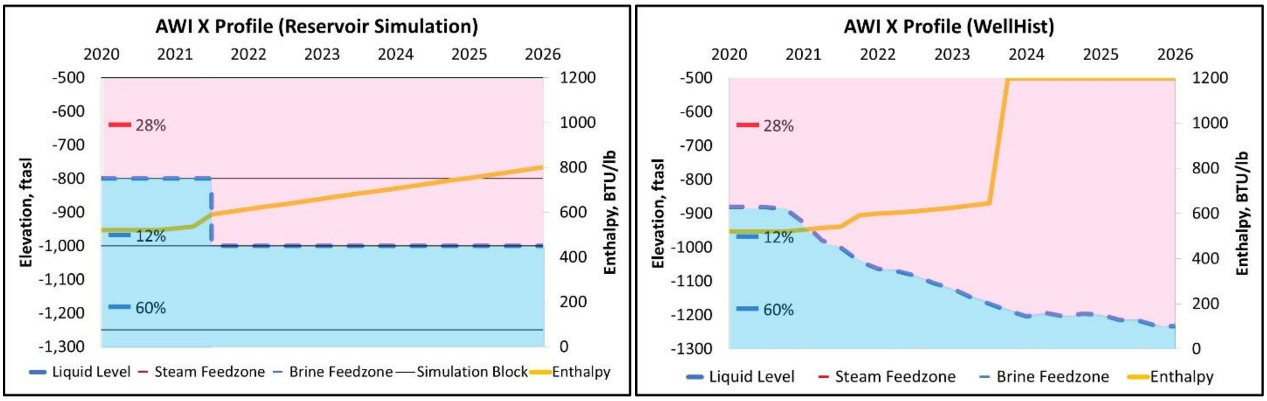

Figure 4: Liquid level and enthalpy forecast with reservoir simulation (left) and WellHist (right).

4. MONITORING SIRP IMPACT AFTER 6 MONTHS OF PSE IMPLEMENTATION USING SIRP MONITORING SYSTEM (SMS)

After a long journey, the PSE has been finally started since Q4 2020 following the full Condensate Out Injection that has been implemented in 2013. In Q4 2020 the PSE was partially implemented by moving 1,300 kph brine from AWI I to southeast injectors in AWI N & O, the full PSE implementation is expected to be performed with total brine diverted from AWI I to southeast injectors approximately 2,600 kph. Furthermore, the BOI was planned to move 1,800 kph brine from AWI I to outfield injectors in AWI R in Cianten Caldera. After those full SIRP has been implemented, it will signify the new injection alignment era of Salak Geothermal Field.

To monitor the actual reservoir response of SIRP implementation, the SIRP Monitoring System (SMS) has been established by using data visualization tool that compares real-time monitoring data stored in Salak database with the forecast results. This system will help Asset Management Team to quickly gain insight and observation of injection realignment response. SMS consists of several dashboards depicting the responses of Salak reservoir pressure and production performance of monitoring wells to SIRP implementation. The SMS was developed using data visualization tool that consists of two elements, namely, (1) actual monitoring data from surveillance program and (2) numerical model forecast that is translated into well level data forecast using WellHist. SMS will enable quick analysis and interpretation of well behavior that can be further processed and correlated to understand reservoir behavior by comparing the actual monitoring data and forecast result as an effort to determine the success measures of SIRP and to provide early warning when the reservoir does not respond as expected. Figure 5 depicts SMS development workflow while the SMS dashboards are shown in the Appendix section.

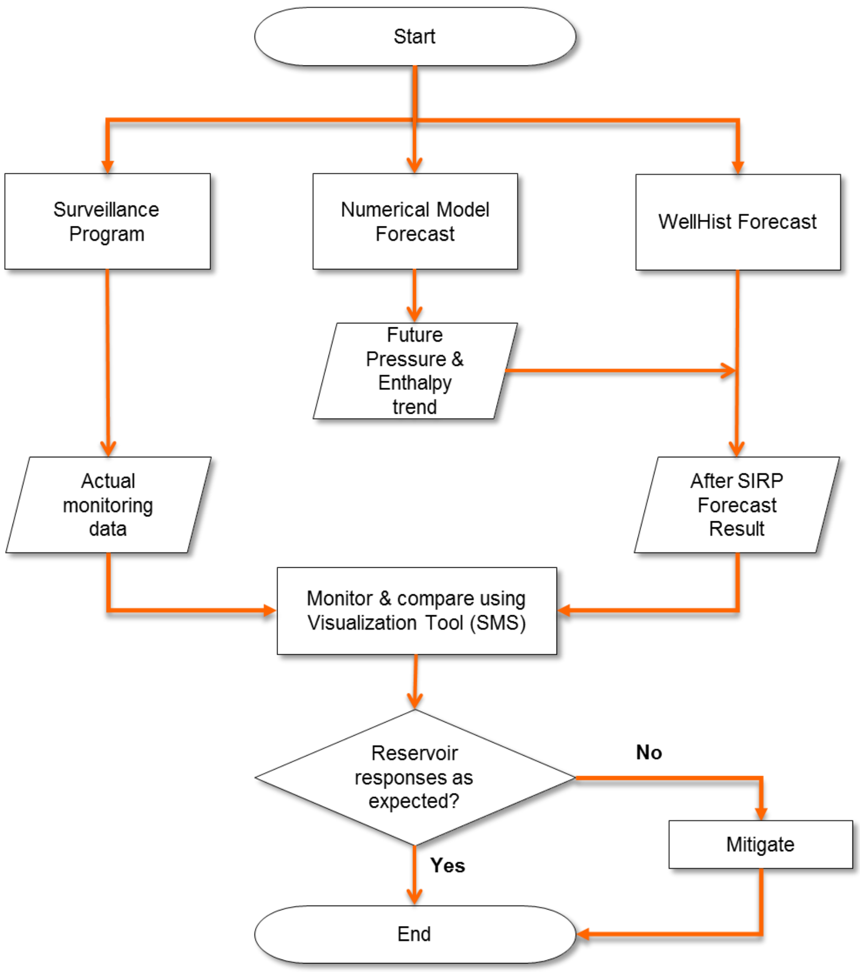

Figure 5: General workflow of SIRP Monitoring System (SMS) development.

Actual deep-liquid reservoir pressure depletion data monitoring (depicted in dots) is plotted over time and compared with forecasted profile for As-Is / without SIRP (in darker color line) and with SIRP scenario (in lighter color line) as shown in figure 6. This plot will be used as a diagnostic tool to indicate the success measurement criteria or to provide early warning if the reservoir does not respond as expected after injection realignment implementation. The SIRP implementation will divert brine from West Salak to Proximal Southeast and Outfield area of Salak reservoir, the reservoir liquid pressure particularly in West area is expected to significantly drop after SIRP implementation (SIRP Forecast). On the other hand, when there is no change in injection strategy the future liquid pressure drop will follow the current actual liquid pressure drop trend (As-Is Forecast).

Up until 6 months of partial PSE implementation, the actual continuous down-hole pressure from five monitoring wells in different sectors were observed to follow the SIRP forecast as depicted in figure 6. The liquid pressure depletion in Central Cell shows obvious pressure depletion following the forecast as observed by AWI C-1 and G-2 monitoring wells. AWI G-2 is located near AWI I injectors and historically impacted by injection breakthrough; thus, the well is responsive to injection realignment. AWI C-1 is also responsive to the injection alignment in AWI I since the tracer test conducted in 2002 and 2009 indicated the injected fluid moves from AWI I towards northeastern area of Salak (Gunderson, 2004; Pasikki, 2011). Despite located in separate cell with AWI I, AWI K-6 still shows similar response due to deep liquid reservoir connection in Salak. Furthermore, the down-hole pressure monitoring in Eastern Cell where AWI B-2 and M-4 is located indicate slower depletion than Central Cell since Eastern Cell is located further from AWI I but located near the southeast injectors in AWI N & O where the brine moved into. The continuous liquid pressure drop is expected to allow steam cap expansion and enhance steam production in Western Salak.

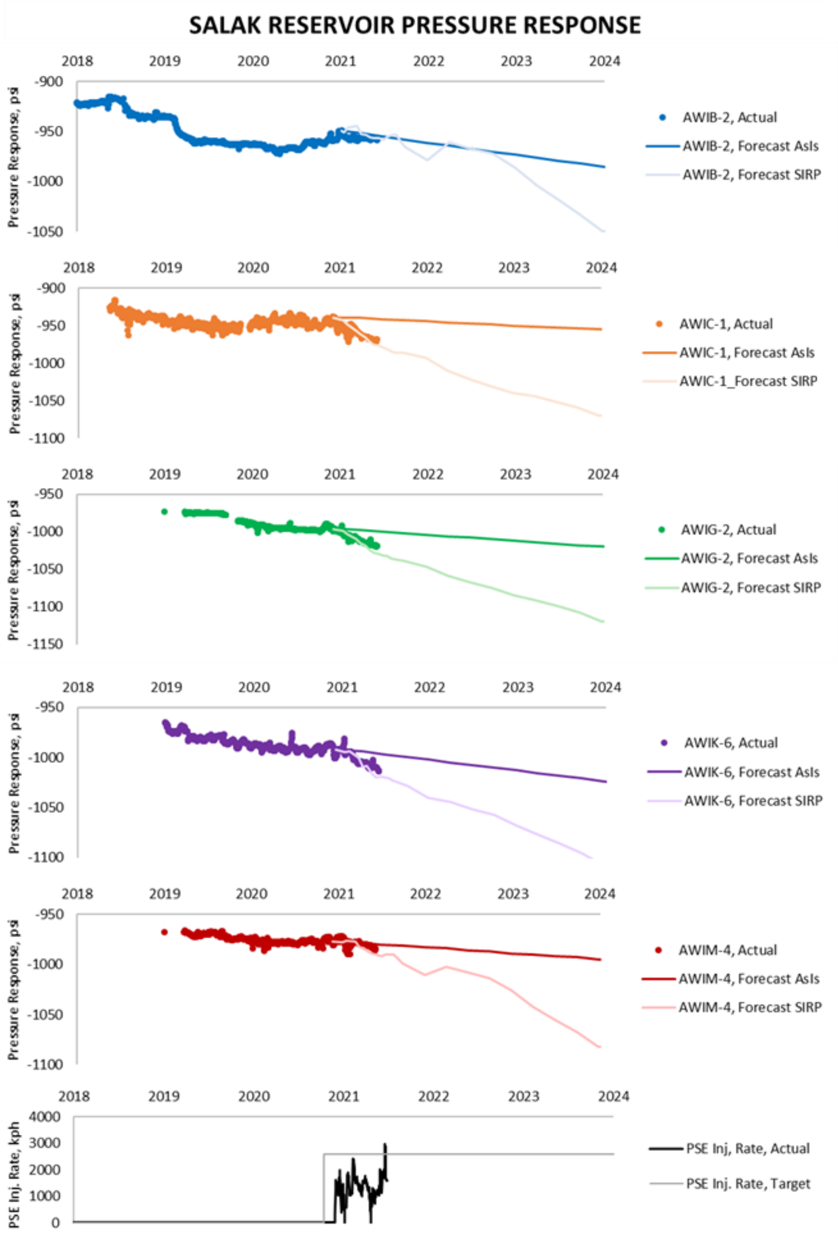

Figure 6: Downhole pressure monitoring data showing good correlations to expected reservoir response after SIRP implementation based on numerical simulation forecast.

Correspond to the down-hole pressure monitoring data, pressure profile of the production wells in the Western Salak confirms faster liquid pressure depletion rate. PT survey in one of AWI G and AWI H, for the example of nearby wells previously impacted by AWI I injectors, indicates that the liquid pressure depletion is faster after SIRP implementation compared to before SIRP as shown in figure 7a. In 2014-2017 period, the normal pressure depletion of AWI G was 11 psi/year and increased to 22 psi/year in the period of 2017-2021 while for AWI H increased from 11 psi/year in period 2013-2014 to 17 psi/year in the period of 2014-2021. The liquid level in one of AWI G is now approaching the 2nd feedzone or shallowest liquid feedzone. Further liquid level drop is expected in the future, and it will trigger feedzone evolution as well as enthalpy increase which eventually will boost production performance by early 2022 or approximately 12 months after partial PSE implementation (Figure 7b).

The liquid temperature changes after SIRP implementation also continuously monitored. Besides the upside potential of SIRP implementation where liquid temperature will increase due to less cooling from injection breakthrough, there is also downside risk since SIRP rapidly increases liquid pressure depletion rate inside the reservoir that may potentially invite colder fluid from the marginal area. The PT survey in one of AWI G & H wells in 2021 still showing no indication of marginal recharge cooling since the temperature trend still following the normal temperature decline in respective wells as depicted in figure 8.

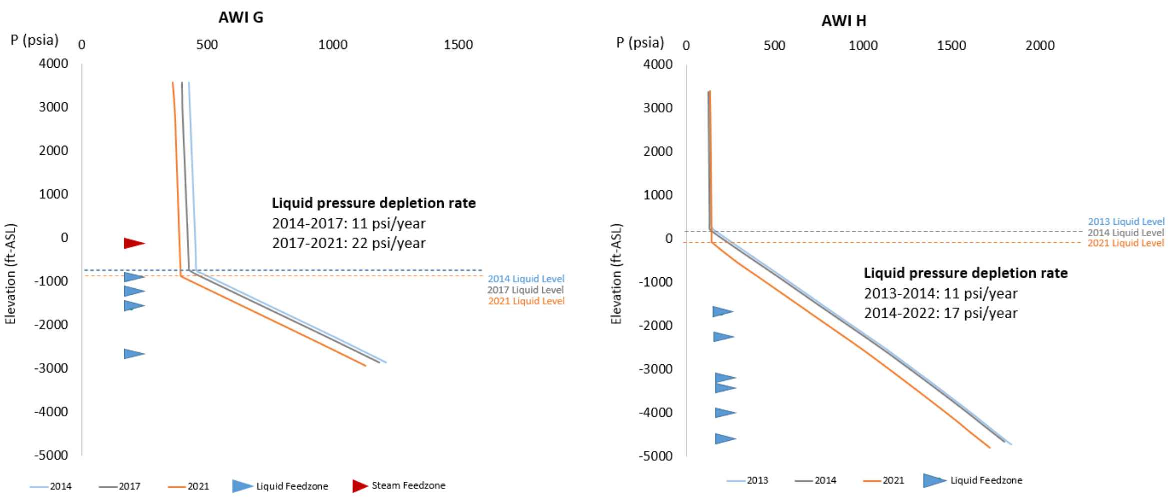

Figure 7a: AWI G and H liquid pressure drop after SIRP

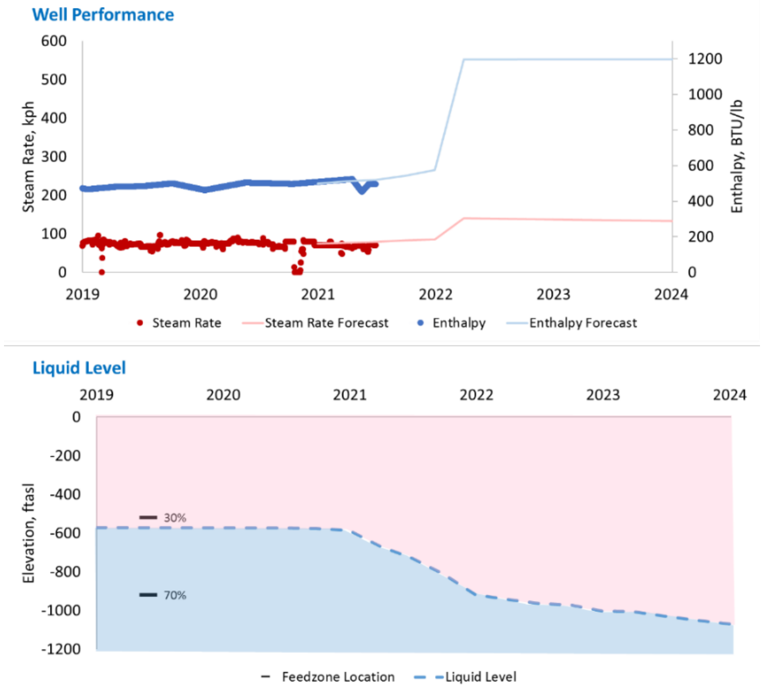

Figure 8b: Forecasted well performance of AWI G showing steam rate increase after SIRP implementation when liquid level falls below the liquid feedzone and eventually evolves into dry steam well.

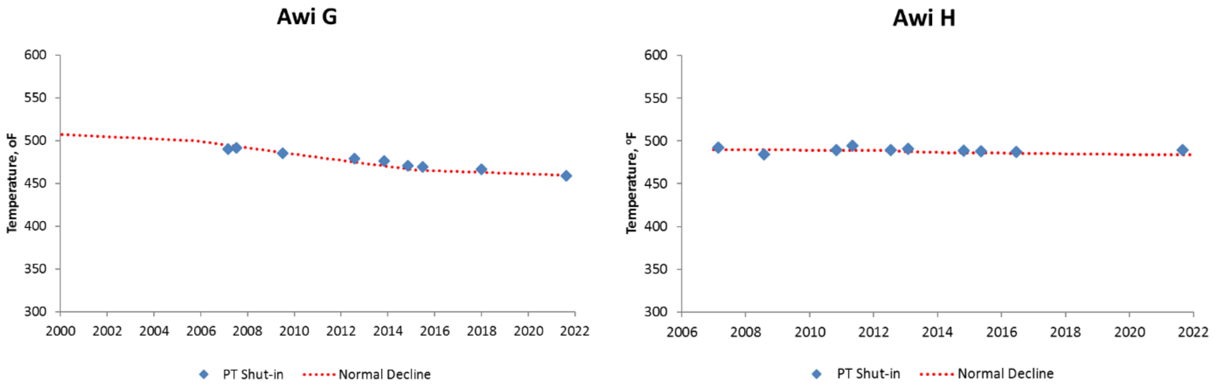

Figure 9: Liquid temperature decline after SIRP implementation does not indicate any excessive cooling from marginal fluid invasion.

Furthermore, close geochemistry monitoring in Salak two-phase wells particularly in West area have also been performed continuously. Up until 6 months of partial PSE implementation, the geochemistry monitoring shows decreasing chloride (Cl) content in West Salak two-phase wells, example of AWI G Cl content is shown in figure 9. There are two possibilities of processes that cause this decreasing chloride trend: less brine injection breakthrough, or marginal recharge (MR) influx. Chloride concentration in brine injectate is higher than the initial mass-in-place (MIP). Therefore, if the well is impacted by brine injection breakthrough, there will be increasing chloride trend through time, and vice versa. Meanwhile, MR has low chloride concentration (typically 100 – 500 ppm at Salak), thus, if there is MR influx, then chloride concentration in produced brine will decrease through time. Even though temperature trend (Figure 8) indicates no excessive cooling from marginal recharge, to confirm which process occurring to the well, complete chemistry analysis using seven elements is conducted. An approach to extract the quantity of the various fluids supplying the producing wells was developed using 7 chemical species (Cl, B, SO_4, HCO_3, NH_4, Ca, and Mg) (Sunio and Molling, 2009). The multi-species mixing model evaluates the proportions of recycled brine/condensate injectate and marginal recharge, and estimates amount of original Mass in Place (MIP) composition still being produced per well (Julinawati et al., 2011). Analysis of 7-element geochemistry mixing model on one of AWI G wells shows that there is less brine injection breakthrough after SIRP implementation and no significant increase of MR composition (Figure 9). Those monitoring and observations suggest positive direction of reservoir response to SIRP implementation.

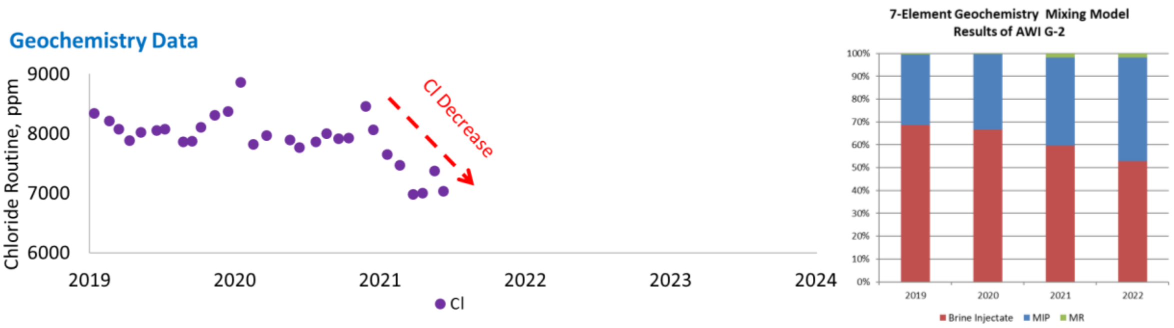

Figure 10: Reservoir Cl content decreased after SIRP and results of 7-element geochemistry mixing model suggest less injection breakthrough on AWI G

CONCLUSION AND FORWARD PLAN

SIRP is the key of Salak reservoir management strategy which intends to mitigate the cooling issues and to accelerate steam cap expansion at West Salak. On the other hand, SIRP has downside risks that can threaten the reservoir performance such as less pressure support and marginal recharge (MR) influx entering the Salak reservoir. It is necessary to forecast and monitor well and reservoir behavior after SIRP implementation to determine the success measurement criteria and to provide early warning if the reservoir does not respond as expected.

As the SIRP has finally started since Q4 2020 by first implementing the partial PSE, the SIRP Monitoring System (SMS) has also been established successfully and ready to be used as the main tool to provide prompt analysis of injection realignment program response in Salak Field. The tool integrates the forecast result along with actual data obtained from field measurement to provide a real-time reality check to the forecast. After 6 months of partial PSE implementation, the reservoir is responding positively according to forecast. The actual responses of SIRP will be continuously monitored, evaluated, and considered to enable most suitable forward plan in the future.

ACKNOLEDGMENT

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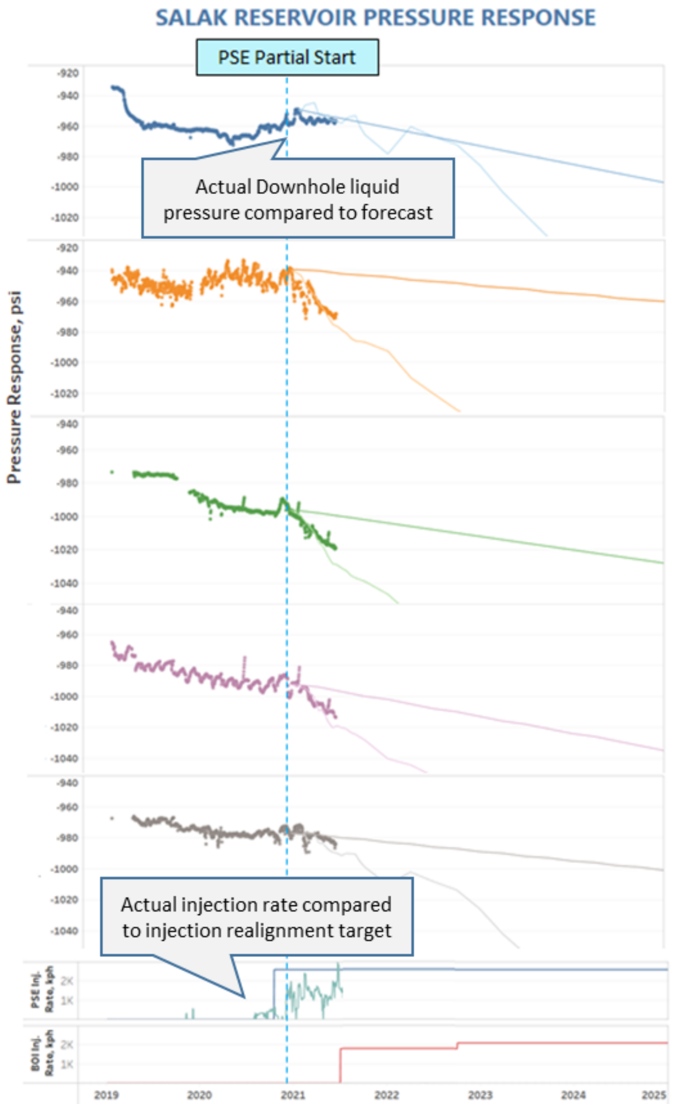
APPENDIX

Downhole Liquid Pressure Monitoring Dashboard



Production Performance Monitoring Dashboard