CONNECTIVITY OF WELLS IN THE EAST SALAK STEAM CAP: RESULTS OF NCG INTERFERENCE TESTING

Risa Prameswari Putri and Tri Julinawati

Star Energy Geothermal Salak, Sentral Senayan II, 26th Floor, Jl. Asia Afrika No. 8, Jakarta 10270, Indonesia
risaprameswari@starenergy.co.id

Keywords: *Salak, Awibengkok, Non-condensable Gas, gas interference, reservoir connectivity*

ABSTRACT

Most of the wells at East Salak were drilled shallow and produce steam with higher Non-Condensable Gas (NCG) concentration relative to the wells in the central and western portions of the field. Continuous mass extraction in East Salak has led to the development of a steam cap which changed almost all two-phase producers into single-phase dry steam wells. It is believed that NCG accumulated in the shallow portion of the steam cap as a result of natural condensation and/or due to the influx of natural marginal recharge near the top of reservoir. Steam blending is currently being implemented to maintain the appropriate NCG concentration in the steam supplied to power plants. However, steam blending does not provide consistent and optimum results due to the complicated interconnectivity between wells. The connectivity of Pad A wells at East Salak was analyzed through NCG interference testing. Results indicate that the elevation of permeable entries, their relative distance to each other, and the well's operating setting were the major factors that affect the connectivity between wells.

1. INTRODUCTION

1.1. Salak Geothermal Field

The Salak (also known as Awibengkok) Geothermal Field, located about 70 km south of Jakarta, West Java (Figure 1), is currently the largest geothermal resource in Indonesia with an installed capacity of 377 MW. Commercial production at Salak commenced in March 1994 with the commissioning of the 55 MW Unit 1. Another 55 MW power plant, Unit 2, followed in June 1994 while Units 3, 4, 5 & 6 (4 x 55 MW) were commissioned in 1997. In 2002, Units 4, 5 & 6 were uprated to 65.6 MW each; Units 1, 2 & 3 were uprated in 2004 to 60 MW each. These turbine upratings increased Salak Field's installed capacity to the current 377 MW. Under a Joint Operating Contract (JOC) with state-owned Pertamina Geothermal Energy (PGE), Star Energy Geothermal Salak Ltd. (SEGS) supplies steam to Units 1, 2 & 3 (owned and operated by the Government of Indonesia's Perusahaan Listrik Negara or PLN) and operates Units 4, 5 & 6.

Figure 1: Location map of Salak Geothermal Field.

Currently, there are 77 production wells, 22 injection wells (12 for brine and 10 for power plant condensate), five (5) monitoring wells and six (6) abandoned wells in Salak. Additional steam make-up wells will be required to maintain full generation up to the end of the current Energy Sales Contract (ESC) in 2040.

1.2. Production of High-NCG Steam at Salak

Prior to commercial production, the Salak geothermal reservoir was almost entirely liquid dominated, except the shallowest portion of the reservoir in East Salak sector (Rohrs et al., 2005). The development of a steam cap resulted in the accumulation of NCG at the shallow top of reservoir in East Salak. Julinawati et al. (2017) believed that natural condensation within the upper part of the steam cap creates a concentrated NCG layer. Shallow permeable entries in Pads A, M, and P wells in East Salak typically contain the highest NCG concentration because these wells were completed just below the top of reservoir (Figure 2).

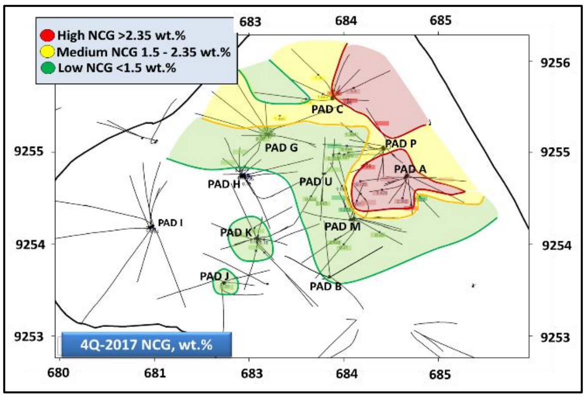

Figure 2: Map of Salak showing contours of produced NCG in steam cap at the end of 2017.

Both condensation and boiling (as a response to mass extraction) in the reservoir control the distribution of gas concentration in reservoir steam. Historical NCG monitoring shows that NCG ranges between 0.5 wt.% and 11 wt.% (Julinawati et al., 2017). The lower gas concentration reflects the gas content of steam evolving directly from boiling of the brine, i.e., the low values generally reflect the composition of the deeper steam cap entries. Meanwhile, the higher gas content reflects condensation along the margins of the reservoir (Rohrs, 2007). Furthermore, the high gas regions at Salak are typically associated where cooler Marginal Recharge (MR) liquid, which condenses reservoir steam, appears to be entering the reservoir, e.g., Pad C (Figure 2). Hence, the regions of high gas (especially along the margins of the field) is often used as an indicator to locate MR distribution (Rohrs et al., 2005).

Wells that drilled into the steam cap exhibit very strong "gas interference" or connectivity. This phenomenon has been observed since 2004 at Well A-4 (Figure 3) which has the highest NCG content (>10 wt.%) among all the production wells in Pad A and the strongest gas interference effect. Well A-4 exhibits strong interference with Well M-6 and weak interference with Wells A-5 and M-3 (Rohrs, 2007). As Pad A wells supply Unit 4, frequent curtailments are experienced in Unit 4 when high-NCG steam reaches the power plant. Well A-4 is normally vented to prevent high-NCG steam at Unit 4. By venting A-4 to the atmosphere, the NCG concentration in surrounding wells A-5, M-3, and M-6 is decreased allowing their produced steam to be used at Unit 4.

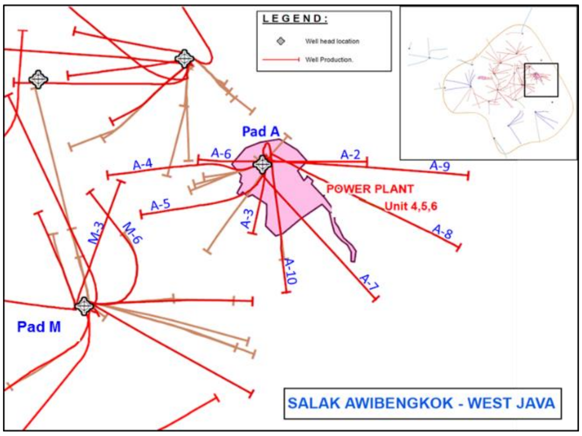

Figure 3: Study location of NCG interference and connectivity at steam cap in East Salak.

2. 2016 NCG INTERFERENCE TEST

In 2016, an NCG interference test was conducted to fully understand the connectivity of high-NCG producers at Pads A and M (Imantoro et al., 2017). This test was conducted after the unsuccessful workover of Well A-4 which resulted to its shut-in and prevented its NCG from being vented. As a result of shutting-in A-4, surrounding Wells A-3, A-5, M-3, and M-6 exhibited an increase in NCG production which impacted steam supply to Unit 4. To shore up steam supply to Unit 4, the Flow Control Valve (FCV) opening of high-NCG producers was adjusted (either by shutting-in or throttling) to obtain the optimum steam with low NCG concentration that could be delivered to Unit 4. However, this method did not produce consistent results due to NCG interference (or interconnectivity) between Pads A and M wells. Therefore, an NCG Interference Test was conducted to determine operating guidelines for high-NCG wells at East Salak and ensure sufficient steam supply to Unit 4.

2.1. Methodology

The main objective of the NCG Interference Test is to determine ideal operating conditions by observing changes in NCG concentration in certain production setting (Imantoro et al., 2017). The ideal condition here refers to the operating condition where only a single well is changed per event while monitoring changes in NCG production of surrounding wells. The NCG Interference Test was completed in 31 days and comprehensively shows NCG interference and interconnectivity between Pads A and M wells.

The first step during the Interference Test was to establish the baseline operating well configuration and measure NCG produced by each well on-site using the Wet-Test Meter. The NCG content (a gas-to-steam ratio) of a well can be calculated by measuring the total volumes of dry gas and weight of condensed steam collected over a period of time. The dry gas volume is measured using a gas flow meter (i.e., Wet-Test Meter) while steam condensate is collected in a bottle trap and the volume weighed. The NCG content (in wt.%) is simply estimated by dividing the gas volume (weight) with the total weight (gas + condensate) (Wijaya et al., 2009).

After collecting baseline data, the Interference Test commenced by changing the operating condition (e.g., from flowing to shut-in) of a particular well and measuring the NCG content of the surrounding wells for three days. It was believed that a well will reach stabilized flow within this period. The resulting NCG content is then compared to the baseline NCG. If there are changes (whether increase or decrease) in the NCG trend of surrounding wells after a particular well's operating setting is changed, these wells are concluded to be connected to that particular well.

2.2. Results

Figure 4 shows an example of the response of nearby wells when Well A-6 was vented. The green line represents the time when A-6 was vented through its 3" wing valve to the Atmospheric Flash Tank (AFT). Wells A-3 and A-5 responded directly to the change in A-6 by producing lower NCG. For this particular test, A-6 was the source of the perturbation and Wells A-3 and A-5 were the interfered wells (Figure 5). During the duration of the NCG Interference Test, the source of perturbation was changed in the following order: A-8, A-6, A-5, A-3, M-6, M-3, and A-2.

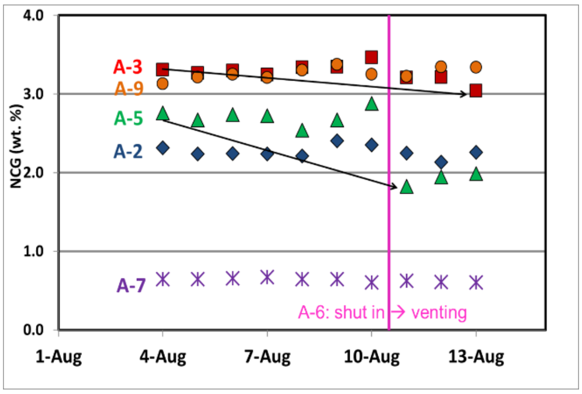

Figure 4: Chart showing NCG concentration of Pad A before and during the A-6 NCG Interference Test. Wells A-3 and A-5's NCG concentration decreased right after A-6 was vented.

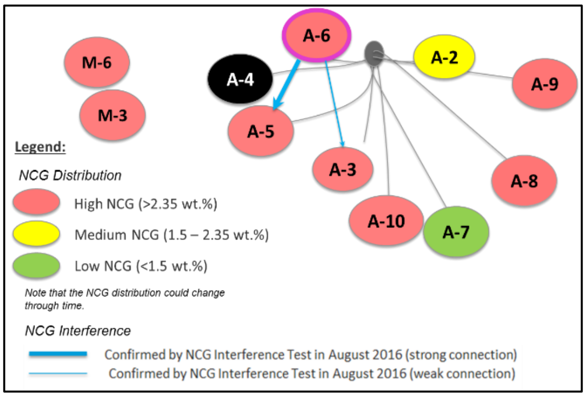

Figure 5: Schematic diagram showing the relative connectivity between wells during the A-6 Interference Test. The blue arrows show that only A-3 and A-5 were impacted when A-6 was vented.

The full results of the 2016 NCG Interference Test is shown in Table 1. The change in NCG in the interfered wells denote their relative connectivity with the source of perturbation. The degree of connectivity can be classified into two types: strong and weak connection. Based on simple statistics, a strong connectivity between wells is identified when NCG changes are in Quartiles 3 & 4. NCG changes in Quartiles 1 &2 (or ≤17%) are correlated with weak connection between wells (Imantoro et al., 2017).

Table 1: 2016 NCG Interference Test Results (Imantoro et al., 2017)

Source of Interference	Interfered wells	Baseline NCG (wt.%)	NCG after being interfered (wt.%)	% change	Connectivity
A-8	A-2	2.2	2.4	5	Weak
	A-3	3.3	3.5	6	Weak
	A-5	2.7	2.9	8	Weak
A-6	A-3	3.3	3	7	Weak
	A-5	2.7	2	26	Strong
A-5	A-2	2.2	2	10	Weak
	A-3	3.3	1.7	48	Strong
A-3	A-2	2.2	3	35	Strong
	A-5	2.7	2.9	9	Weak
	A-7	0.6	1	53	Strong
M-6	A-3	3.3	3.6	11	Weak
	A-5	2.7	3.8	41	Strong
	M-3	3.9	4.6	17	Weak
M-3	A-3	3.3	3.8	17	Weak
	A-5	2.7	3.6	34	Strong
	M-6	5.9	7.7	30	Strong
A-2	A-3	3.3	3.7	13	Weak
	A-7	0.6	0.8	25	Strong
Quartile 1				9	Weak Connection
Quartile 2				17	
Quartile 3				33	Strong Connection
Quartile 4				53	
Median				17	

The full results of 2016 NCG Interference Test is shown in Figure 6. The blue thick lines represent strong connection between wells while and the blue thin lines denote weak interconnectivity. The parameters that affect the interconnectivity between wells are discussed in the next section.

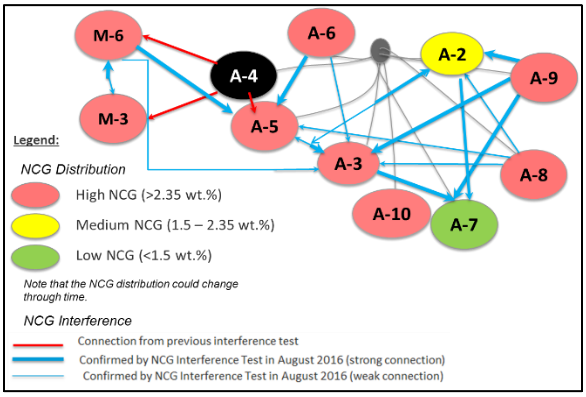

Figure 6: The 2016 Salak NCG Interference Diagram Update at Pad A, M-3, and M-6.

3. DISCUSSION

The parameters that are suspected to control the connectivity between wells are the relative elevation of the permeable entries and the distance between major feed zones between the source of perturbation and the interfered wells. The next section provides evidences for these hypothesis.

3.1. Elevation of Permeable Entries

Almost all the permeable entries encountered by Pad A wells, M-3, and M-6 are within 0-1,000 ft. ASL (Figure 7). The shallowest permeable entry was encountered by Well A-2 at about 1,700 ft. ASL. Only a single feed zone was encountered below the Mean Sea Level, i.e., the major permeable entry at Well A-6. This distribution of permeable zones will most likely lead to some production interference between these Pad A and M wells, although this has not been observed yet.

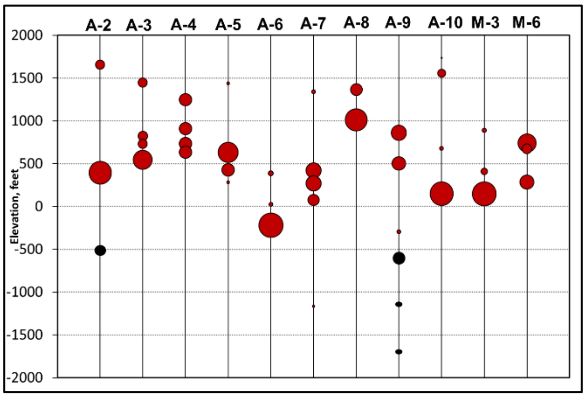

Figure 7: Stick chart showing the relative location of permeable entries (represented by circles) encountered by Pad A wells, M-3, and M-6. The size of the circle shows the degree of mass contribution of each feed zone, i.e., the bigger the circle size, the bigger the mass contribution. The red circles represent steam entries; the black circles represent liquid entries.

3.2. Distance Between Major Permeable Entries

Another working hypothesis during the NCG Interference Test was that the relative distance between permeable entries possibly control the NCG concentration produced by each well. The NCG produced at the surface is a mix of the relative amounts of NCG that enter the wellbore in each permeable entry. It is believed that the most NCG produced by a well comes from the major feed zone as this zone contributes the most mass. Therefore, in this study, the distance between major permeable entries was measured.

The 2016 NCG Interference Test showed that Well A-6 has strong connection to A-5 and, conversely, a weak connection to A-3. Figure 8 shows the major feed zones encountered by Wells A-3, A-5, and A-6. The 3D distance of the major permeable entry (i.e., permeable entry that produces the most mass) at A-6 vis-à-vis those major entries at Wells A-3 and A-5 was measured using the 3D Static. Table 2 shows the results of all measurements between the major permeable entry in each well.

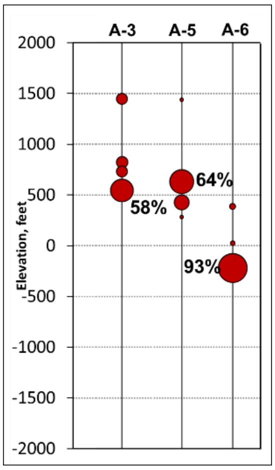

Figure 8: Entry of A-3, A-5, and A-6. Major entry is determined from the biggest mass contribution. The major entry is located at 545 ft. ASL, 631 ft. ASL, and -219 ft. ASL in A-3, A-5, and A-6, respectively.

Table 2: Distance from source of perturbation to interfered wells

Source of Interference	Interfered wells	% changes	Connection	3D Distance (m)
A-8	A-2	5	weak	283
	A-3	6	weak	435
	A-5	8	weak	599
A-6	A-3	7	weak	438
	A-5	26	strong	310
A-5	A-2	10	weak	454
	A-3	48	strong	248
A-3	A-2	35	strong	360
	A-5	9	weak	248
	A-7	53	strong	273
M-6	A-3	11	weak	653
	A-5	41	strong	309
	M-3	17	weak	128
M-3	A-3	17	weak	610
	A-5	34	strong	321
	M-6	30	strong	128
A-2	A-3	13	weak	360
	A-7	25	strong	302

By correlating the relative connectivity based on changes in NCG concentration with the distance between major permeable entries, it appears that wells with major feed zones that have ≤360 m (~1,180 ft.) distance will have strong connectivity (Table 2). However, there are four cases where the distance is ≤360 m (~1,180 ft.) but the wells have weak connectivity; these are A-8 and A-2, A-3 and A-5, M-6 and M-3 and A-2 and A-3 (Table 2, blue colour font).

3.3. Wells A-8 and A-2

Well A-8 appears to have a weak connection with A-2, A-3, and A-5 (Table 2). When A-8 was vented, the NCG content at A-2, A-3, and A-5 showed minor changes (i.e., 5 to 8%) only indicating weak connectivity. The distance between the major feed zones between A-8 and A-3 and A-5 is >360 m; thus, the weak connectivity as shown by the minor change in NCG concentration. However, the distance between the major entries at A-8 and A-2 is about 283 m which should exhibit a strong connection (Figure 9).

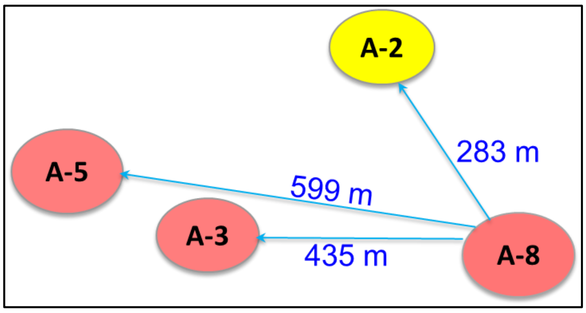

Figure 9: Interference diagram showing the relative distances between major feed zones of Wells A-8, A-2, A-3, and A-5.

This discrepancy may be explained by the relative location of the major feed zones between A-2 and A-8. The major entry at A-8 well is located at 1,012 ft. ASL, the shallowest major entry among Pad A wells (Figure 10). As NCG is most likely to accumulate at the top of reservoir, it would be less likely for NCG to flow to permeable entries at lower elevation. Note that the major feed zone at A-2 is at 394 ft. (~120 m) ASL although it is only 283 m away.

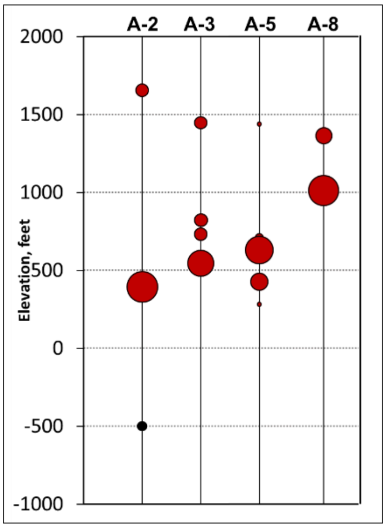

Figure 10: Stick chart showing the relative elevation of major permeable entries encountered by Wells A-2, A-3, A-5, and A-8.

3.4. Wells A-3 and A-5

Well A-3 has strong connection with A-2 and A-7, and weak connection to A-5 (Figure 11). When A-3 was shut-in, Wells A-2 and A-7 were fully opened at normal Flowing Well Head Pressure (FWHP) of ~120 psig while A-5 was vented to the AFT at ~257 psig FWHP (Table 2). These operating settings indicate that the NCG more likely flowed to wells operating at lower pressure (i.e., A-2 and A-7) than at A-5 during the Interference Test.

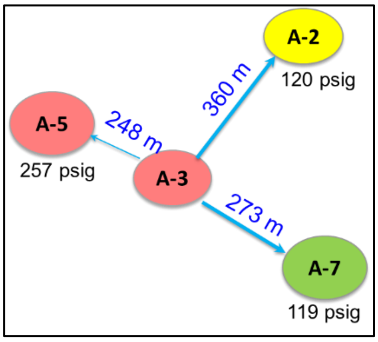

Figure 11: Interference diagram showing the relative distances between major feed zones of Wells A-2, A-3, A-5, and A-7. Also shown are the FWHP of the interfered wells during the Interference Test.

3.5. **Wells M-6 and M-3**

Well M-6 has weak connectivity to M-3 and A-3, and a strong connection to A-5 (Figure 12). When M-6 was shut-in, M-3 was operated in throttled condition (FCV opening at 15%) with FWHP ~150 psig. The high FWHP in M-3 may have prevented NCG from M-6 to flow to M-3; thus, the resulting minor change in NCG concentration and postulated weak connection. Another possible explanation to the weak connection between M-6 and M-3 is the relative location of their major permeable entries. Figure 13 shows that the major feed zone encountered by M-6 is shallower (at 739 ft. ASL) compared to the major entry at M-3 (at 147 ft. ASL). NCG will most likely flow or accumulate at the top instead of the deeper portion of the reservoir.

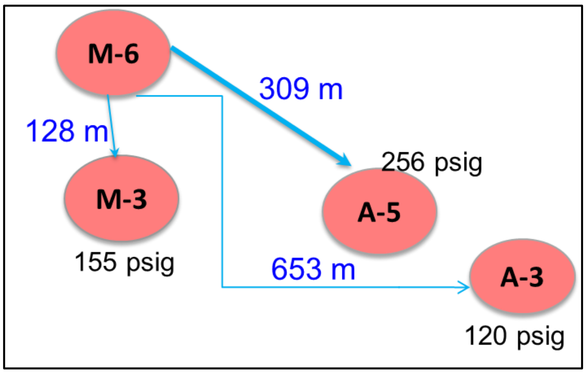

Figure 12: Interference diagram showing the relative distances between major feed zones of Wells M-3, M-6, A-3 and A-5. Also shown are the FWHP of the interfered wells during the Interference Test.

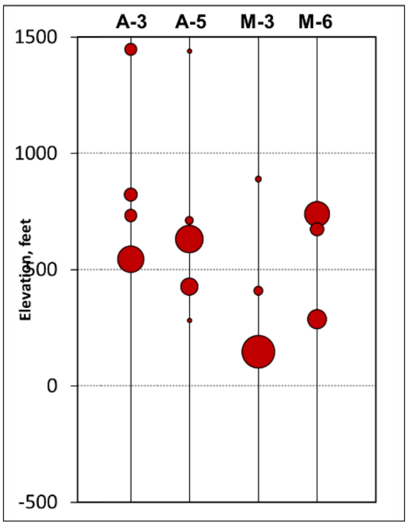

Figure 13: Stick chart showing the relative elevation of major permeable entries encountered by Wells A-3, A-5, M-3, and M-6.

3.6. **Wells A-2 and A-3**

Well A-2 has strong connection with A-7 and weak connection to A-3 (Figure 14). During the Interference Test, both Wells A-3 and A-7 were fully opened at about ~120 psig FWHP (Table 2). However, A-3 is located close to A-5 that has higher FWHP (~255 psig). It is possible that this high pressure in the area prevents the NCG from flowing to A-3, and as consequence, the NCG flows to the area with lower pressure (which is A-7). This creates the weak connection with A-3 when A-2 was shut-in.

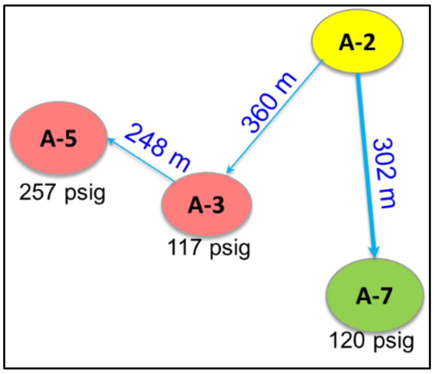

Figure 14: Interference diagram showing the relative distances between major feed zones of Wells A-2, A-3, A-5, and A-7. Also shown are the FWHP of the interfered wells during the Interference Test.

3.7. **NCG Interference at Pad P**

Looking at historical data, changes in NCG concentration were also observed at Pad P when new wells drilled on this pad were put online. When Well P-3 was first produced in 2002, the NCG concentration of Wells P-1 and P-6 immediately plunged, while P-2 showed no significant changes in NCG concentration (Figure 15).

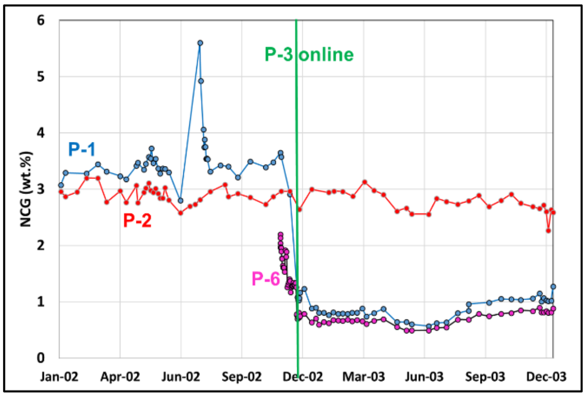

Figure 15: Chart showing historical NCG concentration of Pad P wells.

Based on the 3D distance between major permeable entries encountered by the Pad P wells, the major feed zone at P-3 is about 342 m and 360 m away from the major entries at P-6 and P-1, respectively (Figure 16). Wells P-6 and P-1 appear to have strong connectivity with P-3 based on their NCG response, and their relative major feed zone distance supports the observations at Pads A and M. The major feed zone at P-2 is about 560 m away from the major entry at P-3; thus, the minor response in NCG content and the postulated weak connectivity.

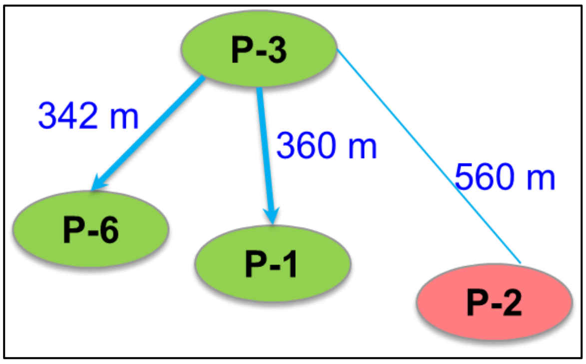

Figure 16: Interference diagram showing the relative distances between major feed zones of Wells P-1, P-2, P-3, and P-6

4. CONCLUSIONS AND RECOMMENDATIONS

The relative connectivity between wells in the steam cap in East Salak could be determined with the conduct of an NCG Interference Test. By changing the operating settings of a well, the response in terms of NCG content of surrounding wells provides a qualitative measure of their connectivity.

The factors that impact the NCG response during the Interference Test are the relative distance and elevation of the major permeable entries of the wells and the wells' operating setting. Wells with major entries about ≤360 m away tend to have significant NCG interference, and were considered strongly connected. In some cases, wells have major entries within ≤360 m from each other but the NCG response is minor (i.e., they were considered weakly connected). The elevation of major permeable entries appears to control these wells' connectivity. If the major feed zone in the source of perturbation is significantly shallower than the interfered wells, these wells will exhibit a weak connection. Lastly, interfered wells that operated at higher WHP (e.g., throttled condition) tend to show weak connectivity with the source of perturbation.

Results of the NCG Interference Test should be conducted periodically especially, among others, when the system operating settings are changed and new wells are put online. The relative connectivity between wells as a result of the NCG Interference Test should be used to further characterize the fracture network in this part of the field.

ACKNOWLEDGEMENTS

We would like to thank Star Energy Geothermal Salak (SEGS) and Pertamina Geothermal Energy (PGE) for granting permission to publish this work. Massive thanks to the SEGS Asset Development Group for the support in finalizing this paper.

REFERENCES

Imantoro, D., Hidayaturrobi, A. D., Putri, R. P., Utami, A.A., High NCG Wells Interference Test for High NCG Wells Optimization in Salak Geothermal Field, *Proc. The 5th Indonesia International Geothermal Convention and Exhibition*, Jakarta, Indonesia. (2017).

Julinawati, T., Paramitasari, H., Putri, R.P., Hidayaturrobi, A.D., Salak NCG Interference Evaluation to Enhance Steam Production in High NCG Wells, *Proc. The 5th Indonesia International Geothermal Convention and Exhibition*, Jakarta, Indonesia. (2017).

Putra, F. J., Aprilina, N. V., *Salak 3D Static Model: Stratigraphy and Reservoir Property Modeling*, Chevron Internal Report. (2016).

Rohrs, D., Gunderson, R., Melosh, G., Suminar, A., Nordquist, G., Molling, P. Sirad-Azwar, L, and Acuña, J., *Salak 2005 Conceptual Model Update*, Chevron Internal Report. (2005).

Rohrs, D., *Salak 2007 NCG Production History and Forecast*, CGS Internal Report. (2007).

Wijaya, B.A., Suminar, A. R., Ganefianto, N., *Resource Management Geosciences Well Sampling Two-Phase Flow Standard Operating Procedure*, Chevron Geothermal Salak Internal SOP. (2009).