Kawah Kamojang Pilot Injection Test: Production Monitoring Evaluation and Numerical Reservoir Modelling Study to Support Kamojang Injection Optimization Program

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ABSTRACT

Injection optimization strategy is an essential component of geothermal resource management, as it plays a pivotal role in ensuring the security of steam supply. Presently, Kamojang geothermal field continues to produce at full capacity at 235 MW from about 515 kg/s of steam production and giving an excess of 95 kg/s condensate to reinject. Condensate injection in the Kamojang field began in 1978, corresponding with the initiation of commercial production and to date the condensate injection strategy in the field is predominantly focused on the central area.

Superheat, as a potential threat to the security of Kamojang steam supply, is periodically monitored using surface superheat measurements. The monitoring program has observed a steady rise in superheat levels since 2017, with the most notable increase in superheat reaching up to 10°C. This increase is particularly evident in wells located in the vicinity of Kawah Kamojang area in the northeastern part of Kamojang. Several initiatives are currently being undertaken to counter the propagation of superheat. One such initiative is the injection pilot test in Kawah Kamojang area. There are currently 6 production wells and 1 non-commercial well in Kawah Kamojang area. The sole inactive well, situated in the northernmost part of Kawah Kamojang was selected as the injector candidate where the pilot injection test was conducted over a duration of 2 months.

A surveillance program was established to monitor the production of wells and the surface superheat in order to observe the responses of the reservoir to the pilot injection test. The collected data is used to evaluate the impact of injection changes on the reservoir.

The numerical reservoir model of Kamojang was employed to demonstrate the substantial extension of the steam supply forecast following the pilot injection scenario and to help determine the next step in the Kamojang injection optimization program.

1. INTRODUCTION

Kamojang geothermal field is located about 42 km south east of Bandung, West Java, Indonesia. The field is owned and operated by PT. Pertamina Geothermal Energy. Kamojang has a total generation capacity of 235 MW from 5 geothermal power plant units.

Kamojang is the very first field that was developed for geothermal energy extraction in Indonesia. It is one of the gems amongst geothermal fields since it has only produced high enthalpy steam with no brine and only condensate to manage as the excess product. The geologic setting and conceptual model of Kamojang are described by Imam et al. (2020) and summarized by O'Sullivan et al. (2023).

The exploration of Kamojang by the Dutch Indies colonial government dates back to 1926. It drilled 5 shallow exploration wells and encountered a shallow vapor dominated reservoir that is presently still discharging vapor within the Kawah Kamojang tourist area. The initial phase of non-direct geothermal development was the generation of 0.25 MW from a mono-block unit in 1978 and followed by the construction of power plant Unit 1, online for 30 MW. The following years, multiple drilling campaigns were carried out to continue the field expansion. Units 2 & 3 (2 x 55 MW) were online in 1987 and subsequently were followed by Unit 4 (60 MW) in 2008 and Unit 5 (35 MW) in 2015. After nearly 40 years of development, a total of 94 wells have been drilled of which 58 wells are currently active as production wells, 6 wells are used for injectors, 8 wells have been abandoned and 1 shallow exploration well is used as a tourist attraction.

Currently the field is producing 235 MW at full generation capacity from about 515 kg/s of steam production and giving an excess of 95 kg/s of condensate to reinject. With a field contract life until 2045, it is imperative for Kamojang to have a proper resource management strategy so that the field can sustain an adequate steam supply for full generation through to the end of the contract life.

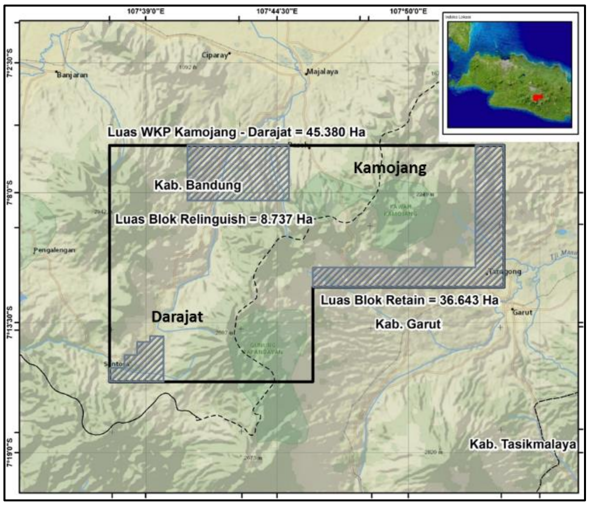

Figure 1: Map of Kamojang field in West Java, Indonesia.

Superheat development is a common issue to overcome with respect to steam supply in a dry steam geothermal reservoir development. During production, as the reservoir pressures decline, the immobile water boils to form steam which then flows towards the production wells. Since the reservoir is not replenished by natural recharge and, after some years of production, parts of the reservoir may run out of immobile water and become superheated (O'Sullivan, 2010).

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Superheat in Kamojang is monitored through surface superheat measurements, which are preferred due to their ease of execution and higher frequency compared to well measurements. Surface superheat monitoring is expected to offer an early indication of superheat within the well. In the broader context, Kamojang has exhibited a steady rise in superheat since 2017 and a considerable upward trend, from 2019 onward. This upward trend varies across different parts of the field, with the most significant increase reaching up to 10 C. This superheat increase is particularly evident in wells located in the vicinity of Kawah Kamojang area in the northeastern part of Kamojang.

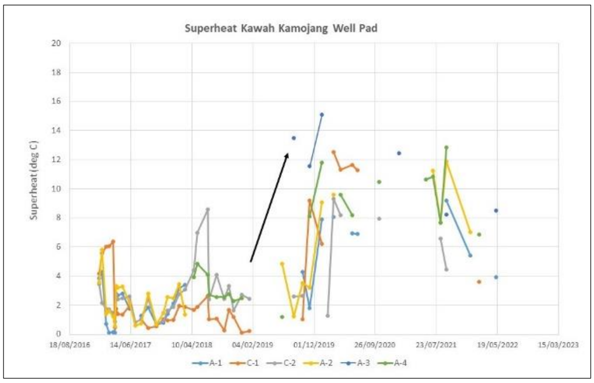

Figure 2 The surface superheat for Kawah Kamojang well pad in the northeastern part of the Kamojang field

One way to counter the superheat increase is good injection strategy. The injection strategy is one of the vital components in resource management. Injection of condensate in Kamojang field began in 1978 when commercial production commenced and to date, condensate injection is mainly done in the central part of Kamojang field. An effective injection strategy has to be defined to mitigate the superheat increase in this north east area and this may lead to the requirement of an injector well in the area.

There are several major factors that we believe are key for optimizing the injection strategy, especially for a dry steam geothermal field, such as: determining new injection location, and availability; assessing reliability of an injector well candidate, if it is existing well; quantifying the optimum rate for injection of condensate; designing the required surface facilities; designing new injection wells if needed. In line with those factors, there are several initiatives that are currently being undertaken to counter the propagation of superheat in Kamojang. The one initiative presented here is our injection pilot test where one inactive well in the Kawah Kamojang area was selected as the candidate for this pilot injection test.

A set of surveillance program was set up to monitor the reservoir response to the pilot injection to evaluate the impact of injection changes. In this paper we highlight and evaluate the changes we observed during the injection pilot test and we compare them to the long term forecasts from our numerical reservoir model. Reservoir simulation forecasts a substantial extension of the steam supply following the pilot injection test. The comparison of the actual data with the numerical model forecast results serves as proving point to test the robustness of the numerical model in representing the actual reservoir processes. With this validation, the numerical model can be used to help determine the next step in the Kamojang injection optimization study.

2. PILOT INJECTION

There are currently 2 active well pads in Kawah Kamojang area and both are dedicated for supplying steam to Kamojang Unit 5. From those pads, there are 6 active production wells and 1 inactive non-commercial well in the Kawah Kamojang area. The sole inactive well situated in the northermost part of Kawah Kamojang was selected as the injector well candidate for the pilot injection test.

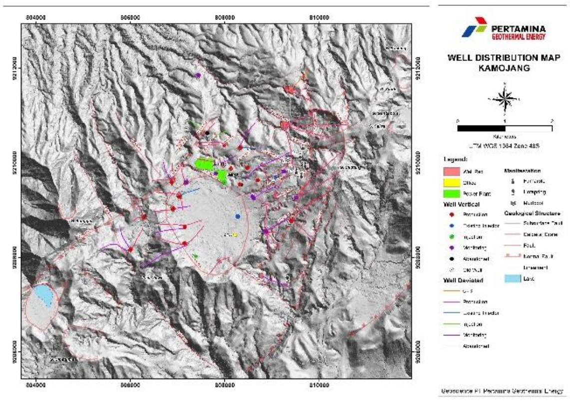

Figure 3: Map of Kamojang field and its exisiting wells.

The aforementioned well, namely C-3 was drilled in 2012 as part of the Northern Kamojang exploration drilling campaign for the development of Kamojang Power Plant Unit 5. The heat up pressure temperature profile of C-3 shows a peak temperature that is about 10-12℃ lower then adjacent wells and along with the deficient flow test results that for both flowing pressure and steam rate produced indicates C-3 has the characteristics of a well at the reservoir margin and it was denoted as the north boundary of the Kamojang reservoir.

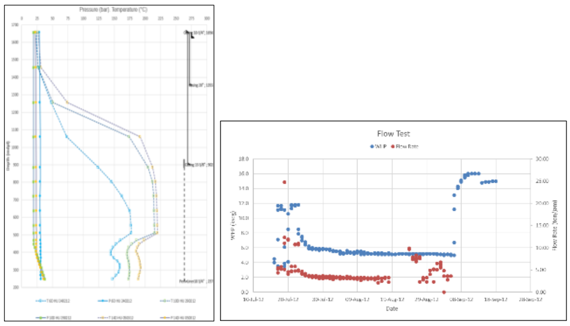

Figure 4: Pressure temperature profile from the heat up survey and flow test results for well C-3.

There are 3 main purposes that are to be achieved by this pilot injection test; the first purpose is the confirmation of reservoir interconnectivity between wells inside the Kawah Kamojang area. The ideal injection location should give fluid support to the production zone without giving too much thermal interference that may disrupt the production performance. The second purpose is the evaluation of impact from the pilot injection test to the local rising superheat level that is evident from the surface superheat measurement. The third purpose is the validation of the newly developed and calibrated numerical reservoir model. The validation from the pilot injection test data will improve our confidence level in utilizing the numerical model to investigate the optimum injection strategy in the future reservoir simulation studies.

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2.1 Injection Scenario

The existing injection scenario in Kamojang field is to distribute 95 kg/s of condensate to 4 existing injector wells situated in the central part of Kamojang. Historically, there was small part of the condensate injected to the west part of Kamojang, but since the associated well was damaged and the workover effort failed to recover the well, Kamojang condensate injection strategy is predominantly focused on the central area.

The pilot injection test took about 47 kg/s of condensate from the existing total injection rate. The injection rate was based on the minimum quenching rate that was measured from the C-3 well test. The pilot injection test was planned to be run for a duration of 6 months but due to budget and planning constraints it was cut short to 2 months.

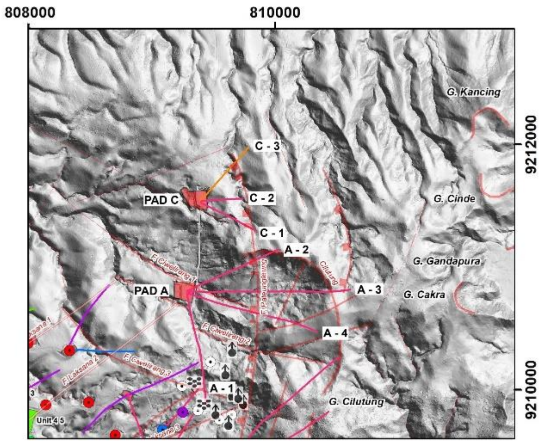

Figure 5: Map of wells on Kawah Kamojang area.

A surveillance program was established to monitor the production parameters and the surface superheat of surrounding production wells to determine the response of the reservoir to the pilot injection test. The data evaluation from the pilot injection test is constrained to the Kawah Kamojang area and is limited to the observation of the impact from adding injection to Kawah Kamojang area. Hence the impact of reducing the existing injection rate to the rest of the Kamojang field was set aside and will be included in the future Kamojang injection optimization study.

2. PRODUCTION MONITORING

2.1 Production parameter

Production parameters of all Kawah Kamojang wells were monitored during the pilot injection to observe whether the condensate injection at Well C-3 was impacting the flow rate and operating well head pressure or not. If the condensate injection lowers the reservoir temperature, condensation will occur near the wellbore and inhibits steam production resulting in a lower steam production rate. The flow rate is also dependent on the operating conditions of the well. Increasing well head pressure will result in a flow rate decrease and vice versa. For this injection pilot test, the aim was to keep all wells at their optimum operating conditions.

The figures below show the flow rate and well head pressure before and during the pilot injection test at Well C-3. The condensate injection flow rate increased during the injection test with rates of 2000, 2400 and 2800 lpm sequentially. The increased rate was a necessity following the quenching requirement for Well C-3.

The data in wells that share the same pad with Well C-3 show a decline in flow rate and well head pressure for both Wells C-1 and C-2. Well C-2, as the nearest well to Well C-3 shows immediate production decline as soon as the injection starts and shows a loss of about 1.5 tph of steam production near the end of the injection test. Well C-1 also shows an impact from the injection but it is not as apparent as for Well C-2. Well C-1 lost about 0.3 tph of steam production near the end of the injection test. We neglect the flow rate and well head pressure data near the end of injection test period for data evaluation as it clearly shows the well operating conditions were changed for steam supply needs.

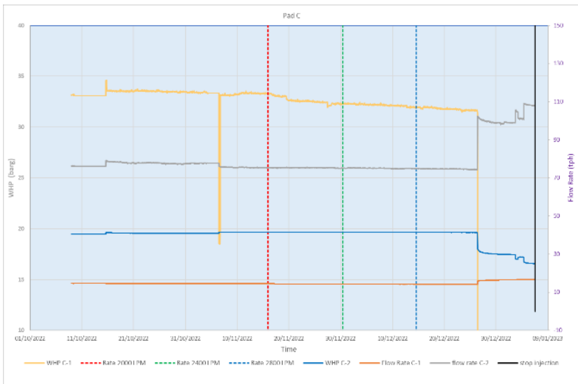

Figure 6: Declining flow rate and well head pressure profile for Pad C wells during injection.

All the monitored production wells in pad A, about 1 km south of pad C (Well A-1, A-2, A-3 and A-4) shows almost no changes in flow rate and well head pressure except for Wells A-3 and A-4. The flow rate decline with stable well head pressure in Well A-3 was verified in the field, and it was found that there was dirt plugging its Barton chart gauge. After purging, the reading went back to stable value again. It was believed that the flow rate decline in Well A-3 was questionable and it was decided that it was not suitable for data evaluation. For Well A-4, the sudden flow rate decline at the end of December, with a stable well head pressure, is strongly believed to be caused by changing operating conditions in the surrounding wells. This is the type of conditions that we ideally wanted to avoid during the injection test but could not due to steam supply prioritization.

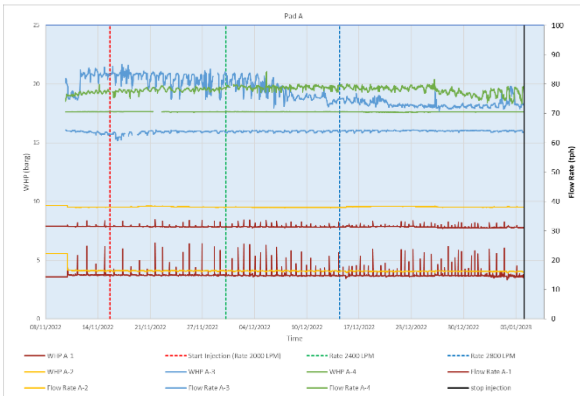

Figure 7: Relatively stable flow rate and well head pressure profile for Pad A wells during injection.

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2.2 Surface superheat monitoring

Surface superheat monitoring was conducted for the monitored wells during the injection into well C-3, including A-1, A-2, A-3, A-4, C-1 and C-2 wells. These observations were carried out daily for weeks following the reinjection. The change in the value of this indicator against the background value during the injection process is attributed to the influence of well C-3 injection. Therefore, any shift in superheat in a well during injection indicates a connection with the injection well, namely C-3. However, it should also be noted that surface superheat is also influenced by the operational parameters of the well. As a result, surface superheat measurements are often guided by the well WHP observations. Kecuali 79 90 91

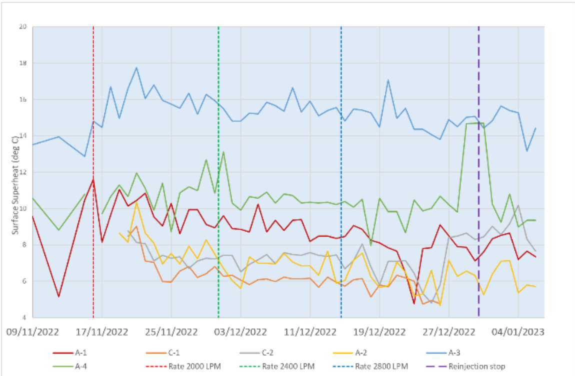


Figure 8: Superheat surface monitoring chart during reinjection at Well C-3

As shown in the chart in Figure 8, the monitoring results show that surface superheat measurements indicate an average decrease of 2°C on the 3 nearest wells; C-1, C-2 and A-2. There is no indication of superheat decrease on the 3 farthest wells; A-1, A-3 and A-4. Throughout the monitoring process, there were minimal changes observed in the wellhead pressure (WHP). As a result, this shift is thought to originate from processes within the reservoir, likely triggered by the reinjection activities at C-3. Based on this superheat shift, it is inferred that the wells exhibiting superheat changes are connected to the C-3 reinjection well. To further confirm the positive impact from the injection, it has to be noted that well C-1, C-2 and A-2 does not have proper surface superheat data prior to injection to serve as reference data.

3. RESERVOIR MODELLING STUDY

3.1 Current state of reservoir model

A new numerical reservoir model of Kamojang was developed during 2022 in a collaboration between PT. Pertamina Geothermal Energy and the University of Auckland, using an integrated modelling framework developed at the University of Auckland that allows the direct creation of a numerical model from a Leapfrog-based digital conceptual model (O'Sullivan et al., 2023; O'Sullivan et al., 2019; Popineau et al., 2018). Hence formations, structures and the alteration zone are all represented explicitly in the model as unique rock types and provide potential heterogeneity in rock properties to be varied for model calibration. The model can be run in AUTOUGH2, a variant of the industry -standard simulator TOUGH2, or in Waiwera, a highly parallelised, open-source simulator developed by the University of Auckland and GNS Science. For this application, we chose to utilize Waiwera running in a parallel cloud computing environment thus achieving a much faster computing time.

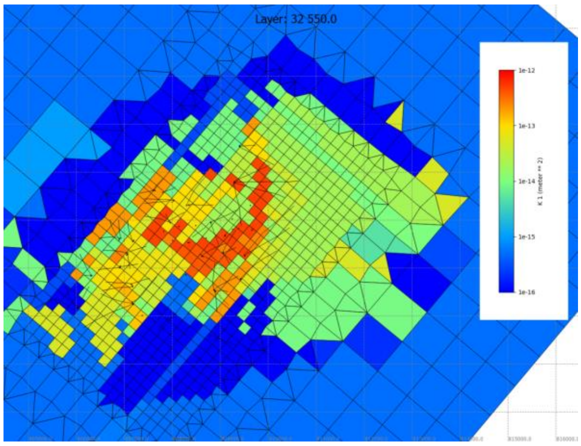


Figure 9: Lateral Permeability distribution of the current Kamojang reservoir model on 550 masl.

The state of the Kamojang reservoir model was described by O'Sullivan et al. (2023). The model was further calibrated by the author under a technical support program between PT. Pertamina Geothermal Energy and the University of Auckland. The state of model calibration achieved in both natural state and production history model was improved, especially the match to the pressure response of Kamojang during the exploitation period.

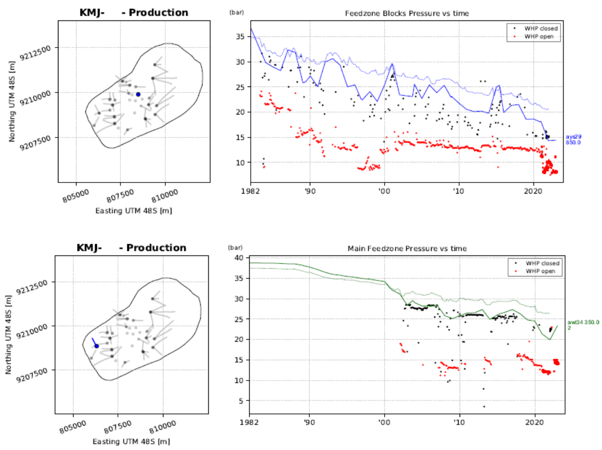


Figure 10: Samples of improved pressure response match for the Kamojang reservoir model after recent calibration

The superheat level in a model block in the numerical model was calculated by the temperature ℃ above the boiling temperature for the pressure in the same block. The superheat in the numerical model was then compared with the actual downhole temperature measurements made in 2009 by Pertamina Geothermal Energy. Figure 11 below shows the superheat in the model at 650 and 550 masl elevation compared with the actual downhole superheat measured at 600 masl. The comparison shows a reasonable match was achieved by the numerical model. It should be noted that the superheat results for new calibrated model are almost the same as for the original numerical model. There will be future effort made to improve the superheat match results.

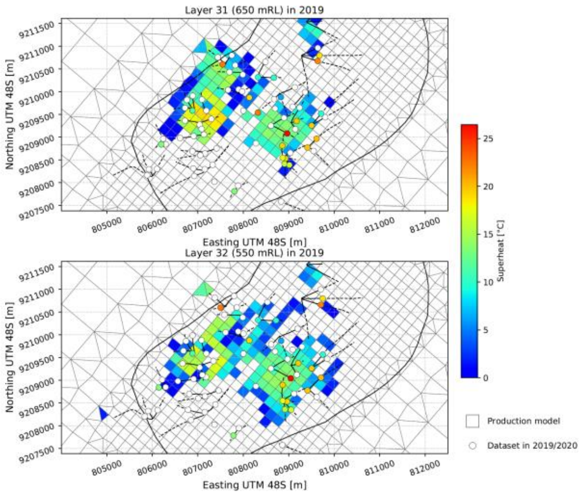


Figure 11: Comparison of superheat from the numerical model with measured downhole superheat

Model calibration is a continuous process and quite possibly only achieves its best confidence level at the end of the commercial life of the field. While a single numerical model may not have captured the range of uncertainty of Kamojang reservoir processes, we believe that the current Kamojang reservoir model gives a good representation of the reservoir processes and we are confident that the new calibrated model is appropriate for simulating this injection study.

3.2 Pilot Injection Test Simulation

A future scenario was set up for the numerical model following the actual pilot injection setup in the field, with the numerical model keeping the injection setup onward to determine the long-term impact of injection in Kawah Kamojang on the reservoir, especially on the adjacent production wells. As a comparison, the existing injection scenario was also simulated as a base-case scenario.

Simulation result shows that the new injection scenario has a negative impact on the production performance compared to base-case scenario and it only affects wells inside Kawah Kamojang area, i.e., the Kamojang Unit 5 wells. The impact on the total production from Unit 5 wells was immediate as soon as the pilot injection starts. The steam supply profile shows a sharper decline than base-case scenario and a loss of total production from about 3 to 5 MW worth of electricity generation over time.

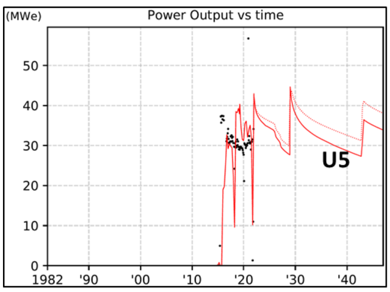


Figure 12: Total generation of Unit 5 supplied by Kawah Kamojang wells. Comparison of base scenario (dotted line) vs pilot injection scenario (solid line)

Results for individual well performance in the simulation were extracted for 2 wells in Kawah Kamojang area, the first well is in the same pad, pad C, and is the nearest well to well C-3 while the second well is in different pad, pad A, and is the farthest well away from well C-3 in the area.

Well C-2 as the nearest well with a distance of about 300 meters, feedzone to feedzone, from Well C-3. It shows immediate impact of the injection as the pressure and temperature immediately drop by 1.5 bar and 2°C, respectively, after the injection at well C-3 starts. These drops result in a sharp production decline with an almost 15% loss in steam production. This simulation result is expected because with the numerical model resolution and distance between the wells as mentioned, the feedzone blocks of each well are situated next to each other diagonally, and hence there is a very direct connection.

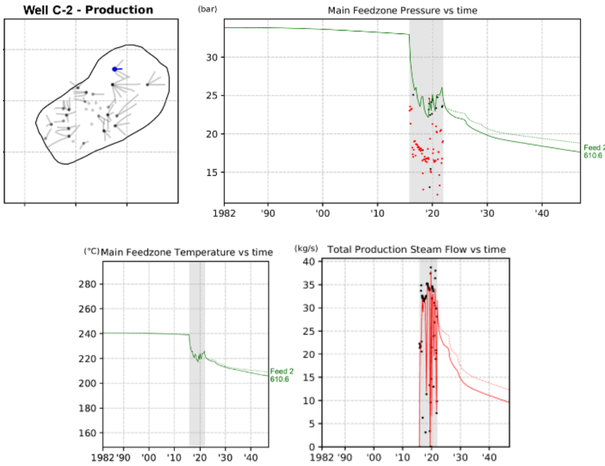


Figure 13: Well C-2 Performance, simulation result. Base (dotted line) vs Pilot injection (solid line)

In contrast to the Well C-2 response, a subtle response is shown by Well A1 which is situated 2 km, feedzone to feedzone, from Well C-3. There is slight pressure and temperature drop after about 5 years after the start of injection. As the farthest well in Kawah Kamojang area from Well C-3, Well A1 still shows a response to Well C-3 injection, confirming a weak connection between the 2 wells.

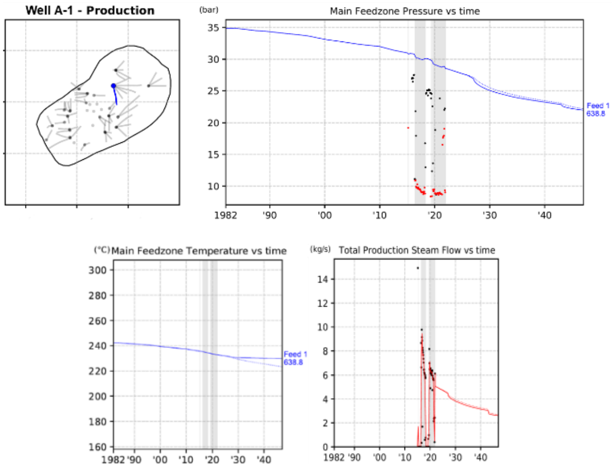


Figure 14: Well A-1 Performance, simulation result. Base (dotted line) vs Pilot injection (solid line)

As well as the simulated trends from these 2 wells above, the simulated behavior of other wells in the area was also extracted but are not presented here. The numerical model suggests that all wells in Kawah Kamojang area are connected with well C3 but experience lesser and delayed impact with increasing distance from the injection point. The trend is consistent with the lateral permeability set in the numerical model following Pateungteung Fault that trends North –

South in Kawah Kamojang area, intersecting all those wells in Pad A and C. In addition, given the result of a delayed impact of injection on Well C-2. It is highly likely that the actual production monitoring of wells in Pad C will shows different production trends for a longer-term injection test.

Further results from the numerical reservoir model can be seen in the figure below. The colors in the block represent the gas saturation while the arrows represent the gas flow between model blocks. The reservoir processes below the Kawah Kamojang area shows movement of cooler water injected into Well C-3 flowing dominantly vertical to the deep reservoir and minimizing the opportunity of the injectate to re-saturate the superheated matrix at a fixed reservoir depth. This process depicted by the numerical model negates the injection effort to reduce the superheat level in the Kawah Kamojang area.

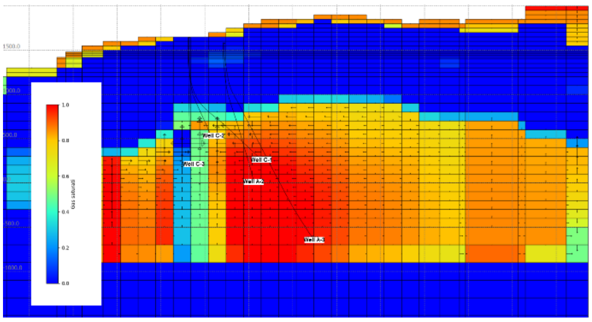
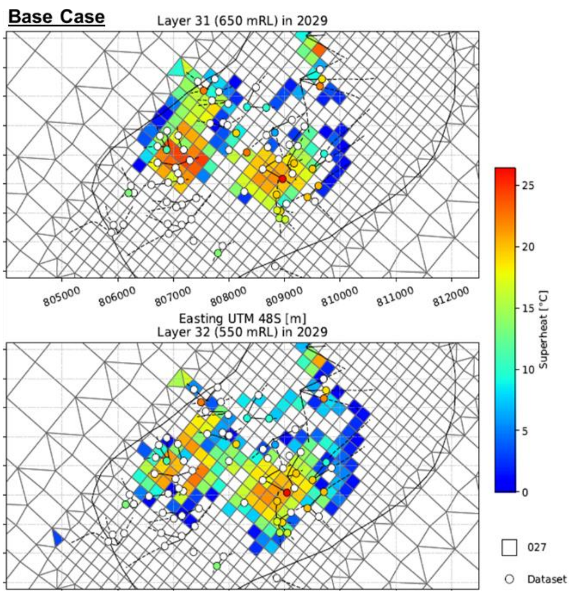


Figure 15: NW–SE numerical model cross section showing reservoir process beneath Kawah Kamojang using pilot injection scenario, year 2024

The numerical model also shows reservoir processes with the cooler injectate from Well C-3 collapsing the steam column below and reducing the reservoir pressures in column blocks. The pressure drawdown caused by Well C-3 injection pulls more steam flow from surrounding Kawah Kamojang wells that are laterally connected. The subsequent impact is more pressure drawdown occurred throughout the surrounding area causing propagation of wider superheat phenomena all over Kawah Kamojang area for the long term Well C-3 injection scenario compared with the base-case existing injection scenario, as shown Figure 16 below.



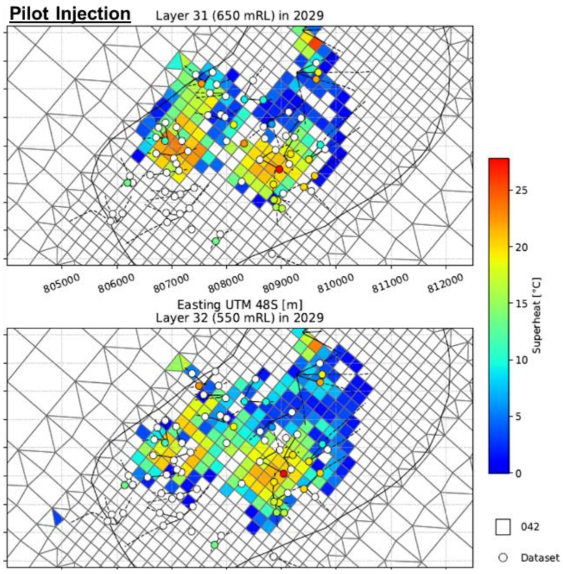


Figure 16: Superheat propagation in the numerical model, at depth 650 and 550 masl by year 2029 comparing the base scenario with the pilot injection scenario.

4. CONCLUSION

The Kawah Kamojang pilot injection test was conducted successfully and marks a new step in the Kamojang injection optimization study. The integration of surveillance datasets with reservoir numerical model simulation results has been used to determine the impact of injection-induced changes at the Kamojang field. The production and surface superheat monitoring data show agreement with the numerical reservoir simulation results for the pilot injection scenario, with both showing confirmation of the interconnectivity of the Kawah Kamojang wells. The conclusion is that the pilot injection test has negatively impacted the other production wells in the Kawah Kamojang area. These agreements between field data and the model results also gives us higher confidence in the the performance of the numerical reservoir model of Kamojang and its further use in future simulation studies of the Kamojang reservoir.

The key factors for optimizing the injection strategy that were mentioned at the beginning of this paper have to be reconsidered for the future injection optimization study in Kamojang field. The future study will begin with developing a new pool of suitable injection well candidates and creating a new reservoir simulation study to forecast a range of production and injection scenarios using those injection well candidates before deciding to start another injection test to confirm the reservoir simulation results. A longer injection test under ideal operating conditions in Kamojang is also desirable for the future injection test to achieve better data evaluation.

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