PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

Discharge Stimulation in Two-phase Liquid-dominated Wells in Dieng Field, Indonesia: Lessons Learned

Zahratul Kamila[1], Ichwan Elfajrie[1], Marchel Supijo[1], Riswan Herdian[1], Ndaru Dwiyatmoko[1], M. Istiawan Nurpratama[1], and Ali Ashat[1]

PT Geo Dipa Energi (Persero), Aldevco Octagon 2nd Floor, Jl. Warung Jati Barat No. 75, South Jakarta 12740 - Indonesia

zahratul.k@geodipa.co.id[1]

Keywords: Non-artesian well, discharge stimulation, air compression, nitrogen injection, well-to-well

ABSTRACT

The Dieng Geothermal Field, Indonesia, is a two-phase high enthalpy reservoir with a current installed capacity of 60 MW. Some liquid-dominated wells near the reservoir boundary are non-artesian, primarily due to a water column above the main feed zones. This paper elaborates on discharge stimulation carried out for several production and idle wells over the past five years, including several methods, such as air compression, well-to-well, and nitrogen injection. The analysis encompasses the discharge prediction, method selection tailored to each wellbore condition and parameter, the designed program, and actual field results while highlighting challenges and lessons learned. In general, most methods have successfully reactivated all liquid-dominated wells. However, when implementing these methods in 25-year-old wells, several technical considerations need to be taken into account to minimize the adverse effects of sudden temperature differences in the well during the transition from non-discharged to discharged conditions.

1. INTRODUCTION

Certain wells exhibit non-artesian characteristics within liquid-dominated geothermal fields, typically characterized by low to medium enthalpy and hydrostatic pressure exceeding reservoir pressure. Grant and Bixley (2011) and Sarmiento (1993) outline various factors contributing to impaired discharge capabilities. These factors include low-temperature recovery, a cold water column above the reservoir, well damage during drilling, deep water level, undeveloped wellhead pressure, poor reservoir permeability, higher pressure drops due to smaller casing size, and high elevation terrain (lower water level). According to Mubarouk (2017), even wells initially capable of self-discharge may transform into non-self-discharge wells over their productive lifespan. This transformation can occur due to reservoir temperature cooling (due to the reinjection breakthrough or groundwater influx), the decline of reservoir pressure, and possibly due to mineral scaling in the formation.

The Dieng Geothermal in Indonesia is characterized as a two-phase liquid-dominated reservoir with a current installed capacity of 60 MW. Currently operational are nine wells dedicated to production and four wells allocated for injection. Most producer wells in Dieng exhibit low to medium enthalpy ranging from 1350 to 1600 kJ/kg. However, several wells encounter the steam cap zone, leading to substantially higher enthalpy values within the 1800 to 2700 kJ/kg range.

Nearly all active production wells in Dieng Field can flow naturally during initial well testing. High enthalpy wells are expected to exhibit artesian characteristics, given their high energy content nature and the low density of the produced steam/gas, resulting in low hydrostatic pressure relative to the reservoir. However, after over two decades of production, some low to medium enthalpy liquid-dominated wells in Dieng might require stimulation before recommencing discharge due to the presence of a cold-water section in the upper side of the wellbore, the slow heating-up process, or gradual wellhead pressure development. Furthermore, intermittent discharge stimulations are employed in certain active wells with low productivity and permeability to enhance overall production and wellhead pressure. Hence, the purpose of stimulation goes beyond the reactivation of wells, encompassing the broader goal of improving production outcomes.

This paper aims to present the discharge stimulation efforts undertaken for several production and idle wells in Dieng Field over the past five years, including several methods, such as air compression, well-to-well, and nitrogen injection. The scope of this paper extends to evaluating discharge predictions, selecting methods customized to the conditions and limitations of each wellbore and surface facility, detailing the designed program, and presenting actual field results. The paper also highlights the challenges encountered and lessons learned throughout this process.

2. DISCHARGE PREDICTION

Given the elevated temperature of the Dieng reservoir exceeding 300^{o}C, it is crucial to minimize the thermal cycling in the casing, particularly in response to abrupt temperature changes. Maintaining a minimal discharge (bleeding) is obligatory for the presently active producers during power plant shutdowns or overhaul periods. A risk of thermal shock is possible if wells remain static for an extended period before resuming discharge. This occurs when hot fluid suddenly flows into a previously cold casing due to a gas column or cold fluid. Furthermore, there is no assurance that the wells will resume natural flow.

Nevertheless, there are situations in which wells are intentionally shut down or quenched for investigation, monitoring, or workover purposes. Following such events, efforts are consistently made to restore natural discharge first. This procedure involves the deliberate and gradual opening of the side valve to release non-condensable gases (NCG) from the wellbore to facilitate a gradual reheating of the casing until geothermal fluid begins to flow.

Before initiating flow, the well's potential for self-discharge was assessed using various methods. In many cases, the limited data becomes a determining factor, necessitating the selection of methods to be as simple as possible without requiring extensive input parameters. When current static pressure-temperature (PT) data are available after a thorough heating-up period, discharge predictions can utilize Af/Ac ratio calculations, a method introduced by Sta Ana (1985), which is widely adopted in the geothermal industry. According to this approach, discharge is likely unsuccessful if the Af/Ac ratio is less than 0.7. Figure 1 provides examples of Af/Ac estimation from several wells alongside actual discharge results. While several Dieng cases generally align with Sta Ana's criteria, an Af/Ac ratio of 0 does not always imply that wells cannot achieve self-discharge. Consequently, the Af/Ac method should complement another straightforward approach.

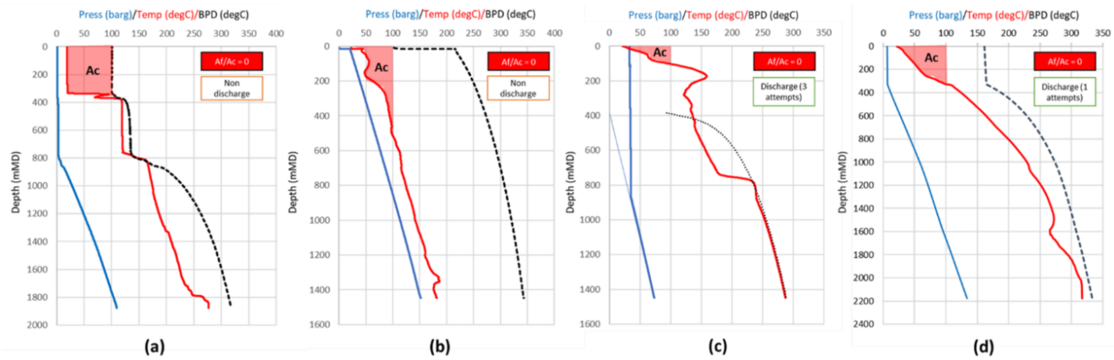


Figure 1. Example demonstrating PT static data on several wells from Dieng, Indonesia. Case (a) and (b) have Af/Ac = 0 and are non-artesian; Case (c) has Af/Ac = 0 and is successfully discharged naturally after three attempts; Case (d) has Af/Ac = 0 but flows naturally during bleed off gas trial (WHP start is 1020 psig)

A study conducted by Hanik (2014) proposes that another determinant for an artesian well is the minimum wellhead pressure needed to initiate flow, which requires at least 60 bar, particularly for deeper wells with a feed zone temperature exceeding 300°C. This prompted an in-house modification of the empirical method based on historical discharge experiences at some Dieng production wells. Figure 2 illustrates the suggested discharge prediction, establishing a relationship between the maximum static wellhead pressure (WHP) and the last flowing enthalpy using various field data in Dieng. The high probability zone lies in a maximum WHP of around 65 barg for low to medium enthalpy, while the required maximum WHP may decrease to 50 barg for high enthalpy. Within the WHP range of 40 – 60 barg, the chance of self-discharge is less likely, necessitating an extended heating-up period or multiple discharge attempts. Lastly, if WHP development fails to reach 40 barg, the expectation for the well to flow naturally is anticipated to be minimal or nonexistent.

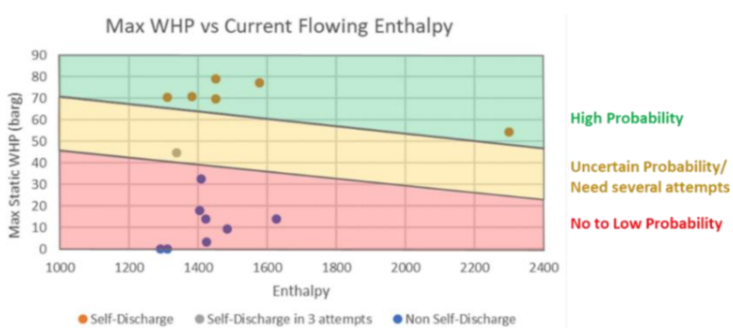


Figure 2. Discharge enthalpy prediction using Max WHP vs current flowing enthalpy (proposed in-house method) with some Dieng field data

Furthermore, the "water level to feed zone (FZ) distance" approach, as introduced by Mubarok (2017), can also be applied to Dieng field data. According to Mubarok, the probability of a well to self-discharge decreases as the distance between the water level and the feed zone increases. It is also predicted that for wells with a feed zone temperature exceeding 200°C, the maximum distance conducive to a self-discharge well is approximately 600 m. Nonetheless, in the case of Dieng, it seems that the maximum distance can be extended to around 850 m, likely due to the higher temperature of its feed zone (290°C-319°C) compared to Mubarok's data range (200-300°C). Figure 3 provides the discharge prediction using Mubarok's water level-feed zone distance method, utilizing field data from the Dieng field.

The compilation of all discharge prediction calculations and the corresponding actual field results in Dieng is presented in Table 1. The discharge prediction methods discussed are expected to apply to high-temperature geothermal reservoirs. Nevertheless, it is imperative to note that explicit testing of this applicability should be carried out in various fields. When discharge predictions suggest a non-flow scenario, substantiated by the observed failure to achieve flow during discharge attempts, preparations for and initiation of discharge stimulation begin.

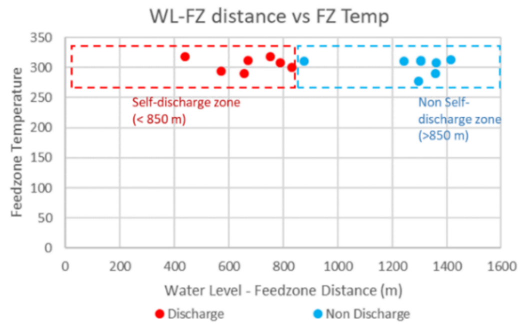


Figure 3. Discharge enthalpy prediction using water level-feedzone distance method in high-temperature geothermal reservoir (modified from Mubarok (2017))

Table 1. The calculation summary of several discharge methods and the actual discharge results in the last five years

No	Af/Ac	Water level (mMD)	Shallow FZ (mMD)	Water Level – FZ distance (mMD)	FZ temperature (ºC)	WHP Max (barg)	Heating-Up duration (days)	Last Enthalpy (kJ/kg)	Actual Result of Self-discharge Capability
1	N/A	1358	1799	441	319	79	14	1451	Discharge
2	N/A	1047	1799	752	319	70	3	1451	Discharge
3	N/A	1015	1587	572	294	55	3	2301	Discharge
4	N/A	1010	1800	790	308	71	38	1382	Discharge
5	N/A	961	1631	670	312	77	7	1580	Discharge
6	0	943	1600	657	290	70	10	1311	Discharge
7	0	748	1580	832	300	45	6	1338	Discharge after three attempts
8	N/A	513	1757	1244	311	9	4	1486	Non-discharge
9	0	452	1757	1305	311	3.2	17	1425	Non-discharge
10	N/A	342	1757	1415	313	18	5	1405	Non-discharge
11	N/A	438	1800	1362	308	14	11	1423	Non-discharge
12	N/A	327	1631	1304	312	14	4	1627	Non-discharge
13	0	303	1600	1297	278	0	10	1292	Non-discharge
14	N/A	240	1601	1361	290	0	0.5	1311	Non-discharge
15	0	400	1600	876	311	32.4	>300	1409	Non-discharge

3. DIENG DISCHARGE STIMULATION CASE STUDIES

3.1 Well-to-well or Steam Heating

The initial step for non-discharging or low-production wells near a well with good production on the same pad involves well-to-well stimulation or steam heating. This technique encompasses injecting steam to transfer thermal energy from the producing source well to the non-discharging well, raising the temperature of the casing and water column in the receiving well.

The steam injection can be delivered through 4" lines to a 3-1/8" side valve or a 12" two-phase line to the master valve. Opting for a larger two-phase line for the non-discharge well after killing/quenching is advantageous to achieve a higher steam rate, thereby maximizing the heating process. This approach's success aligns with the findings of Siega et al. (2005) in the Philippines, where all well-to-well reactivation using large two-phase diameters is successful compared to a smaller side valve line. A larger line is particularly beneficial for wells exhibiting significantly large and cool water columns. For the actively low-producing wells, well-to-well stimulation through the side valve proves sufficient to recover WHP and/or boost the steam rate. The detailed field data of specific well-to-well campaigns conducted in Dieng over the past five years are summarized in Table 2.

In practice, initiating well-to-well stimulation with the lowest feasible steam rate and gradually increasing it to a stabilized level is recommended. This is to consider thermal stress implications to the casing and assess the well's reaction, the integrity of the pipes, and additional supporting facilities during the job.

Table 2. Well-to-well injection campaign summary from several wells in Dieng in the last five years

No	Year	Objectives	Issue	Duration	Line OD	Estimated stabilized steam rate from the source well (tph)	Before	After
1	2020	Reactivation	Undeveloped WHP after WO	16 hours	12”	N/A	Non-discharge. Static WHP 11 barg	Discharge
2	2021	Stimulation	Scaling	Seven days	4”	1.4 tph	WHP 10 barg	WHP 20 barg. Steam rate increased by 17%
3	2021	Stimulation	Scaling	24 hours	4”	3.5 tph	WHP 17 barg	WHP 20 barg. Steam rate increased by 10%
4	2022	Reactivation	Undeveloped WHP after WO	Three days	12”	2 – 7 tph	Non-discharge. Static WHP 14 barg	Discharge
5	2023	Stimulation	Scaling and cooling	14 hours	4”	3.8 tph	WHP 15 barg	WHP 31 barg. Steam rate doubled up

Figure 4 illustrates the throttle opening and WHP profile of a receiving well and a feeder well in the case of reactivation using well-to-well stimulation. The 2-7 tph steam rate was introduced to the receiving well for approximately three days. Although the WHP increase during the first two days of stimulation was not continuous, after an additional 24 hours of stimulation, it gradually provided sufficient thermal energy to initiate the flow.

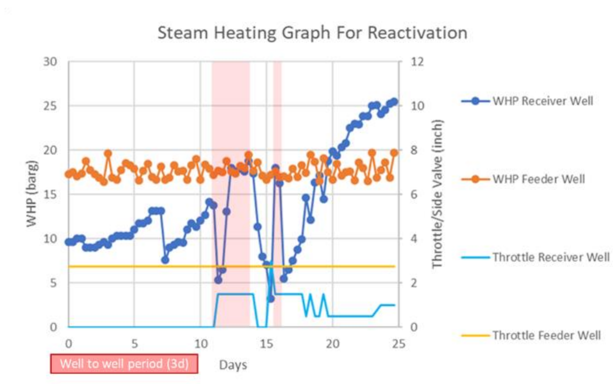


Figure 4. Profile during on-off three-days well-to-well stimulation in Well-9. Following the stimulation, the well successfully discharged, demonstrating an average flowing wellhead pressure (WHP) within the range of 23-25 barg

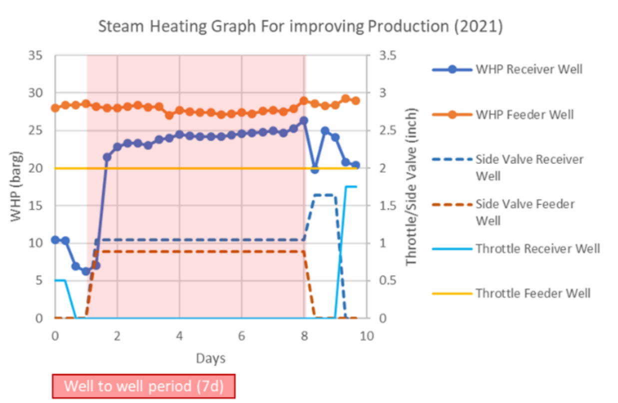


Figure 5. Well-2 profile during well-to-well stimulation for seven days continuously. WHP was improved, and the steam rate increased by 17%

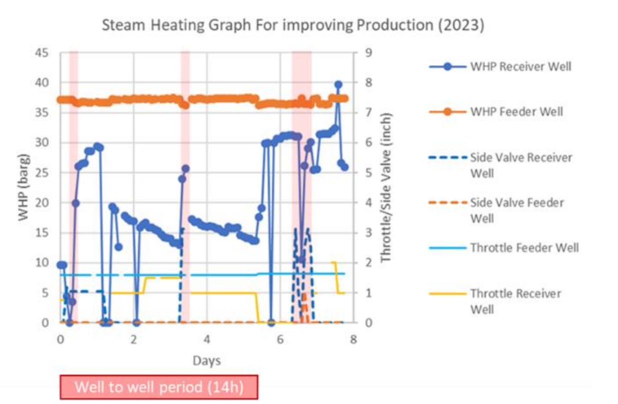


Figure 6. Well-2 profile during well-to-well stimulation for 14 hours intermittently. WHP was improved, and the steam rate doubled up

Figure 5 and Figure 6 depict two cases of well-to-well stimulation for well-2 (receiver well) using a steam source from well-3 (feeder well). Well-2 experienced a significant decline attributed to scaling and cooling. Consequently, well-to-well stimulation was carried out multiple times to enhance WHP and steam rate. The graph on the left represents a campaign conducted in 2021, while the graph on the right corresponds to a campaign undertaken in 2023. In 2023, the stimulation practice was shorter and more intermittent than in 2021, as the 2023 campaign included additional attempts, such as bleeding and horizontal discharge to AFT.

Differences in stimulation outcomes are noted for the same wells between 2021 and 2023. Despite a shorter steam heating duration in 2023, there is a higher increase in WHP and steam rate post-stimulation due to a higher steam delivery rate and the support of discharge attempts in between, leading to improved heating process efficiency and optimizing flashing. The total downtime for stimulation and discharge in both cases is comparable (around 7-8 days), but the latter yields a more optimal result.

3.2 Air Compression

For the air compression method, the pressurized air from the compressor is bullheaded through side valves to restrain and displace the cold water to the deeper hot formation, aiming to achieve a reduced hydrostatic pressure in the well. Subsequently, the well is sealed and held for a period, allowing the fluid to heat up before rapidly opening the master valve. This action creates a buoyancy effect that can stimulate the discharge.

In Dieng, air compressor stimulation is an alternative discharge stimulation method for non-artesian wells not situated on the same pad as other active production wells. This method is cost-effective compared to other stimulation methods and involves relatively simple facilities, installation, mobilization, and operation. However, caution should be exercised when employing this method due to the potential risk of casing crack during abrupt discharge, stemming from the substantial temperature differential between the high-temperature reservoir fluid (>300°C) and the cool casing filled with compressed air.

When calculating the compression pressure required to achieve optimal Af/Ac target, it is crucial to consider the casing burst and wellhead ratings to mitigate the risk of casing and wellhead deformation. Given that the production wells in Dieng have surpassed a 25-year operational span, an additional 50% safety factor is applied to both ratings. Furthermore, suppose the production well exhibits sustained undeveloped WHP for an extended period. In that case, it is necessary to perform a casing/cement integrity survey to confirm the absence of any leaks in the production casing or wellhead before initiating the air compression process.

The air compression campaigns executed in Dieng over the past five years are summarized in Table 3. Conversely, the post-air compression parameters before starting discharge are shown in Table 4. The campaign numbers are organized chronologically. Figure 7 illustrates the compression pressure design derived from the Af/Ac analysis using each campaign's most recent pressure-temperature (PT) data.

Table 3. Air compression campaigns summary from several wells in Dieng in the last five years

No	Target compression pressure	Total Compression pressure	WHP during the holding time	Holding time	Remark	AF/AC before	AF/AC After	Result
1	70 barg	67.6 barg	69 barg	0.33	One stage compression	0	0.57	Discharge
2	45 barg	44.3 barg	84.2 barg	2 hr	One stage compression	0	0.64	Discharge
3	70 barg	71 barg	40 barg	15 hr	Two-stage compressions	0	0.88	Discharge
4	70 barg	73 barg	72.5 barg	17 hr	One stage compression	0	1.25	Discharge
5	100 barg	48 barg	21-23 barg	Two days	Several time compressions	0	0	Non-discharge

Table 4. Post-air compression parameters right before discharge

No	WHP before discharge	Maximum side/throttle valve opening (inch)	Post-stimulation discharge duration	WHP decline	WHT increase	Remark
1	69 barg	3"	12 minutes	2.4 bar/min	No data	Quick discharge
2	84.6 barg	2"	3 minutes	27.6 bar/min	126°C in 38 min	Sudden discharge
3	70.4 barg	No data	Instantaneous	No data	No data	Sudden discharge
4	83.2 barg	1.2"	49 minutes	1.5 bar/min	119°C in 50 min	Slower discharge
5	48 barg	2"	Instantaneous	No data	No data	It could not be discharged since the target compression pressure was not reached.

Table 3 and Table 4 highlight several adjustments in design and implementation during air compression and subsequent discharge. In the first three stimulation campaigns, the compression pressure target was capped at a maximum of 70 bar or 1015 psi. The wells could still flow despite Af/Ac being less than 0.7 in the first two campaigns. This trend continued in campaigns 3 and 4, which achieved an Af/Ac of 0.88-1.25 with an extended holding period. The parameters after air compression for each successful campaign align with the high discharge area/probability depicted in Figure 8. Once again, the high Dieng reservoir temperature proves effective in heating up and flashing initiation. Conversely, the final air compression campaign was unsuccessful as the compression pressure target was not attained. The outcome also corresponds to the post-stimulation data falling into the non-self-discharge zone or uncertain probability area.

Initially, three campaigns encompassed a rapid-to-abrupt discharge, posing a significant risk to casing integrity. One tangible adverse effect was observed in a stimulated well after campaign 3, leading to changes in casing geometry based on the caliper survey two years after flowing. Consequently, the next campaign's discharge adopted a smaller throttle opening during discharge to moderate the flow and release wellhead pressure gradually, minimizing temperature differentials across the casing, wellhead, and production lines. A prolonged holding time at higher compression pressure was also implemented to facilitate a gradual heating-up process. Figure 9 shows the comparative operational parameters during air compression, holding, and discharge between the initial and most recent campaigns.

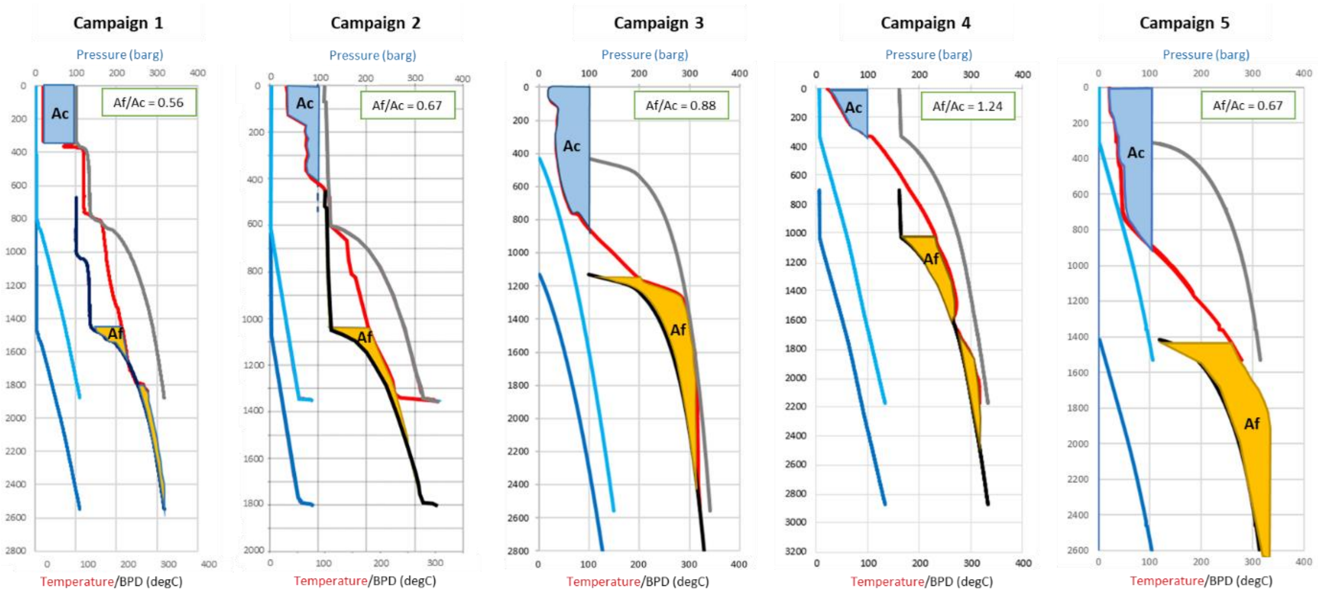


Figure 7. The Af/Ac ratio computation to establish the target compression pressure relies on the latest PT data for each campaign. From 5 executed campaigns, the median design compression pressure target is around 70 barg, whereas the average Af/Ac target ratio is 0.8

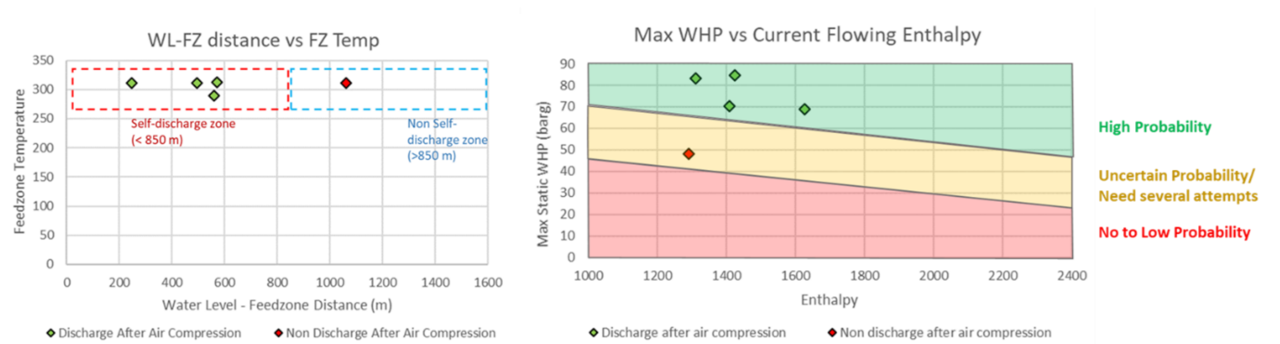


Figure 8. Outcomes about post-air compression parameters are examined in two previously posited discharge prediction methodologies, as delineated in Section 2

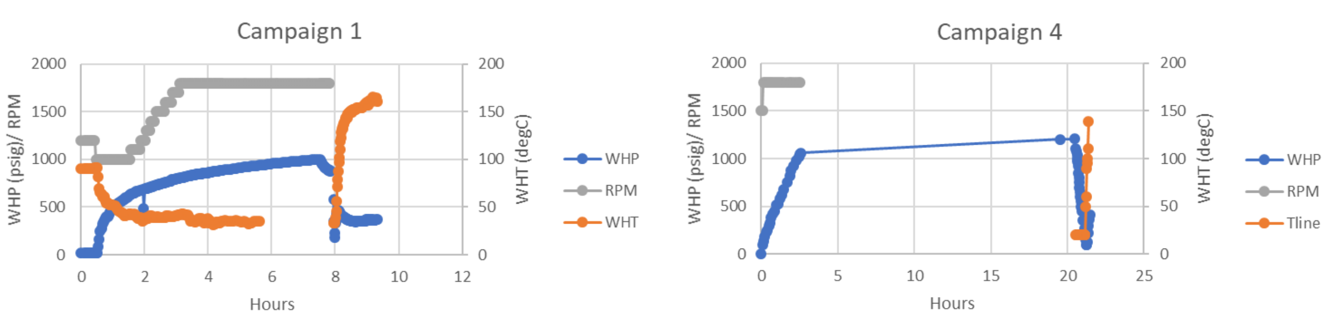


Figure 9. The operational parameters during air compression, holding, and discharge from Campaign 1 and Campaign 4

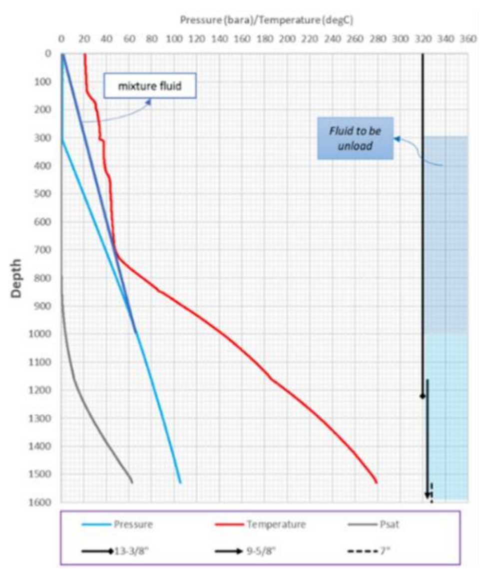
3.3 Nitrogen Lifting/Injection or Unloading

Nitrogen lifting, by default, is the latest option due to its costliness and requires more complex operation compared to previous discharge stimulations. In 2023, this stimulation technique was implemented for the first time in a well following an unsuccessful air compression attempt. The nitrogen lifting method is designed to decrease the water column's density, ensuring that the wellbore pressure becomes smaller than the reservoir pressure, facilitating the flow initiation. Nitrogen gas is injected through the coil tubing unit, mixing and lifting the water column.

The program's theoretical foundation and the calculation of nitrogen volume requirements rely on a study conducted by Aqui (1996). PT shut-in logging provides reference data for the wellbore's water column, pressure, and temperature. The well features a shallow water level with a profound condensation region extending to approximately 700 mMD, where the temperature remains below 50°C. The analysis suggests that unloading at a depth of 1000 m can yield a submerge ratio of 0.7, with temperatures reaching 140°C. This condition enhances the likelihood of flashing and induces the flow of geothermal fluid (Figure 10).

Coiled tubing (CT) deployment was executed on two occasions. The first trial was limited to a depth of 500 mMD, employing 1.5" OD coiled tubing with a 1-7/8" OD BHA (resulting in a submergence ratio of 0.4). Despite not achieving discharge, it provided valuable operational insights. The trial underscored the necessity of incorporating additional foam mixed with water and nitrogen to assist in fluid lifting by lowering the interfacial tension. Otherwise, the fluid would not be lifted at all.

The second attempt utilized the same 1.5" OD coiled tubing but with a slightly larger BHA OD (2-3/8"). Referring to the program outlined in Figure 10, CT was run to a depth of 1000 mMD, incorporating three stationary stages located at depths of 500, 750, and 1000 mMD, respectively. The theoretical design is tabulated in Appendix 1. The projected cumulative fluid volume displacement/recovery for each depth is estimated at 96, 218, and 341 bbl, respectively. If the cumulative displacement volume has been reached at the stationary depth accompanied by a decrease in fluid flow but without signs of steam kick, the coiled tubing is lowered to the next deeper target stationary depth while carefully monitoring the parameters on the CT reel. Several critical parameters observed include CT reel parameters (depth, weight, speed, circulating pressure), Nitrogen tank parameters (gas rate, water rate, foam rate), well parameters (WHP, wellhead temperature, T-line, fluid recovery from outlet AFT, and fluid visual).



Parameter	Unit	Value
Depth of Target 1	mTVD	999
Water Level	mTVD	303
Coil Tubing Setting Depth	mMD	1000
H (kolom air)	TVD	696
Submerged Ratio 1		0.70
Measured temperature at Target depth	°C	142.4254
Measured pressure at Target depth	Mpa	6.6874
Casing Diameter 1	in	12.459
Casing Diameter 2	in	8.681
Coil Tube Diameter	in	1.5
Psat at Target depth	MPa	0.38700

Figure 10. Nitrogen lifting summarized program based on the latest PT shut-in data in Well-6

Figure 11 depicts all field parameters throughout the nitrogen lifting operation until the commencement of geothermal fluid discharge. Fluid began to flow after the CT unloaded water at a depth of 1000 mMD for 8 minutes—a swift and significant increase in WHP, line temperature, and line pressure marked the flowing wells. With the side valve and throttle fully open, the flow process took place instantly, spanning only 2-3 minutes to the AFT, with an estimated thermal exposure of around 165°C.

Table 5 tabulates the results of theoretical calculations with actual field conditions. The measured volume displacement recorded on the turbine flowmeter was 318 bbl, only around 6% to 7% smaller than the theoretical estimates. The observed difference between the actual and estimated values can be attributed to several factors. Firstly, a slight drop in water level could decrease the liquid volume within the well. Secondly, considering the actual measurements were taken only about 2 minutes after CT reached a depth of 1000 m and there was no measurement of the volume displacement immediately before the well discharge, it is reasonable to assume that the actual volume displacement could exceed the recorded 318 barrels. Lastly, given that the unloading duration at a depth of 750-1000 mMD is shorter than the unloading period at a depth of 500-750 mMD and 0-500 mMD, it can be deduced that the fluid can successfully flow before the entire fluid column at 750-1000 is wholly unloaded, resulting in a lower actual volume displacement.

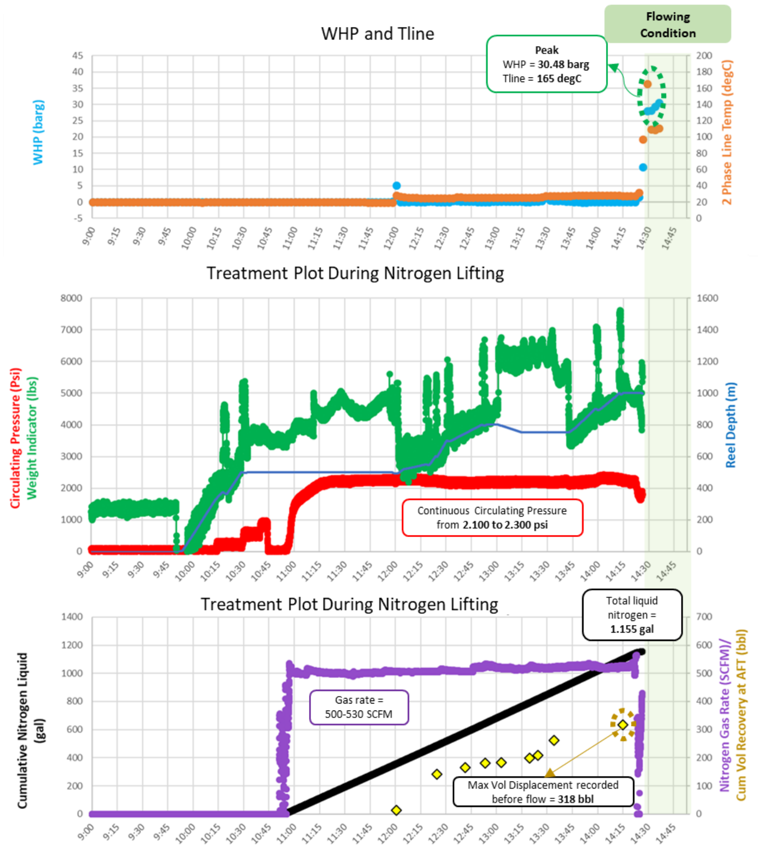


Figure 11. Field data during nitrogen lifting until the well began to flow

Table 5. Comparative analysis between theoretical assessments and actual field outcomes in Well-6

Parameter	Theoretical Analysis	Actual Result	Remarks
Target depth	1000 mMD	1000 mMD	-
Water level	303 mMD	336 mMD (	○ Water level assumption for theoretical analysis is from PT data ○ Actual water level is derived from changes in slope weight and increase in circulating pressure
Submersible ratio	0.7	0.66	Due to a slight difference in estimated vs actual water level
Volume Displacement/recovery	341	318	Actual volume recovery is attained from outlet AFT.
Total Nitrogen Volume requirement until well is flowing (Gal)	1457	1155	The theoretical nitrogen volume estimation for lifting refers to Appendix 1
Total Nitrogen Volume consumption during the job	2914	2022	Total theoretical volume estimation is doubling up the volume required for lifting.
Results	-	Flowing	This well is a good producer.

The submersible ratio, defined as the water column height per total lifting depth, plays a significant role in determining the effectiveness of nitrogen lifting. A higher submersible ratio correlates to an increased likelihood of successful discharge since more fluid is displaced and less hydrostatic pressure is achieved, leading to the flashing and flow. Aqui et al. (1996) suggested that each well has the optimum submersible ratio. In the Dieng Well-6 case with a high condensation area but high reservoir temperature (>310°C), the established submersible ratio of 0.66 has already been proven to initiate discharge. The 140°C temperature on target depth enhances the likelihood of a flashing point within the wellbore. Furthermore, the theoretical framework by Aqui et al. (1996) suggested a nitrogen volume estimate that closely aligns with observed consumption when the submersible ratio falls within the range of 0.7-0.8. In Dieng's case (submersible ratio = 0.66), the actual volume requirement for nitrogen until the well flows was 1155 gal. This is slightly lower than the theoretical program by 21%. Like the previous explanation, effective displacement on lower water volume could contribute to the required nitrogen volume consumption until the flow begins.

The total consumed nitrogen volume for the whole job is 2022 gal. This was to compensate for the additional nitrogen rate required during pulling out to cool the wellbore after hot geothermal fluid flows to minimize detrimental thermal cracks on CT, BHA, and casing.

6. DISCUSSION AND LESSON LEARNED

6.1 Stimulation Selection and Design Program

Choosing an appropriate method for stimulating a non-artesian well in high reservoir temperature geothermal wells needs a thorough evaluation of the reservoir characteristics, wellbore condition, and considerations for cost, operation, and safety. Essential prerequisites include the availability of a recent or stabilized PT profile to monitor the pressure-temperature distribution throughout the well and identify the depth of the water level. Casing and cement integrity assessments may also be imperative for wells exhibiting underdeveloped wellhead pressure (WHP). Based on historical experience and other studies, applying specific criteria becomes crucial in determining the most suitable technique, ensuring safety and operational success. Table 6 encapsulates a comprehensive pro-cons analysis of the discharge stimulation technique implemented in Dieng, complemented by relevant notes guiding the design of the stimulation program.

Table 6. Pros and cons matrix for determining the discharge stimulation method

Stimulation	Pros	Cons	Notes from Program
Well-to-well or Steam Heating	• Straightforward and adaptable operational procedures • Economically efficient and promptly executable upon the availability of the source well and supporting surface facility • Minimal encompassment of quick thermal shift when it's done gradually. • Not requiring any tool to put in the wellbore, which is particularly advantageous for wells experiencing shallow obstructions attributable to scaling	• Need proximity to good production well • The expenses could escalate significantly in the absence of piping and other surface facilities • Thermal energy might not be adequate for the wells with significant wellbore condensation	• Refer to historical experience to pursue the optimal outcome • Initiate the process with the minimal steam rate feasible to achieve a gradual heating effect
Air compression	• Applicable for well that has no producing wells nearby • Straightforward and adaptable operational procedures • Compact footprint requirement for compressor, booster, and treating iron • Medium cost (70,000-150,000 US$/well) • Not requiring any tool to put in the wellbore, which is particularly advantageous for wells experiencing shallow obstructions attributable to scaling • Medium equipment load during mobilization and demobilization	• The timeline is contingent upon the accessibility of the air compression service provider • The air compression technique might become economically unviable and operationally challenging when the compression pressure requirement exceeds 100 bar • Corrosion nature of air • Abrupt discharges highly potential to induce thermal stress on the casing	• PT data is mandatory to estimate target compression pressure by Af/Ac analysis • Rely on historical practices, establishing a minimum Wellhead Pressure (WHP) of 65 barg, as dictated by the discharge prediction method and substantiated by a minimum Af/Ac target of 0.6 • Give safety factor (minimum 50%) for both wellheads MWAP and burst casing rating • Make sure that casing integrity is still preserved
Nitrogen Lifting or Nitrogen Injection (with foam usage)	• Applicable for well that has no producing wells nearby • Nitrogen is non-corrosive than air, chemically stable, low solubility, inert, and non-toxic • Less significant thermal stress is posed to the wellbore than quick discharge (Sophy et al. (2023)), mainly when staged.	• The timeline is contingent upon the availability of the coiled tubing provider • High cost (>250,000,000 US$/well) • More expansive layouts for nitrogen tank, CTU, injector head, water tank, and control cabin • Bigger equipment loads during mobilization and demobilization • Complex operational and safety challenges include the inability to rotate, limited torque tolerance, limited run speed, not placing coiled tubing in compression, fewer tools available, and risk of leaving tools (Rocha et al. (2023)) • Not suitable for wells that have shallow obstruction due to scaling since it needs to run CT to the target depth	• In ascertaining the optimal Coiled Tubing (CT) depth, careful consideration of the target submersible ratio is imperative, coupled with the acquisition of temperature and pressure from the most recent PT data • Wellbore simulation can be added to obtain detailed discharge or flashing points. • It is advisable to have access to casing integrity data to ensure the safety of operations during the Coiled Tubing run. • A comprehensive approach to risk management is essential and should be conducted holistically.

6.2 Operational and Safety Lessons Learned

During several discharge stimulations in Dieng, the operational and safety protocols remain the priority concern. Comprehensive pre-job planning, safety meetings, and thorough preparation constitute pivotal elements in ensuring the safety and success of the operation. Standardized procedures have been established to govern the operation. Before commencing the job, conducting a reasonable inspection of the entire facility and equipment is advisable. This approach has resulted in numerous stimulation campaigns with a commendable safety record, achieving nearly all designated discharge objectives. Nonetheless, there are always valuable insights gained from operational improvisation. Lessons learned for each methodology are shown in Table 7.

Table 7. Lesson learned regarding safety and operation

Stimulation	Lesson Learned
Well-to-well	• Inspect the pipe thickness before the job takes place • Initiating the steam rate from a low level is recommended to mitigate excessively high-temperature differences • The duration of steam heating can be curtailed when the wellhead pressure between the source and receiving well approaches equilibrium. The well-to-well can be alternated by a discharge experiment, utilizing a small opening (bleeding) or a large opening directed toward the AFT to optimize stimulation duration.
Air Compression	• Pressure test should be conducted in an adequate duration for both low and high-pressure • Ensure the absence of air passing through valves, connections, treating iron, wellhead stem, or hand will that is significant enough to decrease wellhead pressure, as failure to do so will hinder the attainment of the compression pressure target that leads to the unsuccessful discharge • It is highly advisable to avoid rapid full LCV and master valve openings, as this could lead to thermal shock that leads to the casing deformation. Suppose the minimum desirable WHP was achieved along with proper holding time. In that case, initiating the opening of LCV cautiously and measuredly is recommended.
Nitrogen Lifting	• A sustained provision of potable water is imperative, serving dual purposes for foam injection and coiled tubing (CT) cooling. • The installation of a turbine flow meter in the fluid outlet zone at AFT is indispensable for acquiring volumetric displacement data. • Nitrogen lifting must be accompanied by foam to lift the fluid column in the wellbore. • Initiating the gas rate from a low level and gradually increasing it allows for assessing its effectiveness in lifting fluid, adjusting to various parameter conditions such as circulating pressure, depth, water column length, etc. Following industry best practices, the recommended gas rate range is 350 – 800 SCFM • Gas bleed-off operation and H2S scavenger injection are essential before nitrogen injection for wells with high gas content. • During Runs 1 and 2, a lot of flowing foam filled the AFT and open channel areas. Consequently, a study of foam volume and an improvised analysis of foam concentration are necessary for future operations, aiming for easier surface cleaning while effectively reducing interfacial fluid tension. Furthermore, incorporating equipment to mitigate the large volume of flowing foam in the AFT, such as adding a mobile water jet pump unit, is imperative to prevent potential social issues arising from foam spills. • The contractor must estimate material and equipment durability at high temperatures. • For future nitrogen lifting endeavors, employing a larger CT string than the current size (1.5") is recommended to have the capability to pump more significant amounts of nitrogen and higher strength. • To minimize thermal shock, especially in wells with significant flow, the initial LCV opening can be kept much smaller than 100%

7. CONCLUSION

Initiating discharge in Dieng's high-temperature geothermal well is relatively straightforward, assuming no wellbore conditions hinder natural discharge capabilities, such as a significant liquid cool body at the top of the reservoir, slow heating up, and WHP build-up. This study incorporates a comprehensive review of discharge prediction practices using Dieng field data. A specific high-temperature well may exhibit discharge even when the Af/Ac method falls below the non-discharge category, as evidenced in the recent static survey findings, as long as WHP development is sufficient. An alternative modified method is proposed to enhance prediction accuracy for specifically high-temperature geothermal systems, supplementing the universal Af/Ac method. The WHP vs. enthalpy method and feed zone-water level distances are also demonstrated as reliable indicators within the Dieng context.

Moreover, this study delves into several case studies involving different stimulation methods, drawing from data collected during actual campaigns executed safely in the Dieng Field. The discussions cover considerations for required data analysis preceding program design, a matrix outlining the pros and cons to determine the most suitable methods tailored to individual wells' characteristics and insights into operational and safety aspects.

ACKNOWLEDGEMENTS

The author would like to thank the management of PT Geo Dipa Energi (Persero) for permission to publish this work.

REFERENCES

Aqui, A.: Well Discharge Stimulation of Some Geothermal Wells in the Philippines by Nitrogen Gas Injection, Project for Diploma in Energy Technology (Geothermal) (1996), Geothermal Institutes, Engineering Science, University of Auckland, Auckland, New Zealand

Grant, M.A, and Bixley, P.F.: Geothermal Reservoir Engineering, Elsevier second ed, (2011), United Kingdom

Hanik, F.: Initiating Geothermal Well Discharge with Coiled Tubing, Proceeding 36th New Zealand Geothermal Workshop (2014), Auckland, New Zealand

Mubarok, M.H, and Zarrouk, S.J.: Discharge Stimulation of Geothermal Wells: Overview and Analysis, Geothermics, 70, (2017), 17-37.

Rocha, S, Faulder, D.D, Capuano III, L, Capuano Jr, L, Walsh, P.: Novel Coiled Tubing Operations in a Hostile Thermo-Chemical Environment, Proceedings 48th Workshop on Geothermal Reservoir Engineering (2023), Stanford University, Stanford, California.

Sarmiento, Z.F.: Geothermal Development in the Philippines, Iceland, Geothermal Training Programme (2) (1993), United Nations University

Siega, C.H, Saw, V.S, Andrino, R.P Jr, and Canete, G.F.: Well-To-Well Two-Phase Injection Using a 10in Diameter Line to Initiate Well Discharge in Mahanagdong Geothermal Field, Leyte, Philippines, 7th Asian Geothermal Symposium (2006)

Sophy, M.J, Bixley, P.J, Newman, K, Wilson, D, and Ryan, T.: Reducing Casing Heatup Rates in Geothermal Production Wells by Using Coiled Tubing Gas Lift, Proceedings 45th New Zealand Geothermal Workshop (2023), Auckland, New Zealand

Sta Ana, F.X.M.: A Study on Stimulation by Air Compression on Some of the Philippine Geothermal Wells, Project for Diploma in Energy Technology (Geothermal) (1985), Geothermal Institutes, Engineering Science, University of Auckland, Auckland, New Zealand

APPENDIX

Appendix 1: Theoretical Design for Nitrogen Lifting in Well D (refer to Aqui (1997))

Parameter	Equation/Symbol	:	Stage 1	Stage 2	Stage 3	Total	Unit
Bottom of Liner (BOL)	BOL	:	2662	2662	2662		mMD
Depth of Target 1	MPZ	:	500	750	999		mTVD
Water Level	WL	:	303	303	303		mTVD
Coil Tubing Setting Depth	MPZ	:	500	750	999		TVD
Kolom Air	H = L-WL	:	197	447	696		TVD
Submerged Ratio 1	H/L	:	0.39	0.60	0.70	1000 mMD lifting	
Measured temperature at Target depth	T @ MPZ	:	43.7759	56.6096	142.8277		°C
Measured pressure at Target depth	P @ MPZ	:	1.98412	4.41571	6.6983		Mpa
Casing Diameter 13-3/8	OD1	:	12.459	12.459	12.459		in
Casing Diameter 9-5/8	OD2	:	8.681	8.681	8.681		in
Coil Tube Diameter	OD CT	:	1.232	1.232	1.232		in
Psat at Target depth	Psat @ MPZ	:	0.009007	0.017018	0.391368		MPa

Parameter	Equation/Symbol		Stage 1	Stage 2	Stage 3	Total	Unit
Delta Pressure at MPZ	dP=(P@MPZ-Psat@MPZ)	=	1.975113	4.398692	6.306932		Mpa.a
Total Lift	L	=	500	750	999		m
Pressure drop along lifting	dp/dL	=	0.003951	0.005867	0.006314		MPa.a/m
		=	3950.701	5866.656	6313.97		Pa.a/m
Density mixture fluid	ρ_{mix} = (dP/dL)/g	=	402.7218	598.0281	643.6259		kg/m^3
Temperature at standard condition	T_1 (at STP)	=	273	273	273		K
Pressure at standard condition	P_1 (at STP)	=	0.101325	0.101325	0.101325		Mpa
Specific volume at standard condition	V_1 (at STP)	=	0.8	0.8	0.8		m^3/kg
Target temperature	T_2	=	316.7544	329.1303	400.3931		K
Target pressure	P_2	=	1.975113	4.398692	6.306932		Mpa
Specific volume gas (Vgas)	$V_2 = (P_1.V_1.T_2)/(T_1.P_2)$	=	0.047618	0.022217	0.01885		m^3/kg
Specific volume water (Vwater)	$V_{water@T2}$	=	0.001009	0.001015	0.001067		m^3/kg
Specific volume mixture	$V_{mixture} = 1/\rho_{mix}$	=	0.002483	0.001672	0.001554		m^3/kg
Mass fraction	$x = (V_{mixture}-V_{air})/(V_{gas}-V_{air})$	=	0.031619	0.030990	0.027358		
Total water column	H = (L-water level)	=	197	750	999		m
Tubing radius	R_1	=	0.015646	0.015646	0.015646		m
Casing radius	R_0	=	0.158229	0.158229	0.158229		m
Pipe characteristic diameter	$D_{ch} = 3.1416[R_1+((R_0-R_1/2)]$	=	0.273124	0.273124	0.273124		m
Bubble velocity	$v_g = [(0.29352).(2g.D_{ch})^{0.5}]$	=	0.679465	0.679465	0.679465		m/s
Rise Time	$tr = H/v_g$	=	289.8457	1103.484	1470.106		s
Void Fraction	α =1/(1+(((1-x)/x)^0.8)*((Vwater/V2)^0.515))	=	0.320221	0.237786	0.201329		
Annulus Area	A =Casing Area-Tubing Area	=	0.077885	0.077885	0.077885		m^2
Gas flowrate	$W_{(x)} = A.(1-a).v_g/V_2$	=	0.755469	1.815566	2.242223		kg/s
Volume gas Liquid	$V_{liquidN2}$=W(x).Rise Time	=	218.9694	2003.448	3296.305		kg
		=	**58**	**529**	**870**	**1457**	gallon
Casing volume from WL to MPZ	Vol Casing	=	15.33876	19.47136	19.47136		m^3
Liquid volume displacement	6.28981077*Casing Volume	=	**96**	**122**	**122**	**341**	bbl