United Nations Educational, Scientific and Cultural Organization · GRÓ GTP Geothermal Training Programme Under the auspices of UNESCO

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Reports 2021
Number 7

STUDY ON POWER PLANT CONFIGURATIONS TO OPTIMIZE MASS FLOW CONSUMPTION WITH RESPECT TO SILICA SCALING FOR DIENG UNIT 2, INDONESIA

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ABSTRACT

Dieng geothermal field located at Central Java, Indonesia is operated by PT Geo Dipa Energi (Persero) with power plant Unit 1 commissioned in 2002 producing 60 MW and a complementary small-scale plant commissioned in 2021 producing an additional 10 MW. Project Dieng Unit 2 is currently under development and will produce another 55 MW. One of the main challenges in Dieng is silica scaling due to the high concentration of silica in the reservoir fluid. Several studies have been carried out, both by a consulting company and the operators, to find suitable design parameters for Unit 2. For testing, a pilot plant was taken into operation using 21.2 bara high separation pressure and 3 bara low pressure and a binary Organic Rankine Cycle (ORC). Recent findings from the pilot plant indicate that significant potential difficulties for operating a binary combined cycle plant at Dieng can be expected due to heat exchanger scaling from high concentrations of heavy metal sulphides in the fluid. After the testing, calculations were conducted using Python and Ms. Excel and verified with EES, using a Silica Scaling Index (SSI) of > 1.2 as the manageable limit, to find the correlation between mass flow from wells and separator pressure including the Specific Steam Consumption (SSC). The power plant configuration is a single flash condensing type and a double flash condensing type with enthalpy assumptions of 1300 kJ/kg and 1600 kJ/kg. Based on this study, the required mass flow for a single flash separator pressure ranging from 12.5 bara to 25.7 bara is 260 kg/s to 405 kg/s with pressure being directly proportional to the mass flow from the wells. For double flash separator pressure, the required mass flow is ranging from 235 to 360 kg/s and the separator pressure is correlated proportionally with mass flow. The pressure is inversely proportional to the SSC. Based on these findings, the recommendation is to install a double flash separator using a high pressure of 25 bara and low pressure of 12.5 bara or, alternatively, a single flash separator using 25 bara. This recommendation, especially the double flash, needs to be checked in the pilot plant to gather more comprehensive information about the SSI and silica scaling rates.

1. INTRODUCTION

Located in Central Java, Wonosobo, and Banjarnegara Regency, the Dieng geothermal power plant Unit 1 has operated since 2002, producing 60 MW, and a complementary 10 MW small scale unit has been operating since 2021 as shown in Figure 1. Furthermore, development of project Dieng Unit 2 started in 2019 with the goal of producing another 55 MW. Dieng is located close to an inhabited area sustained by both agriculture and tourism, which makes the field more interesting for study. Several direct use options have been developed and studied for the Dieng area. Scaling of silica in surface facilities and reinjection wells are challenges that have been experienced since the project was put into operation almost 20 years ago. Based on the operating experience to date, another study has been conducted to ensure the technology selection of Unit 2 is suitable for exploitation for at least 30 years of operations. The previous study which consists of a feasibility study, silica mitigation study, and brine management study, concluded that the experimental study in the field needed to answer several questions regarding design and operation of the Dieng Unit 2. This experimental study in the field was later known as pilot plant design and testing.

FIGURE 1: The field location, Dieng, Central Java, Indonesia

In Dieng geothermal field there are 4 reservoirs named Sileri, Candradimuka, Sikidang, and Pakuwaja. Based on the available data, the reservoir temperature in Dieng is 280-330°C. Initial data show that the reservoir temperature has reached more than 330°C in Sileri Area, the production area which is used for Unit 1. Separated brine and power plant condensate is reinjected to both the Sileri and Sikidang areas. The Dieng geothermal reservoir is water dominated with a dryness of approximately 30% and an area of around 6.2 km^2 (Geo Dipa Energi, 2019).

Unit 1 was initially operated using hot brine injection, with separated brine pumped directly to reinjection wells for disposal. The brine handling system included an acid dosing system for pH control. Scaling rates in surface piping and injection wells were unacceptable, even when pH modification was in operation. The Dieng Unit 1 brine system was subsequently converted into a cold injection system, requiring a series of storage ponds where brine is held and conditioned to enable silica to deposit in the ponds, reducing the scaling load on surface facilities and wells. The brine conditioning ponds present an environmental risk through potential brine spills, particularly during the wet season, and the ongoing requirement to recover and dispose of silica scale deposited in the ponds. Consequently, the development plan for Unit 2 anticipates the adoption of hot brine disposal. Unit 1 uses wellpad separators with separation pressures in the range of 10-11 bara. Geothermal fluids discharged from the wells are typically near-neutral pH and high salinity with total dissolved solids at the production separators ranging from 20,000 to 35,000 ppm. Based on the historical data, well HCE-7C produced the highest levels of silica in flashed brine with a geothermometer quartz temperature of 330°C. Well HCE-30 has produced the second-highest levels of silica in flashed brine with a geothermometer quartz temperature of 318°C. In these two wells, the average silica concentration is 800 ppm. It has been established that the silica saturation temperature of Sileri fluids ranges from 195°C to 220°C, which is higher than the flash temperature in the Unit 1 separators. Therefore, separated brine typically has an SSI of greater than 1.0. An example of silica scaling in a brine pipeline is shown in Figure 2.

FIGURE 2: Silica scaling at brine line piping

Financial closing was achieved as part of the feasibility study in 2019, and in 2020 the loan agreement with the Asian Development Bank (ADB) was signed; therefore, the documentation of the project will also be available on the ADB website. Furthermore, the development plan for Dieng Unit 2 as established in the feasibility study, considering the silica scaling challenge and a binary combined cycle power plant as the preferred technology, recommended that 10 wells would be drilled to ensure the fluids available to generate 55 MW and to return the fluid to the geothermal reservoir. The total amount of fluids required by the combined cycle is still uncertain, depending on average enthalpy which is 1300-1600 kJ/kg, but amounts to about 1049 t/h or 6 dedicated production wells. For the single flash, the required mass flow is 1667 t/h or 7 dedicated production wells (ELC, 2019). The development map, which consists of the well pad, preliminary piping routes, and power plant location shown in Figure 3, needs to be updated with the findings of pilot plant testing and front-end engineering design (FEED).

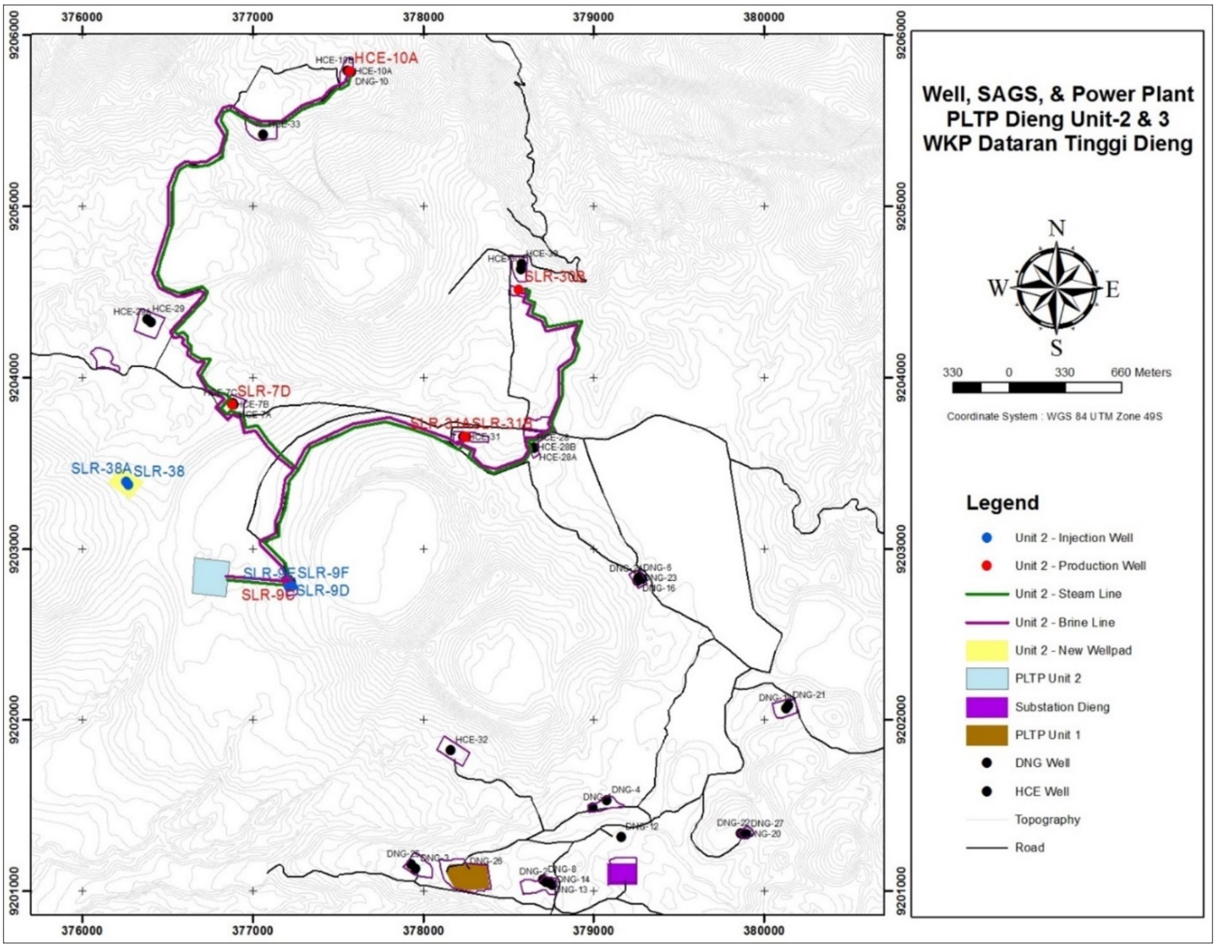

FIGURE 3: The development map of Dieng Unit 2 (Geo Dipa, 2019)

The main objective of this paper is to develop a design of the power plant taking the silica scaling test results of one of the representative wells into consideration. Other objectives are the evaluation of findings from the pilot plant, calculating the silica scaling based on thermodynamic condition, and proposing power plant configurations based on these findings and calculations. Several parameters of the operation are varied to find optimal values for mass flow consumption. The assumptions made are based on earlier studies including the pilot plant testing results. The study result in this paper needs to be confirmed with further pilot plant scaling experiments in Dieng. At the current stage, the effort is focused on finding preliminary design parameters of Dieng Unit 2. Preliminary testing using the pilot plant indicates significant potential difficulties in operating a binary combined cycle plant at Dieng due to heat exchanger scaling from high concentrations of heavy metal sulphides in the fluid. At this point, a steam flash cycle offers better operational reliability and is currently the preferred development option. Hence, this paper is limited to the configuration design only for single flash and double flash condensing types.

2. PILOT PLANT DESIGN AND TESTING

2.1 Silica scaling studies

The states of silica are crystalline and non-crystalline. Crystalline silica can take several forms such as quartz, cristobalite, tridymite, and four other rare forms. The differences between each form manifest in the arrangement of individual atoms that form the crystal lattice for each mineral. Quartz and amorphous silica are the forms related to the silica scaling problem in geothermal systems. Generally, the geothermal fluid in the reservoir will be in equilibrium with quartz. Flashing or cooling the geothermal fluid will make the fluid become oversaturated with respect to quartz. Fortunately, the precipitation of silica at lower temperatures is controlled by amorphous silica equilibrium which is more soluble than quartz (Nugroho, 2011). In solution, silica exists as monomers, and if the condition thermodynamically allows, there will be polymerization (Figure 4). These polymers form colloids and eventually precipitate through a process called coagulation. In turbulent flow, monomeric deposition is likely to take place; in non-turbulent flow, however, silica polymerization is the favourable process.

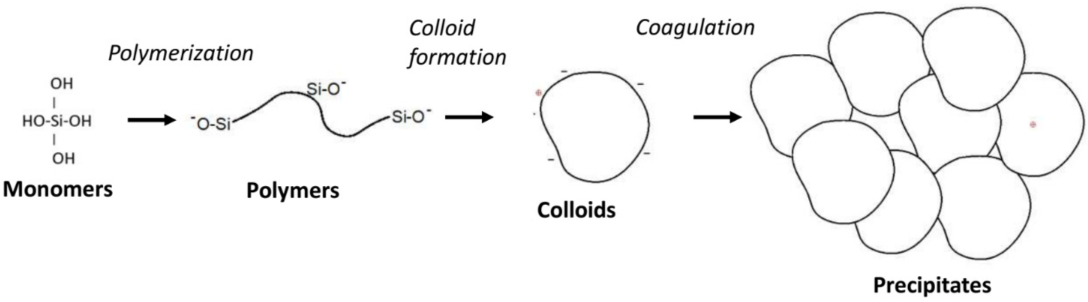

FIGURE 4: Formation of silica precipitation (Hauksson, 2021)

In this study, the most discussed silica form is amorphous silica. The silica deposition can be divided into thermodynamics and kinetics. Thermodynamics predicts that processes will take place as equilibrium is reached. The kinetics explain the duration until equilibrium is obtained (Brown, 2011). Equilibrium constants for silica derived from the equation of silica solubility developed by Fournier and Rowe (1977) are shown in Figure 5.

The actual behaviour of silica is much less predictable than theoretical thermodynamic calculations and is not well understood or quantified. While thermodynamic calculations predict the worst possible outcomes, calculations based on kinetics tend to allow more flexible solutions to the problems of silica scaling. Fournier and Rowe (1977) derived an equation for the solubility of amorphous silica which is valid for temperatures from 0°C to 250°C:

$$T = \frac{731}{4.52 - \log S} - 273.15 \tag{1}$$

where T = Temperature [°C]; and
S = Silica concentration [ppm].

To determine the silica precipitation, the values of the silica concentration after flashing or cooling and the equilibrium amorphous silica concentration are calculated with Equation 1, so that the SSI can be calculated with Equation 2.

$$SSI = \frac{S}{S_{eq}} \tag{2}$$

where SSI = Silica saturation index;
S = Silica concentration [ppm]; and
S_{eq} = Silica equilibrium concentration [ppm].

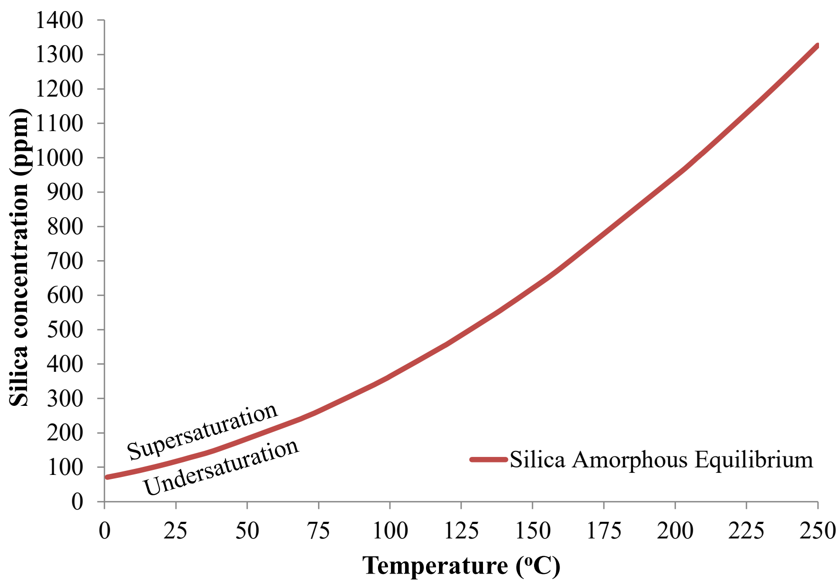

FIGURE 5: Solubility of amorphous silica as a function of temperature (from Equation 1)

A silica concentration after flashing or cooling higher than the equilibrium solubility of amorphous silica (SSI more than 1) means that silica will tend to precipitate. In several geothermal fields, the kinetics of the solid silica deposit formation are relatively slow, therefore, the actual limit of SSI to indicate silica precipitation is probably higher than 1. In addition, it controls the rate at which a supersaturated solution will deposit.

An experiment in the laboratory and the field has shown that several factors affect the kinetics of silica deposition. Some of the more important factors are the degree of supersaturation, pH, temperature, flow rates, aeration, and other impurities in geothermal fluids (Brown, 2013). The concentration of silica in the brine at the separator or pressure vessel outlet increases and the brine temperature is further decreased. The silica is oversaturated and precipitates as amorphous silica or reacts with available cations, for example Fe, Mg, Ca, Zn, or Al to form silicate deposits. These deposits cause a serious reduction in fluid flow from production wells, separators, surface facilities, and injection systems (Burton et al., 2003). In over-saturated geothermal fluids, amorphous silica forms deposits of monomeric silica on surfaces or silica polymers. The process also depends on the dynamics of the flow. In turbulent flow, monomeric deposition on surfaces results in silica scaling in parallel to silica polymerization. The brine in the reservoir is in equilibrium with quartz but becomes supersaturated with respect to amorphous silica due to boiling as the fluid flows up the well and monomeric silica begins to polymerize after a time known as the induction period. There are several common solutions to silica scaling in surface facilities (Óskarsson, 2021):

1. Separating steam at high pressure and temperature
   High separation pressure is used for geothermal fluids and the brine is injected before the temperature facilitates super-saturation of amorphous silica. The typical separation temperature must reach about 100°C below the reservoir temperature. As an example, at Reykjanes reservoir temperatures range are from 275 to 310°C and the separator pressure is around 18 barg or 210°C.
2. Diluting separated brine with condensate
   This method may cause carbonic acid corrosion due to low pH. Another consideration is the amount of available condensate, which may be limited. If condensate from a direct contact condenser is used, oxygen may be introduced promoting corrosion of steel pipelines. The method of diluting separated brine with cold groundwater is not recommended due to the Mg silicate precipitation.
3. Polymerization ponds
   The aqueous phase of silica forms polymers in solution which decrease monomeric silica and consequently, the supersaturation of amorphous silica occurs. Reduced supersaturation results in slower precipitation. Pre-treatment of brine with acid slows precipitation in surface cooling ponds.
4. Acidification (pH modification)
   Low pH affects the surface properties of amorphous silica and silica colloids and prevents them from growing kinetically. Corrosion problems can occur if pH is less than 5.5. Mixing with condensate lowers pH a little bit. Experiments with geothermal H_2S which is oxidized to H_2SO_4 and mixed with separated brine have been successful in reducing the scale formation.
5. Inhibitors
   Inhibitors are injected into the brine at the surface to prevent the formation and growth of colloidal silica particles but are relatively expensive. Inhibitors have not been proven to work in geothermal brines.
6. Crystallizing silica in suspension and separate from solution (CRC)
   Seed crystals are added to the separated brine to initiate precipitation from the solution on the grain surfaces in the suspension and not only on pipe walls. The solid material is separated from the liquid by sedimentation or in cyclonic separators, resulting in clarified brine that is undersaturated with silica. This method is relatively expensive.

Due to silica scaling being affected by several parameters that are site-specific, silica scaling precipitation experiments have been done in several fields worldwide. For example, in Iceland, the chemistry of the brine in the Svartsengi area is similar to the brine in Reykjanes, but is lower in salinity suggesting that the silica precipitation could be controlled by the addition of alkali. A precipitation process for manufacturing silica for use as an additive in paper was developed in Kawarau in New Zealand. Precipitation of silica in a crystallizer reactor clarifier has been successfully utilized in the highly saline fields of the Salton Sea in California. A process without any chemicals for silica precipitation is used in Svartsengi at the Blue Lagoon (Hauksson et al., 2020). Some of the strategies of silica handling and the pilot plant will be discussed further in the next chapter. The comparison between geothermal fields in this study needs to be conducted carefully due to the varying impurities concentration and other differences.

2.1.1 Reykjanes geothermal field

As one of the power plants in Iceland where silica scaling is a challenge, the operators of the Reykjanes power plant developed and tested a process for clarifying brine during production and injection. The scaling occurred due to high silica concentration and high salinity when the brine is flashed to lower temperature in the separator. The brine with temperatures from 250 to 320°C from the reservoir flows to 2 units of the power plant which produce 50 MW each. The mass flow of steam is 85 kg/s to each unit at 18 bar separator pressure and then the brine is condensed by a surface condenser at 40-45°C. The hot brine with a temperature of 207°C in the separation station is reinjected or disposed of in the ocean. The energy content of the disposed brine is considerable and can be used to generate 30 MW of electricity. The testing was conducted in a separator that could be operated without the use of acid with

25 kg/s of 207°C brine and flashed in two stages at 155°C and 108°C (Thórólfsson et al., 2020). Several experiments were done with varying process parameters such as flow, recirculation ratio, solids concentration in reactor, NaOH concentration in flocculator, and stirring speed. The experiment resulted in silica that could be removed from the Reykjanes brine, and the silica supersaturation and concentration of suspended solids could be lowered sufficiently for reinjection. The use of acid for scale mitigation is effective but a new separator technology was developed to control the silica scaling with critical nozzles and without the use of chemicals in a combined vertical and horizontal separator (Hauksson et al., 2021).

The Reykjanes brine contains 950 mg/kg of SiO_2 flowing at atmospheric pressure from the separators. The concentration of silica (SiO_2) is controlled by the equilibrium with quartz in the rock at reservoir temperature. At a separation pressure of 18 bar in the power plant the silica concentration is 750 mg/kg and therefore below the amorphous silica solubility in the brine. When the brine is separated in the bottoming process to atmospheric pressure the silica concentration rises to 940 mg/kg which is above the solubility of silica. The sodium (Na) and chloride (Cl) concentration in the reservoir brine is comparable to the concentration in seawater. Magnesium (Mg) and sulphate (SO_4) concentrations are lower while the calcium (Ca) and potassium (K) concentrations are higher. Chloride content is relatively high, which causes the solubility of metals such as iron (Fe), manganese (Mn), zinc (Zn) and lead (Pb) to be considerable in the reservoir brine (Hauksson et al., 2021).

The brine from the low-pressure separator entered the reactor through a barometric pipe which controls the brine level in the pipe and keeps the fluid depth in the reactor at 4 meters. The reactor volume was 40 m^3 and the holdup time at design flow of 20 l/s was 33 min. The temperature of the brine entering the tank was 108°C, and it boiled in the reactor to 100°C. The precipitation of silica took place in the tank and the silica slurry was stirred by the up flow of steam in the tank and carried to the clarifier. The clarifier had two chambers. In the inner chamber, sodium hydroxide was mixed with the brine forming large silica flocks which settled in the outer chamber. The settled silica slurry was pumped from the bottom with a slurry pump to the reactor to increase the precipitation rate of the silica. The concentration of dissolved SiO_2 in the inflowing brine after boiling to 100°C was 940 mg/l in the reactor while the solubility of SiO_2 is only 356 mg/l at 100°C. The experimental runs showed that the precipitation rate is highly affected by the concentration of silica slurry in the reactor. Without any slurry recirculation, the dissolved SiO_2 concentration in the brine only lowered to 600 mg/l, but when the slurry concentration was increased the precipitation rate increased, and the silica concentration got closer to silica saturation. By keeping the silica slurry concentration above 6 vol% the concentration of dissolved silica could be lowered below 400 mg/l. The tests demonstrated that it is vital to keep the slurry concentration as high as possible in the reactor to increase the silica precipitation rate and reduce the silica supersaturation in the outflowing brine (Hauksson et al., 2020).

An experimental two-stage separator unit was built close to the high-pressure separators of the power plant and connected to the discharge pipes. It was capable of separating 25 kg/s of 207°C brine and producing 2.8 kg/s of medium pressure (MP) steam at 155°C and 2.0 kg/s of low pressure (LP) steam at 108°C as shown in Figure 6. Treatment of 295 kg/s of brine requires an intake of 7500 kg of concentrated sulfuric acid per month to decrease fluid pH values to the range of 5.5-5.6, which costs about $3,000.00 per month. The bottoming plant in Reykjanes will have two brine separating lines with a brine flow of 2 x 150 l/s. Based on the findings in the pilot test runs, a full-size process was proposed. An atmospheric separator with a diameter of 8 meters will be installed under the LP separator. The barometric pipe from the separator will extend 4 meters into the brine. The steam will be separated from the brine in the reactor and the brine will flow into a separate reactor tank with a holdup time of 40 min. Sodium hydroxide will be added to the brine under slow stirring to flocculate the small silica particles at a pH of 8.3. The consumption of sodium hydroxide for handling 300 l/s of brine is estimated to be 400 kg per day. The slurry collected in the clarifier will be recirculated from the clarifier bottom to the reactor where it mixes with the inflowing brine. The recirculation rate will be 10% of the inflow. The brine will flow from the flocculating zone to the settling zone in the clarifier where the silica particles will be separated from the brine. The brine will finally be diluted to undersaturation with condensate and, if necessary, clarified in a secondary clarifier or filtered for reinjection (Hauksson et al., 2020).

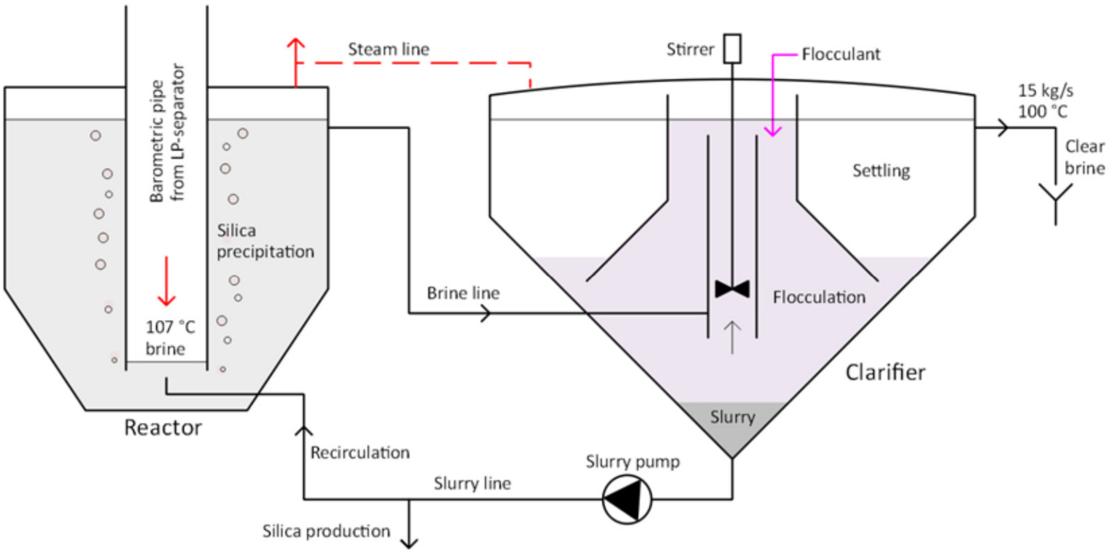

FIGURE 6: Schematic pilot plant for silica precipitation and brine clarification in Reykjanes (Hauksson et al., 2021)

Each separator was combined with a horizontal droplet settler with a vane mist eliminator to improve the separator efficiency. The experiments confirmed that by using a critical nozzle separator the silica scale can be controlled successfully without any chemical use. The scaling is manageable, and the separators can be operated continuously for several months by using a nozzle drill for reaming the nozzles in operation. Full-size separators are being designed, based on these experiments (Lund et al., 2020).

2.1.2 Theistareykir geothermal field

In Theistareykir geothermal field located in Iceland, the challenge of amorphous aluminum silica is addressed using several mitigation actions:

1. pH modification by acid injection to affect pH dependent solubility.
2. Brine dilution with mixed condensate or low silica brine.
3. Inhibiting precipitation by sequestering or application of dispersant inhibitors may be possible. This method is in the testing stage and has not been proven to be effective.
4. Keeping a high wellhead pressure, around 30-40 bar, may lead to less scaling in the wellbore and promote increased scaling downstream of control orifice. Soft and hard scale can be removed by hydro blasting.

At very high temperatures and pressure, silica dissolves in the steam and precipitates out of the steam when pressure is decreased. Silica carryover or dust carryover from dry wells is carried with the steam through the separator and mist eliminators. Silica dust in dry steam from high enthalpy wells which forms scale in the turbines can be mitigated by steam washing (Hauksson, 2021).

2.1.3 Berlin and Ahuachapán geothermal fields, El Salvador

LaGeo S.A. de C.V. did a series of pilot sized silica scaling tests at the Berlin geothermal field from 2003 to 2011 to study the effectiveness of acid dosing and inhibitors at various brine temperatures with the main objective to optimize the size of a brine binary power plant with respect to silica scaling issues. The equipment designed by Sinclair Knight Merz (SKM) consists of a heat exchanger, residence tank, deposition tubing, metering pumps of chemical agents, and mixture tanks. The polymerization trials took place with zero flow through the residence tank and water samples were taken. To determine the behavior of silica polymerization in the conditions previously established in the fluid, pH, monomeric silica, and chloride content were analyzed in each sample in the field laboratory while total silica concentration was determined in the LaGeo main laboratory. The target of silica polymerization trials is to determine the induction time available before the silica deposition is starting at the temperature of the brine in the study.

In 2004, five test rigs were installed near the flashers in Ahuachapán geothermal power plant and experiments showed different polymerization speeds depending on the fluid temperature. A pH of 5.5 in the fluid was found effective to control the silica polymerization for the cooled fluid. In the post commissioning period in 2008, the binary power plant resumed operations with an average of 7.2 MWe with geothermal water that flows through the plant and loses an average of 45°C in the heat exchange with the working fluid, lowering its temperature to 140°C. During the first year of operation, the brine was treated with HCl to reduce the water pH to a value of 5.5. However, due to serious corrosion problems in the acid dosing system (pumps, capillary tube, etc.), it was not possible to obtain continuity in the chemical treatment. As a result, silica scaling of 1.0 to 2.8 mm thick deposits occurred in the tubes of heat exchangers. In 2009, the heat exchangers were subjected to chemical cleaning with a mixture of hydrofluoric acid and phosphoric acid, which cleared about 90% of the inlay. After seven months of operation and after the first chemical cleaning, the exchanger tubes showed embedding 0.5-1.8 mm thick, so they were subjected to a second chemical cleaning. Since that date, sulfuric acid was used for brine treatment to a pH of 5.5-5.6, which helped to decrease the corrosion problems in the dosing system. The use of H_2SO_4 allowed more effective chemical treatment than HCl so that after 15 months of operation the inlay in the exchanger tubes did not exceed 0.4 mm in thickness. Price comparison of different silica inhibitors shows that pH modification using sulfuric acid is the least expensive option for silica control. Data suggest that the scaling rate is lower at pH 5.5 than at pH 6.0 (Guerra and Jacobo, 2012).

2.2 Pilot plant design and testing, Dieng

As discussed in the introduction, the following timeline describes the Unit 1 coping mechanism applied to operate the surface facilities from 2002 to 2021.

- **2002** Hot separated brine was pumped at separator temperature directly to reinjection wells for disposal. The brine handling system included an acid dosing system for pH control. Scaling rates in surface piping and injection wells were unacceptable, even when pH modification was in operation.

- **2005** The brine system was subsequently converted to cold injection, requiring the use of a series of storage ponds where brine is held and conditioned to enable silica to deposit in the ponds, reducing the scaling load on surface facilities and wells. The acid injection was implemented after the separator to reduce scaling rates in the piping and equipment between the separators and holding ponds. Brine is aged and cooled in holding ponds prior to injection.

- **2019** A polymerization field test was conducted in HCE-30 and confirmed that very high amorphous silica scaling rates are occurring. Two-phase piping after the flow control valve (FCV) and polymerization was initiated with a very short induction time. In the polymerization test, the rate of mass loss from solution equates to a deposition rate of about 16 mm/year, assuming all the polymers eventually deposit. That value is in the range of the estimated scaling rate of 21 mm/yr as observed in the piping from HCE-7C. The scaling rate downstream of the HCE-30 production separator is expected to be lower than in the two-phase piping upstream of the separator due to the deposition losses upstream. Based on a study in 2019, the proposed silica scale mitigation process requires pH-modification using sulfuric acid injection. There are no commercial scale inhibitors effective in treating the aluminum-rich amorphous silica scale. It is also unlikely that oil-field inhibitors which have limited success in metal sulfide scale mitigation, would be viable for the high-temperature Dieng wells downhole. Based on recent studies, the minimum recommended wellhead temperature is 225°C (25.7 bara) and the minimum separation temperature is 215°C (21.2 bara). The acid injection was recommended upstream of the two-phase flow control valves, before the production separators, on each well. The initial target pH is 4.75, but this will be optimized later based on pilot-testing and during operations. Also, rates of loss measured in the Hold-Up Vessel (HUV) may have been underestimated since the vessel was static with no fluid turbulence, which enhances particle deposition processes. These data confirmed that the very high scaling rates in the two-phase piping at current separator pressures are due to polymerization and particle deposition, in addition to molecular deposition which always occurs to some extent at any level of supersaturation. Polymerization and particle deposition processes are primarily responsible for the massive deposits of silica such as those observed in Dieng 1 piping downstream of the FCV and the injection system. A molecular deposition usually dominates at lower supersaturation and low pH. Fortunately for Dieng, the polymerization and particle deposition processes can be effectively eliminated through temperature and pH control. At sufficiently low pH (~ pH 5), polymerization will not occur for hours and there is only the need to manage molecular deposition through the gathering system, plant, and injection system (Thermochem, 2019).

- **2019** A feasibility study was carried out and resulted in a development plan for Dieng Unit 2 which recommended, based on a binary combined cycle power plant as the preferred technology, that 10 wells would be drilled to ensure the fluids available to generate 55 MW and to return the fluid into the geothermal reservoir.

- **2020** Pilot plant design awarded to a joint venture between Mannvit, ÍSOR, CBN, and Kemía (JV MICK).

- **2021** Pilot plant testing started for HCE-7C with two test programs.

2.2.1 Overall pilot plant flow diagram

The principal design of the pilot plant is based on the experimental pilot units which were used in Reykjanes and Theistareykir in Iceland to study and test the different process cycles and to find the most effective method to inhibit silica scaling in geothermal brine for bottoming plants. JV MICK was contracted to execute the design and to construct, install, and operate the pilot plant. Testing included two mandatory tests to establish initial operating parameters for single flash, double flash, and binary configurations. The pilot plant is installed in a 40 feet container on a trailer and can be transported to the site partly assembled. The acid tank, holdup vessels, silencers, cooling tower, and water circulating pump are installed outside the container. As it is installed on a trailer, the pilot plant will be readily relocated to dedicated Unit 2 wells for further testing once wells are drilled.

A schematic illustration of the pilot plant is shown in Figure 7. The pressure inline spool is controlled to ensure that the pressure in separator 1 (high pressure (HP) separator) is higher than in separator 2 or the low-pressure separator. The separator pressure is controlled by an automatic steam control valve in the steam line and the two-phase stream from the well is controlled by an orifice. Acid was dosed into the two-phase line to reach the required pH in the brine flowing from the HP separator. After a short test during commissioning which indicated rapid corrosion in the two-phase lines, it was decided to select the proposed alternative method of acid dosing and instead of dosing into the two-phase line, the acid was dosed into the brine line from the HP separator. The steam from the two separators is throttled and condensed in a shell and tube condenser at atmospheric pressure and excess steam and non-condensable gases (NCGs) are released into the atmosphere with a steam vent.

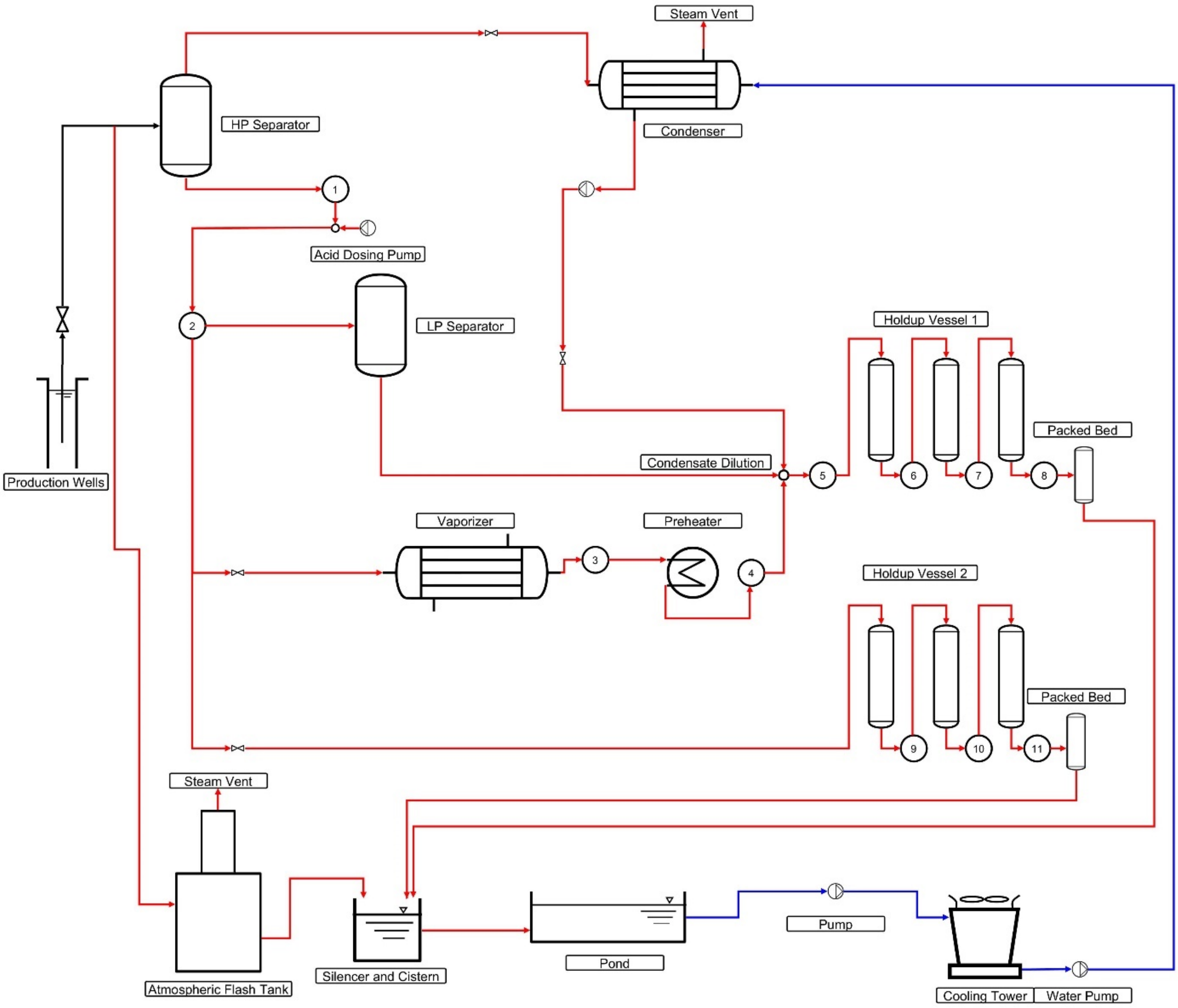

FIGURE 7: Pilot plant overall flow diagram, modified from JV MICK design

The brine from the separator is divided into parallel tests. One is for the single flash with high pressure separation and injection. The other for simulating an ORC system with an outlet separator brine line stream to the vaporizer and preheater. The fluid in the vaporizer is heated and condensed internally using multiple tubes to study fouling rates at several temperatures. Then the fluids flow to the preheater, with multiple cooling tubes and closed loop circulation on the cold side. The orifice and control valve are located at the outlet for brine flow. After cooling the brine down to 25°C, the pH is measured. Prediluted acid is pumped into an online mixer made of Hastelloy C-276 with a hydraulic actuated diaphragm pump where the acid is further diluted with condensate. Injection of diluted acid into hot brine is achieved by a tantalum metal injector while the mixing spool is of duplex alloy. Condensate is cooled and pumped at 32 bar and used for diluting acid and mixing with the brine to simulate injection conditions. A holdup vessel is used to increase the residence times to 1 hour to simulate the silica polymerization in the brine injection lines which consist of vertical pipes with serial configurations and downward flow to avoid the separation of suspended solids. After that, the brine flow is controlled by an orifice and directed to a packed bed filled with rock cuttings. The samples were taken in the coupon for corrosion and scaling. Fluid samples were also taken. For two phase lines, the pipe size is 2” and for brine, the line is 1”. The coupon locations include the inlet, mixing spool, separator inlet 1, separator inlet 2, test line 2 in, vaporizer out, preheater out, test line 1 out, test line 2 in, and test line 2 out.

Some parts of equipment displayed in Figure 7 are not included in the JV MICK setup, such as the air compressor, cooling tower, pond, atmospheric tank, and piping from the wells to each mentioned piece of equipment. The 3D design of the pilot plant is shown in Figure 8.

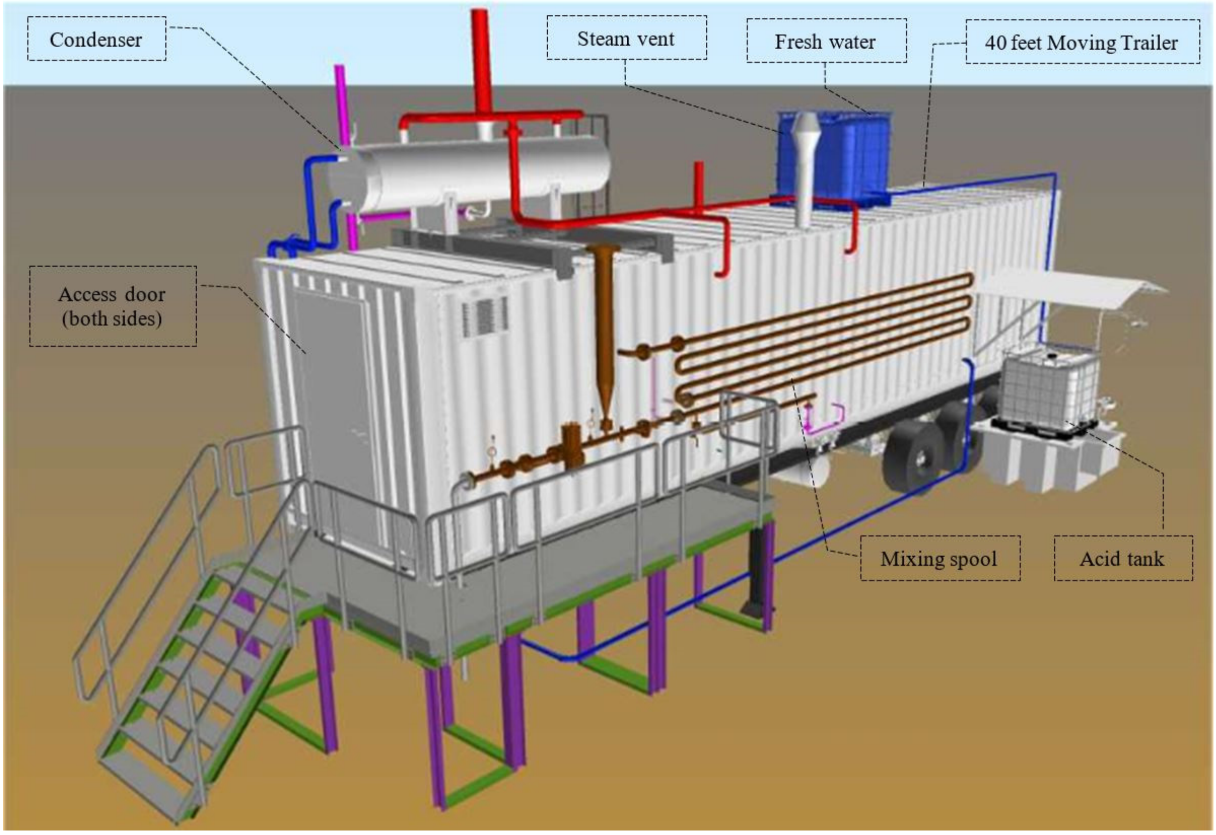

FIGURE 8: Pilot plant 3D Drawing (JV MICK, 2021)

2.2.2 Findings and improvement

At the procurement stage of the pilot plant, the preliminary or schematic design of the pilot plant is not detailed. To reach a better understanding between contractor and buyer, this should be considered in the future so that the evaluation of the procurement stage becomes more approachable. Additionally, the minimum requirement is that the estimated cost is near the contract price. After the procurement stage by the company is completed, the detailed design stage begins.

During the commissioning, the inlet pressure fluctuated due to rock particles carried from the fluids from the crown valve. After a few short start-ups and re-commissioning, the corrosion coupons inserted in the two-phase inlet in front of the HP separator showed a decrease in weight, indicating a corrosion rate of 3 mm/year which was assessed to be unacceptable. It was therefore decided to modify the design of the acid dosing and to inject acid into single-phase brine instead of into a two-phase line before separation.

The duration of test 1 was 13 days for the combined cycle single flash and ORC including hot injection. Line 1 uses ORC and line 2 single flash with high temperature without cooling. The chemical composition of brine and condensate in test 1 is given in Table 1. Test 2 lasted for 4 days. The results of test 2 is given in Table 2.

The steam flash options were not conclusive for several reasons. These included the pressure set point in the first stage separator being set based on average field conditions. This set point was not high enough to ensure that the silica saturation index was < 1.0 when the acid was injected and this was not

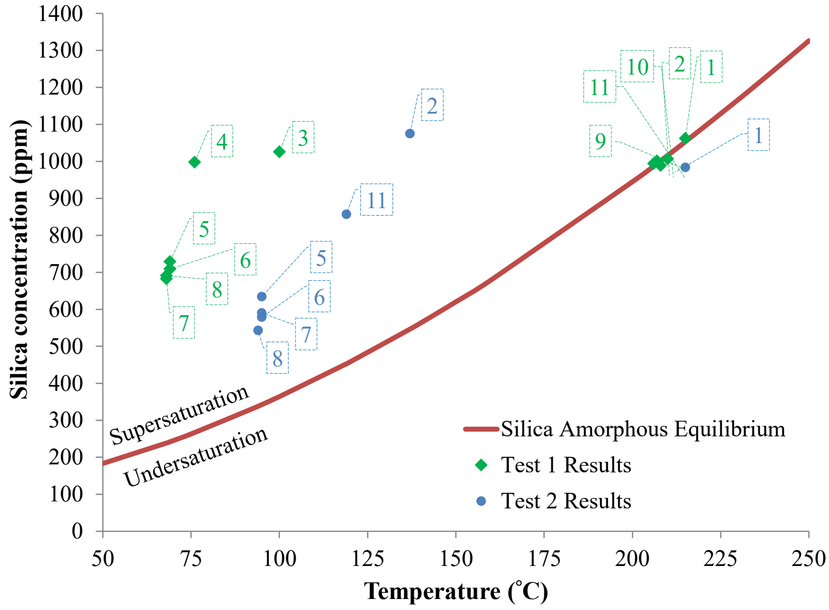

FIGURE 9: Plotting result of silica concentration for Test 1 and 2

discovered until the brine samples were tested during the pilot plant tests, so test conditions could not be adjusted to correct the SSI. Debris from the well also caused clogging in the pilot plant, foreshortening some of the tests. The single flash option appeared to perform adequately with limited scaling but the impact on project viability needs to be evaluated as developing a single flash with high separation pressure will require several more production wells, affecting the project economics. Double flash tests used a very low (3 bar) second stage separation and significant scaling in the second stage piping was observed. For the double flash system, the low pressure needs to be tested further to establish suitable operating pressures that limit scaling. Also, the acid injection needs to be tested more to get a more comprehensive pH modification and acid dosing.

TABLE 1: Result of test 1 pilot plant

Parameter	1 Separator 1	2 Separator 1 after acid injection	3 Vaporizer	4 Preheater	5 Condensate dilution	6 Holdup vessel 1-1	7 Holdup vessel 1-2	8 Holdup vessel 1-3	9 Holdup vessel 2-1	10 Holdup vessel 2-2	11 Holdup vessel 2-3
Temperature (°C)	215	210	100	76	69	69	68	68	208	207	206
pH	6.2	4.9	-	-	-	-	-	-	-	-	-
SiO_2 total (ppm)	1145	1130	-	-	-	-	-	-	-	-	-
SiO_2 monomer (ppm)	1062	1007	1026	998	729	709	683	691	989	1001	994
Silica equilibrium (ppm)	1053	1016	364	267	242	242	238	238	1002	994	987
SSI	1.01	0.99	2.82	3.74	2.93	2.93	2.87	2.90	0.99	1.01	1.01

Test 2 lasted for 4 days for double flash line 1 (brine diluted with condensate) and line 2 (brine not diluted).

TABLE 2: Result of test 2 pilot plant

Parameter	1 Separator 1	2 Separator 1 after acid injection	3 Vaporizer	4 Preheater	5 Condensate dilution	6 Holdup vessel 1-1	7 Holdup vessel 1-2	8 Holdup vessel 1-3	9 Holdup vessel 2-1	10 Holdup vessel 2-2	11 Holdup vessel 2-3
Temperature (°C)	215	137	-	-	95	95	94	94	-	-	1119
pH	6.2	4.9	-	-	-	-	-	-	-	-	-
SiO_2 total (ppm)	1145	1130	-	-	-	-	-	-	-	-	-
SiO_2 monomer (ppm)	984	1075	-	-	634	579	543	543	-	-	857
Silica equilibrium (ppm)	1053	547	-	-	342	342	338	338	-	-	453
SSI	0.93	1.97	-	-	1.85	1.69	1.61	1.61	-	-	1.89

In the ORC or binary test, the findings were that, although the pH modification appeared effective at mitigating amorphous silica scaling, Dieng fluid has high arsenic and antimony sulphide concentrations. Therefore, in order to control heavy metal sulphide deposition in binary heat exchangers, allowable minimum brine temperatures from binary heat exchangers would be much higher than in equivalent plants on other projects, including binary projects in Indonesia. This reduces the thermal efficiency of a binary plant as minimum brine temperatures are likely to be around 140°C rather than 80°C. Due to the low solubility of the arsenic sulphide at low pH, further acidification will not be beneficial. The dissolved silica (SiO_2) was analyzed with two methods which are the conventional colorimetric method used for brines and AAS (Atomic Absorption Spectrometry) method for total silica. The total silica was constantly 10% higher than monomeric silica in all samples due to the presence of polymerized silica. The scale at the surface is predominately aluminum-rich amorphous silica scale.

$$x = \frac{H_l^{T1} - H_l^{T2}}{H_v^{T2} - H_l^{T2}} \tag{3}$$

where x = Steam fraction; and
H = Enthalpy [kJ].

The silica concentration can be estimated based on the dryness (steam fraction) and the previous field experiment to the target pressure or temperature. Because the concentration of amorphous silica will follow the liquid phase, the new concentration can be calculated by dividing with the wetness:

$$S_{SiO2\ at\ T2} = \frac{S_{SiO2\ at\ T1}}{(1-x)} \tag{4}$$

where x = Steam fraction; and
$S_{SiO2\ at\ T2}$ = Concentration of silica [ppm].

Using Equation (4), the graph in Figure 10 shows silica concentration as a function of temperature. The calculated saturation pressure varies from 3.3 to 20 bara. A pressure of 19 bara is the first data point underneath the silica equilibrium curve of SSI limit below 1 (red line in Figure 10). In some cases of geothermal utilization, a silica scaling index of a bit more than 1 is acceptable. It does restrict the energy that can be extracted from a geothermal resource and more recent geothermal developments have utilized methods to cope with brines which are oversaturated with amorphous silica that allow for energy to be extracted while still keeping the amorphous silica undersaturated. Even at low levels of supersaturation, that is, SSI < 1.2, the level of scaling may be acceptable. There may be a sufficiently long induction period so that silica scaling is avoided in reinjection wells and reinjection pipelines. (Brown, 2011). From Figure 10, we conclude that the pressure at the separator may vary at least by 11.57 bara without violating the condition of SSI < 1.2. The impurities in Dieng fluids, aluminum-rich amorphous silica, can also alter the silica saturation index and rates due to the effect of the silica saturation temperature which is higher when dealing with pure amorphous silica.

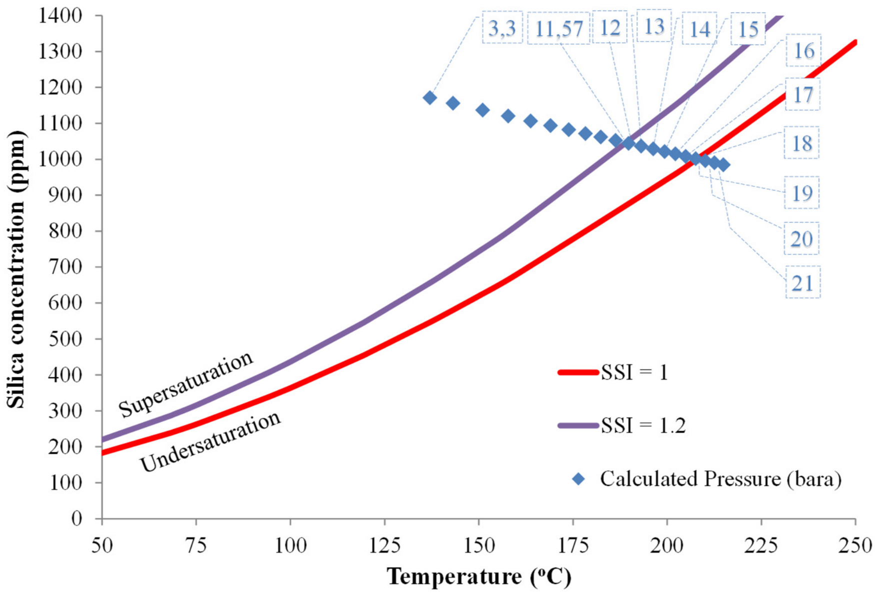

FIGURE 10: Forecast silica precipitation for several temperatures

Besides the SSI, the pilot plant also simulates the scaling rates using coupons inserted and the thickness measurement using scanning electron microscope (SEM/EDS) show the silica scaling rates on the coupon. These silica scaling rates are relatively difficult to model since silica precipitation also occurs due to kinetics factors. Several parameters of the kinetics of silica precipitation (essentially a polymerization process) are (Brown, 2011):

1. Degree of supersaturation;
2. Temperature;
3. pH of the solution;
4. Flowrates;
5. Salinity or molality of the solution; and
6. Aeration.

The preliminary conclusion of the pilot plant testing is that at the wellhead and the two-phase piping the scaling rates are minimal with 1-2 mm/year before acid injection and in the two-phase piping and the production separators after acid injection with < 1 mm/yr. Currently, scaling rates at these locations are roughly 8 mm/year and 30 mm/year, respectively. The scaling rate in the high-pressure separator using the hot injection process is found to be 1-2 mm/year.

Parallel with this study, the pilot plant testing will be conducted with other pressure settings to have a more comprehensive result. This next step will take approximately 2 months to finish.

3. POWER PLANT DESIGN AND OPTIMIZATION

3.1 Calculation basis

The feasibility study comes to the conclusion that the preferred technology is the combined cycle which consists of a single flash, backpressure steam turbine, ORC bottoming turbine, and ORC brine. The high minimum brine temperature required to control heavy metal sulphides deposits means that the improved thermal efficiency of a binary plant is unlikely to be achievable. Hence, the power plant configuration in this study is single flash with condensing turbine and double flash with condensing turbine. The thermodynamic equations of the power plants were modelled with properties of the fluid database called CoolProp, using the Python programming language. Optimization of the power plant configuration is conducted to find the mass flow consumption and steam consumption for the net power output of each power cycle. The optimization process in this study followed these basic steps:

1. Design of a schematic model for single flash condensing system and double flash condensing system.
2. Defining the design variables and assumptions.
3. Calculating the heat and mass balance.
4. Finding the values of required total mass flow from wells.
5. Analysing the results based on steam specific consumption.

The framework of the study is shown in Figure 11. The turbine inlet pressure needs to be considered carefully in Dieng. The fluid composition of wells supplying Unit 1 is considered as representative for likely fluid composition from Unit 2 wells. The Silica Saturation Temperature (SST) for the bulk of the Unit 1 wells, if well HCE-31 is excluded, is very low indicating that there is probably a condensate feed or other dilution into the well ranging from 195°C to 220°C. This temperature represents separation pressures of about 19-24 bara. If the bulk of the wells for Unit 2 are at the lower end of this temperature range, then it would be preferable to set the power plant inlet pressure lower so that the mass flow and flash ratio for these wells could be maximized. If a well exhibits higher SST, then the separation pressure for that well could be set higher so that SSI < 1.0 and the steam pressure reduces using a steam line pressure control valve after that separator. The selection of the lowest possible turbine inlet pressure potentially increases the steam production from the field by up to 11%.

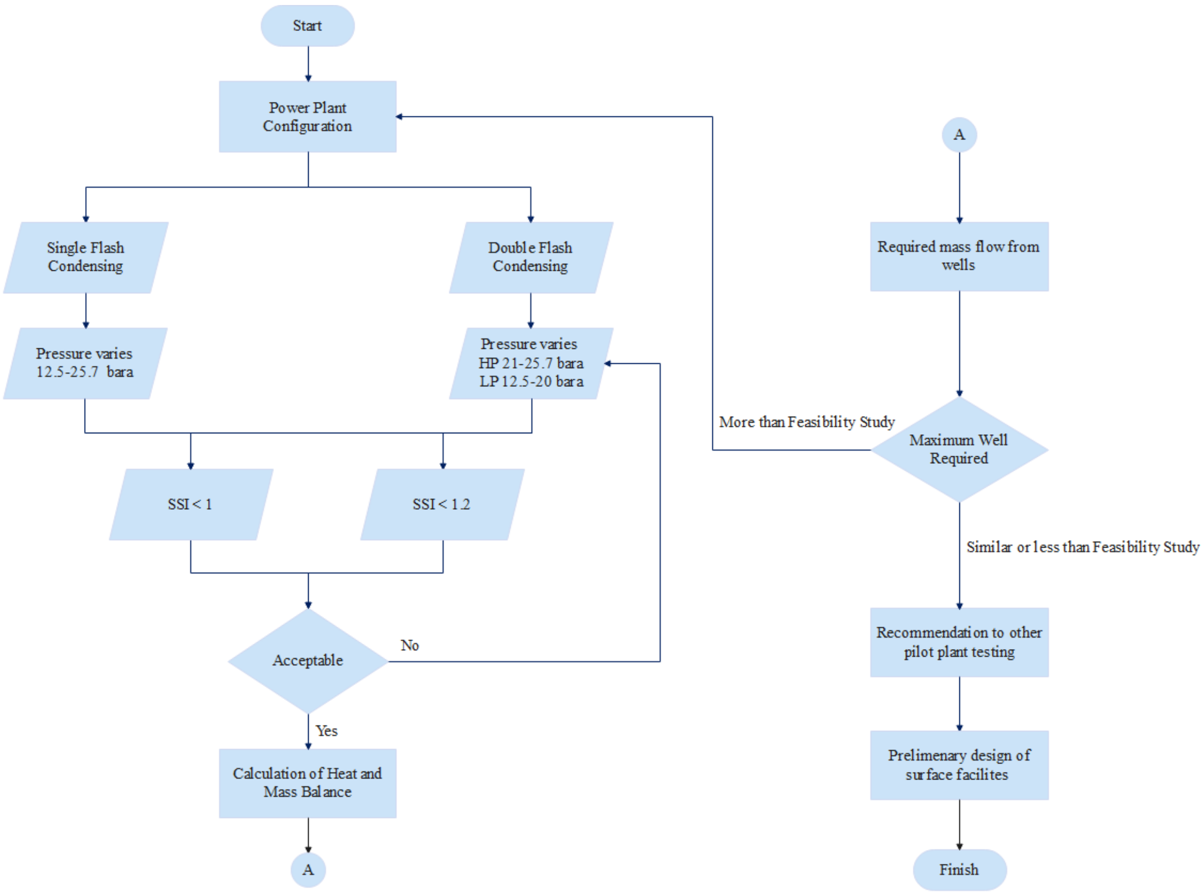

FIGURE 11: Framework of the study

The pilot plant results show that the pressure of the HP Separator is recommended to be 21.2 bara to 25.7 bara. Findings in the pilot plant will guide another additional testing parameter. To provide an alternative engineering design, the engineering division can calculate the optimization of the condensing units of the power plant. This recommendation needs to be more detailed in further steps including conducting another parameter test. In Table 3 and Table 4, the design parameters and assumptions used for the calculation are listed. The SSI which is shown in Figure 10 suggests that the lower pressure has to be greater than 11.57 bara with an acceptable SSI of > 1.2; then, by assuming approximately 1 bara as pressure drop from the separator to the turbine, it can be concluded that the lowest separator pressure is 12.5 bara.

The wide enthalpy range is one of the identified resource risks and needs to be mitigated by the optimization of equipment sizing using detailed engineering to avoid over/under specification and the designation of the power plant needs to be flexible to accommodate enthalpy input. The calculation is limited regarding the NCGs, and further research is needed to include NCGs of 0.3% to 2.3% by weight.

TABLE 3: Design variables for power plant

Power plant configuration	**Separator pressure**	**Constraint**
Single flash	12.5 – 25.7 bara	SSI ≤ 1.2
Double flash	High Pressure 21.2-25.7 bara Low Pressure 12.5-20 bara	SSI ≤ 1.2

TABLE 4: Assumptions of power plant

Assumption	**Value**	**Basis of assumption**
Power (net)	55 MW	Energy Sales Contract (ESC)
Reservoir temperature	300-330°C	Based on feasibility study report
Enthalpy of fluids at the wellhead	1300-2100 kJ/kg	Based on feasibility study report
Efficiency of a dry steam turbine	85%	Wet expansion in single and double flash units, the turbine efficiency is corrected by using the Baumann rule
Efficiency of pumps	70%	
Pressure loss of turbine valve	1 bara	
Temperature of condenser	45°C	
Pressure of condenser	0.08 bara	
Wet bulb temperature	20°C	Average wet bulb temperature measured in the field
Temperature of cooling tower approach	8°C	
Auxiliary power (Parasitic load)	3 MW	

3.2 Single flash condensing system

The major components of the surface facilities of this plant consist of wellhead, separator, mist eliminator, steam turbine, generator, condenser, ejector, cooling tower, and pumps. A simplified schematic diagram for the single flash system with a condensing turbine is shown in Figure 12, showing major components such as a separator, turbine, surface condenser, NCG ejectors or compressors, pumps, and cooling tower. The alternatives demonstrate the impact that a single flash will have on the production and reinjection well requirements when compared with the base case (10 wells) included in the feasibility study.

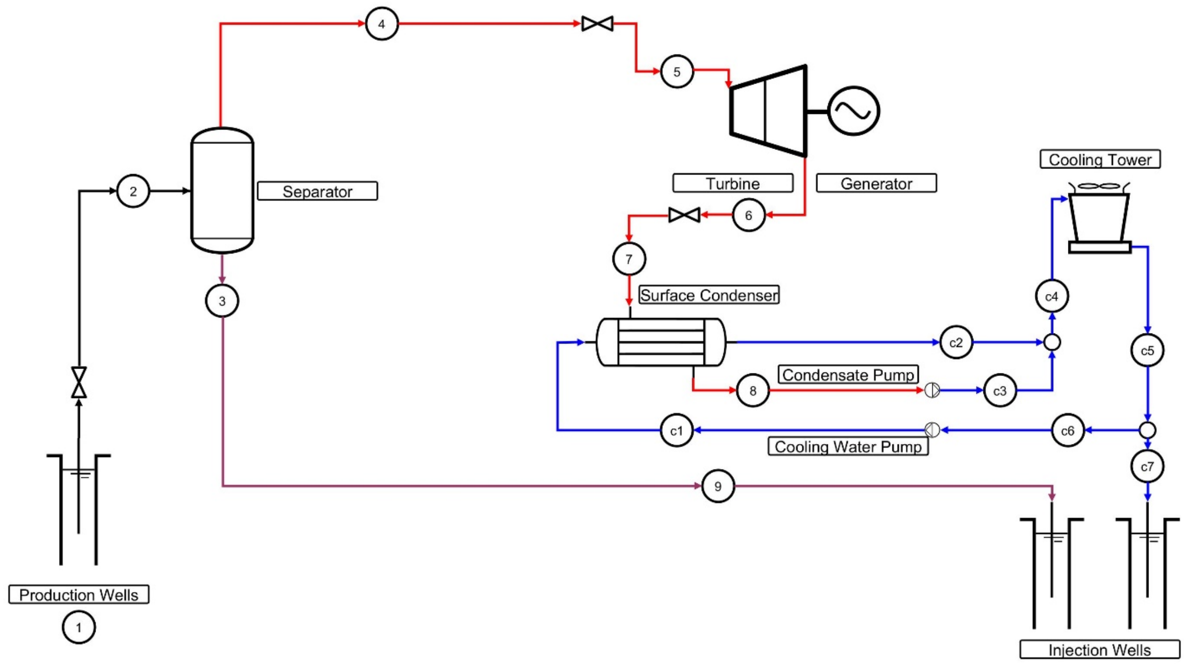

FIGURE 12: Single flash preliminary design

The assumptions are that the injection in the single flash is made by a hot brine injection system and that separate wells are used for brine and condensate injection. The brine ponds are only used for start-up and to set up operating conditions. Reservoir simulation study, including rock properties, for Sileri and Sikidang have been done. The results show for a single flash power plant, the development will need 7 productions wells, 4 injections wells, and 5 make up wells (Geo Dipa Energi, 2019). The calculation in this study is conducted using separator pressure as a variable to find the preferred design parameters for Dieng Unit 2.

Equations (5) to (11) describe the equilibrium of mass and enthalpy for a single flash system. The numbers in figure 12 refer to these equations.

$$h_1 = h_2 \tag{5}$$

where h = Enthalpy [kJ/kg].

The separation process at a certain pressure, is an isobaric process with quality or steam fraction, x, of the steam that forms after the separator.

$$x_4 = \frac{h_2 - h_3}{h_4 - h_3} \tag{6}$$

where h = Enthalpy [kJ/kg]; and
x = Steam fraction.

The steam mass flow, $\dot{m}_4$, can be calculated with Equation 7:

$$\dot{m}_4 = x_4 \, \dot{m}_{total} \tag{7}$$

where $\dot{m}$ = Mass flow [kg/s]; and
x = Steam fraction.

And the mass flow of separated brine, $\dot{m}_3$, can be calculated using Equation 8:

$$\dot{m}_3 = (1 - x_3) \, \dot{m}_{total} \tag{8}$$

The gross electrical power developed by the turbine is calculated using:

$$w_t = n_t \, \dot{m}_5 \, (h_5 - h_{7is}) \tag{9}$$

where w_t = Power [kW];
n_t = Efficiency of turbine (%);
$\dot{m}_s$ = Mass flow of steam [kg/s]; and
h = Enthalpy [kJ/kg].

In the Dieng geothermal field, a well is estimated to have an output of 58 kg/s. With this value, the number of wells required can be obtained using Equation 10:

$$n_{well} = \frac{\dot{m}_{total}}{58 \, kg/s} \tag{10}$$

where n_{well} = Number of wells; and
$\dot{m}_{total}$ = Mass flow of required geothermal fluids [kg/s].

To further study the power plant efficiency, the SSC parameter can be used as described in Equation 11:

$$SSC = \frac{\dot{m}_{steam}\ x\ 3600}{w_t} \tag{11}$$

where SSC = Specific Steam Consumption [ton/h/MWnet];
$\dot{m}_{steam}$ = Mass flow of steam [kg/s]; and
w_t = Power (kW).

For the single flash system, the higher the separator pressure, the higher the total mass flow from the wells but the lower the Specific Steam Consumption (SSC) which can be found in Figure 13, Figure 14 and Appendix I.

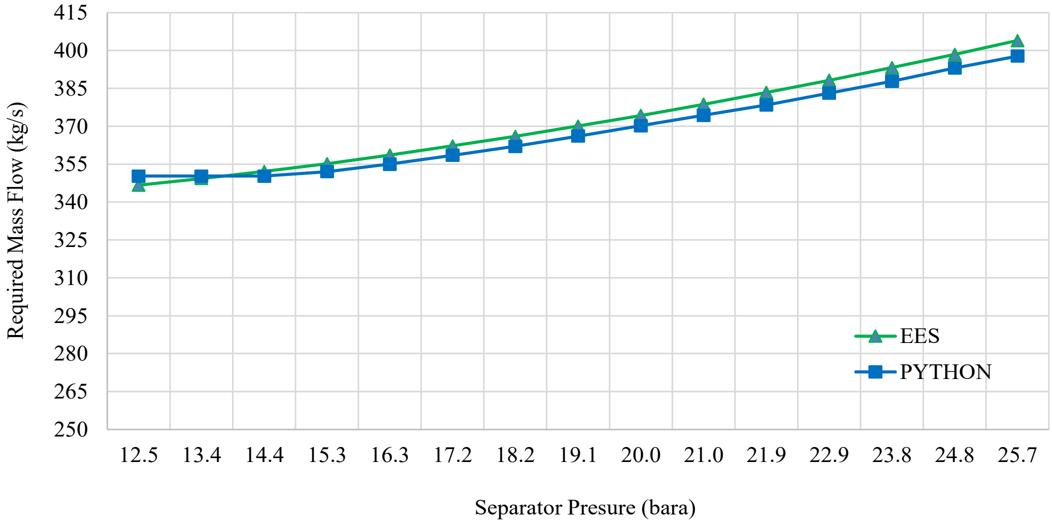

FIGURE 13: Single flash calculation result (Enthalpy = 1300 kJ/kg)

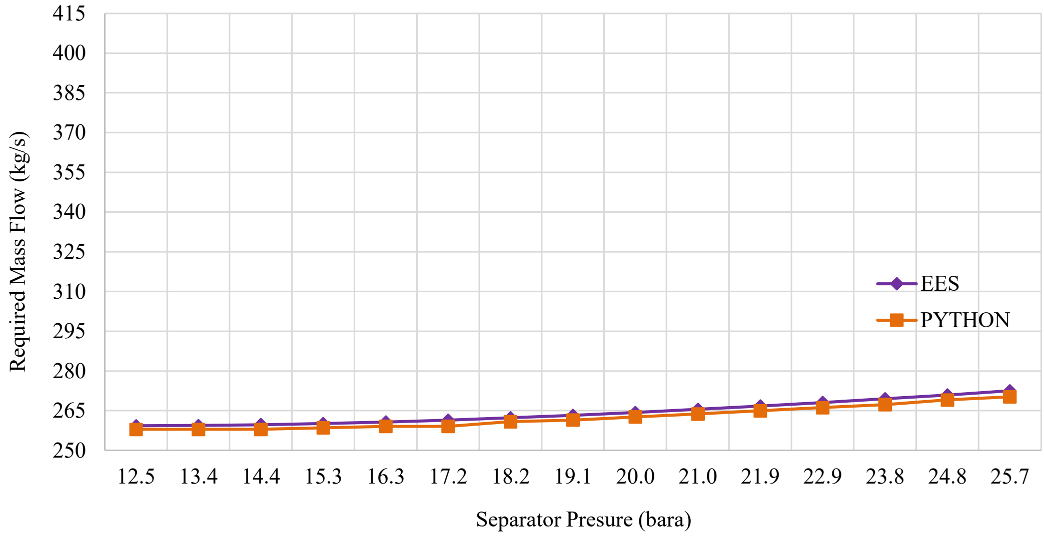

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FIGURE 14: Single flash calculation result (Enthalpy = 1600 kJ/kg)

3.3 Double flash condensing system

The major components of the surface facilities for the double flash system are similar to the single flash system with additional installations such as two separators, high pressure and low pressure, and steam turbines in two pressure inlets. The simplified schematic diagram for the double flash system with a condensing turbine, separators, condenser, NCG ejectors or compressors, and cooling tower are shown in Figure 15. The double flash system was not included in the feasibility study.

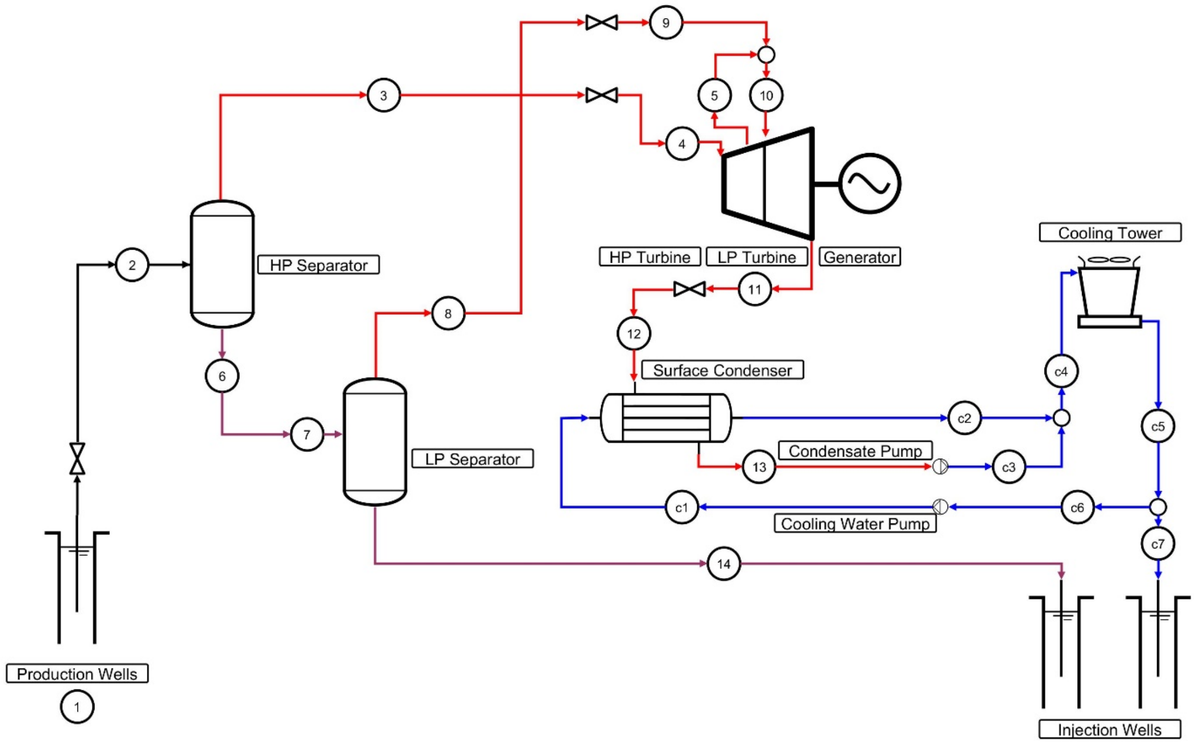

FIGURE 15: Double flash preliminary design

A double flash steam plant can increase production by 15-25% with the same geothermal fluid conditions compared to the single flash design. For larger power output, for example 55 MW or higher, double-flow turbines would be a good choice to minimize the length of the last-stage blades. Usually, the last-stage blades in geothermal turbines are at most 25-27 in (635-686 mm) long (Dipippo, 2012). It is advised to use a surface condenser and to not dilute the brine with condensate since the high pH of the condensate will increase the pH of the brine so that silica scaling will start after the condensate injection point. If the injection well for Unit 1 still has adequate capacity, it is recommended to dispose of the condensate from Unit 2 by mixing with the Unit 1 condensate. Condensate should be handled separately from the brine, even if a surface condenser is used. Even if the concentration of dissolved oxygen in the condensate is only parts per billion, the risk of corrosion in the brine system and reinjection wells is too high.

Double flash design and optimization on lower pressure using Python:
The separation process at a certain pressure is an isobaric process with quality or steam fraction, x, of the mixture that forms after the separator.

$$x_3 = \frac{h_2 - h_6}{h_3 - h_6} \tag{12}$$

where h = Enthalpy [kJ/kg];
x = Steam fraction.

The steam mass flow ($\dot{m}_3$) can be calculated with Equation 13:

$$\dot{m}_3 = x_3\, \dot{m}_{total} \tag{13}$$

where $\dot{m}$ = mass flow [kg/s];
x = steam fraction.

And the mass flow of separated brine ($\dot{m}_6$) as Equation 14.

$$\dot{m}_6 = (1 - x_3)\, \dot{m}_{total} \tag{14}$$

The separation process at a certain pressure, as an isobaric process with quality or steam fraction, x, of the mixture that forms after the separator.

$$x_8 = \frac{h_7 - h_{14}}{h_8 - h_{14}} \tag{15}$$

The mass of steam, $\dot{m}_8$, can be calculated with Equation 16:

$$\dot{m}_8 = x_6\, \dot{m}_7 \tag{16}$$

And the mass flow of separated brine, $\dot{m}_{14}$, is described by Equation 17:

$$\dot{m}_{14} = (1 - x_8)\, \dot{m}_7 \tag{17}$$

The gross electrical power generated by the turbine is equal to the total power from high pressure turbine with additional power from the low pressure turbine as described in Equations 18, 19, and 20 below.

$$w_{HP} = n_t\, \dot{m}_3\, (h_4 - h_5) \tag{18}$$

$$w_{LP} = n_t\, \dot{m}_{10}\, (h_{10} - h_{11}) \tag{19}$$

$$w_t = w_{tHP} + w_{tLP} \tag{20}$$

where w_t = Total power [kW];
w_{HP} = Power from HP turbine [kW];
w_{LP} = Power from LP turbine [kW];
$\dot{m_3}$ = Mass flow of steam HP Separator [kg/s];
$\dot{m_8}$ = Mass flow of steam LP Separator [kg/s];
n_t = Efficiency of turbine (%); and
h = Enthalpy [kJ/kg].

In Dieng geothermal field, a well is estimated to have an output of 58 kg/s, then the number of wells required can be obtained using Equation 10.

To further study the power plant efficiency, the SSC parameter can be used. It is described in Equation 21.

$$SSC = \frac{\dot{m}_{steam}\ x\ 3600}{w_t} \tag{21}$$

where SSC = Specific Steam Consumption [ton/h/MWnet];
m_{steam} = Mass flow of steam [kg/s];
w_t = Power (kW).

The silica scaling potential is a constraint that limits the lower separator pressure. The next tests in the pilot plant should be focused on confirming the minimum allowable separator pressure that achieves acceptable scaling levels of silica and aluminum rich silicate for single flash options, establishing the feasibility of acid dosing to control brine pH and silica deposition rates (test results from first stage tests were inconclusive), define the minimum acceptable second stage flash pressure that achieves acceptable scaling rates (note that scaling will not be zero, but we need to have a system that only needs to be cleaned out occasionally), possibly running a further set of tests for the binary combined cycle option to define the minimum acceptable brine outlet temperature that would avoid heavy metal sulfide deposition.

Since the enthalpy of fluids varies from 1300 to 2100 kJ/kg, in this study the calculations were conducted for an enthalpy of 1300 and 1600 kJ/kg (Figures 16 and 17). Other calculation results are shown in Appendix II.

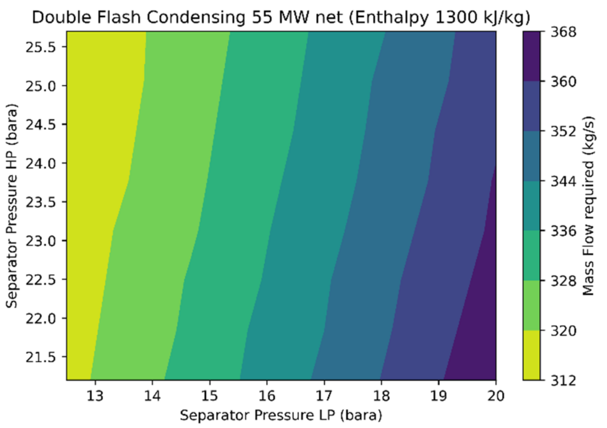

FIGURE 16: Double flash calculation result (Enthalpy = 1300 kJ/kg)

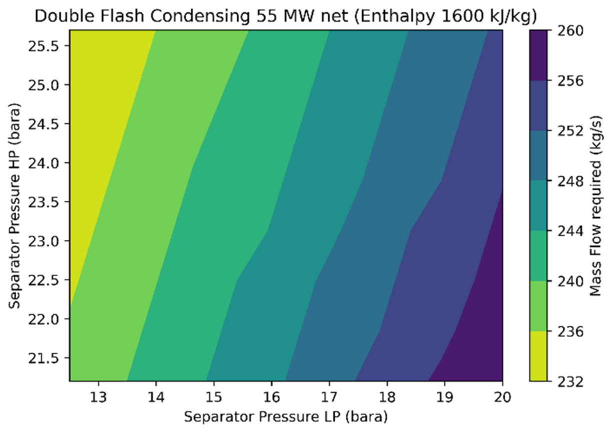

FIGURE 17: Double flash calculation result (Enthalpy = 1600 kJ/kg)

4. DISCUSSION

Geothermal field characteristics are site specific regarding the thermodynamics and chemical contents which requires different approaches to develop these fields. Dieng, a brownfield with existing facilities and data, nonetheless needs to be comprehensively studied to identify the best approach for the power plant to be improved and adapted to the geothermal field. Dieng operating conditions are impeded by high silica concentrations. To ensure that Dieng's Unit 2 design and operations will last and be appropriate for at least 30 years, a pilot plant test was conducted as proposed by several previous studies. The pilot plant design and testing were started in 2020. Figure 18 shows the number of production wells, the different power plant types and enthalpies based on the separation pressure. To minimize cost, the minimal number of wells needs to be identified. We found that a smaller number of production wells is needed with the double flash condensing type where 4 wells might be sufficient. This is of course depending on the output of the wells for Unit 2, but when using the same assumptions that were used in the feasibility study, the number of production wells is in the range of 4-7 wells.

Having lower pressure for the second stage flash reduces the number of wells required to achieve 55 MW. Calculations show that the "optimum" LP flash would be around 3.95 bar, assuming no silica saturation index constraints. If an LP steam pressure as low as 3.95 bar can sustain operations, then it could be beneficial to consider a triple flash system with an LP flash pressure in the range of 10-12 bar. This would mean a similar configuration to the Fuji units installed at Hudson Ranch, USA, and Nga Awa Purua, New Zealand. However, this will not be applied in Dieng, since the high silica concentrations will probably require a higher LP flash pressure to manage the SSI. A publication by

Kevin Brown (2011) provides a useful reference point. The LP pressure of 11.5 bara could be tested again in the next set of pilot plant trials at Dieng.

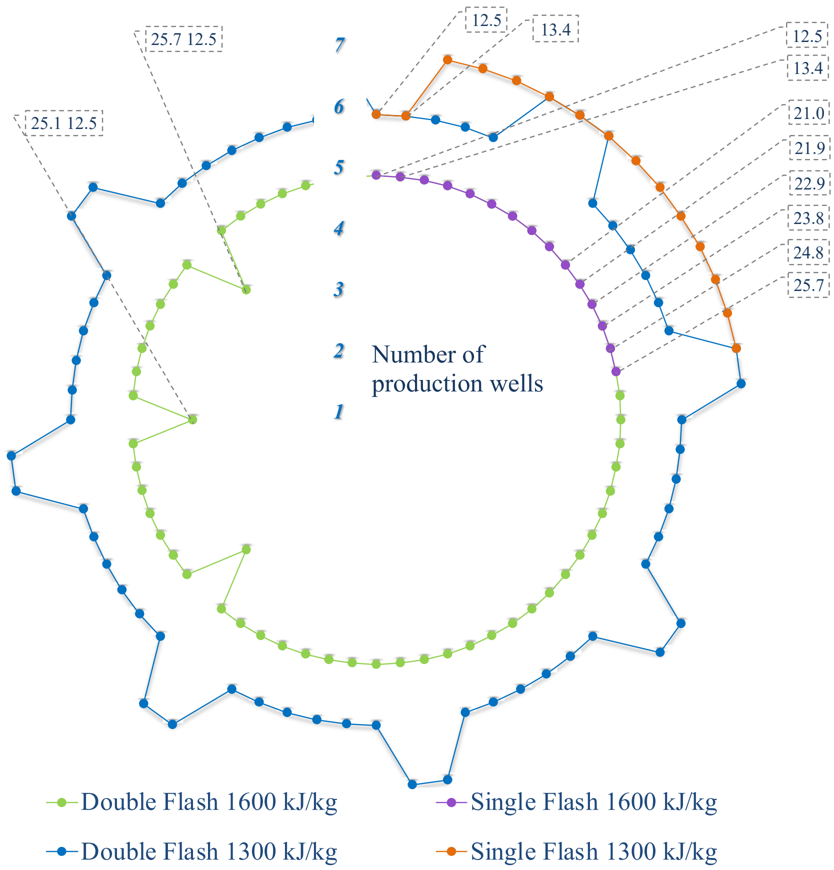

FIGURE 18: Number of production wells required

The SSC can provide us with useful information. A lower SSC means that the power plant is more efficient, and therefore means that the SSC improves as the LP flash pressure increases. Note that the best SSC would be realized in a single flash plant. Even though the SSC might be better (and hence power plant costs would be lower) with higher LP flash pressure, the number of wells required to supply the plant would also increase. It is worth to calculate the SSC for the range of options as has been done, but it is important to note that the SSC is only an indicator of the efficiency of the power plant itself, which is illustrated in Figure 19. This SSC is an approximation with an optimistic approach, as shown in the assumption of Table 4. The overall project development costs will be lowest when the total cost of the power plant and the cost of drilling the wells and connecting the SAGS (steam above ground system) is optimized. The steam consumption is almost the same using enthalpy 1300 kJ/kg or 1600 kJ/kg. Nevertheless, the mass flow required from the wells is increased with lower enthalpy. Another interesting value to be analysed for the double flash system is the additional steam gathered from the second flasher or low pressure separator. The higher the percentage of steam gathered in the low-pressure separator, the more advantage can be gained, calculated as 9-16% depending on pressure.

Considering the possibilities of pad locations and two phase geothermal pipes, assuming separators are wellhead separators, then pipelines from well pads to power plant consist of steam and brine pipes, and reinjection pipelines from the power plant to injection wells. If the preferred power plant technology is not the combined cycle, then the pipeline routes have to be reconsidered. One of the findings of the pilot plant study is the value of acid injection to achieve pH modification. This implies that a centralized separation plant would be preferable to simplify the pH injection system as these can be quite complex. However, the chemistry of the produced fluid varies across the field. Combining the fluids before injecting acid could lead to a higher overall separation pressure than would be the case with well pad separators. A vertical separator configuration is preferred due to maintenance effectiveness.

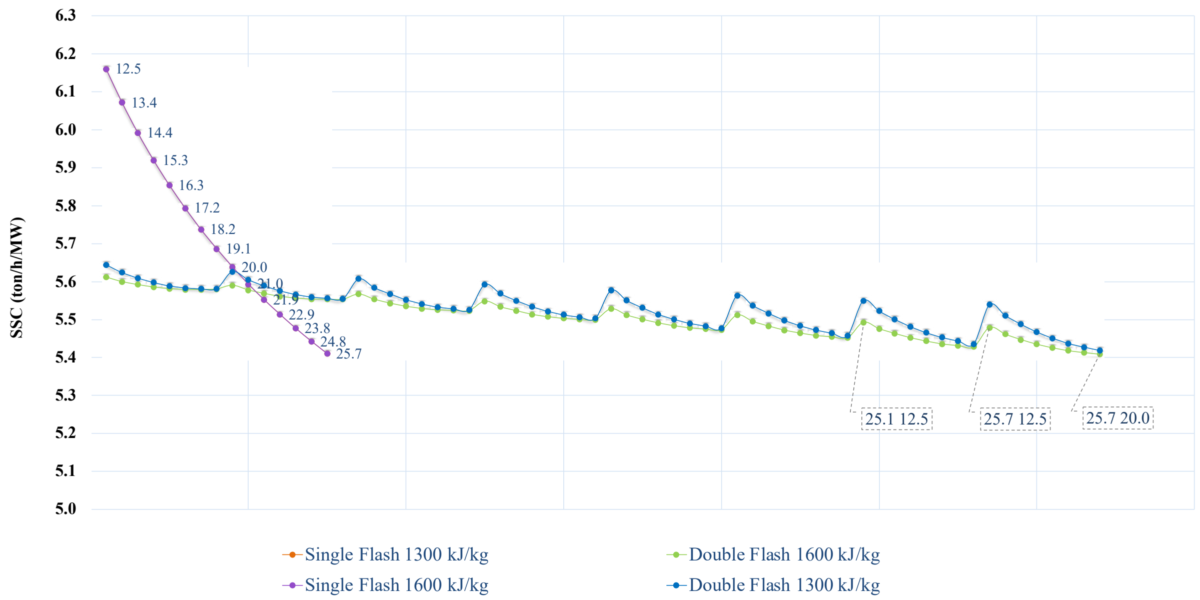

FIGURE 19: SSC for single flash and double flash

To select the separator, further study is necessary. Power plants which are influenced by New Zealand technology use vertical separators but since the 1990s horizontal gravity separators have been used in Icelandic power plants. First installations in Iceland used vertical separators but in newer installations horizontal separators have exclusively been used. Experience from decades of operation of horizontal separators in Icelandic geothermal power plants is good. Both vertical and horizontal designs can obtain a separator efficiency of 99.9%. The efficiency of the cyclone separator is highly dependent on inflow velocity and achieves the highest efficiency when the steam inlet velocity is between 30 and 40 m/s. For higher velocities the efficiency decreases rapidly (Thórólfsson, 2020).

Injecting CO_2 into the subsurface may cool down the reservoir and the low pH can cause corrosion. The most appropriate power plant configuration is double flash. Currently, the most common power plant configuration in high temperature fields is a single flash condensing system, due to its low risk for silica scaling (Nugroho, 2011).

5. CONCLUSIONS AND RECOMMENDATION

We conclude that the pilot plant is one of the strategies to learn how to cope with silica or other chemical impurities which vary between fields. The pilot plant design and testing may take years to optimize the design for power plants, but will help to sustain power plants' operations for 30 years or more.

Several findings from the pilot plant in Dieng field show that acid injections are not effective in the two-phase line and instead high pressure, and hot injection might be the better option for Dieng Unit 2. Another finding was that to control heavy metals the temperature needs to be higher. Thermodynamically, the silica saturation index value 1 corresponds to a pressure of 19 bara, but if an SSI of 1.2 is acceptable, the low-pressure turbine recommendation is higher than 11.57 bara. Assuming less than 1 bar of pressure loss, the lowest separator pressure should be 12.5 bara. The silica scaling rate modelling will be taking more time, but as mentioned in the pilot plant result, the scaling rates are 1-2 mm/year. Using lower pressure for operations will increase the scaling rates. Qualitatively, the scaling rates may be stated as higher than 2 mm/year and need to be tested accordingly.

The power plant configurations studied are a single flash condensing type and a double flash condensing type with enthalpy assumption of 1300 kJ/kg and 1600 kJ/kg. Based on this study, the required mass flow for a single flash separator pressure ranging from 12.5 bara to 25.7 bara is 260 kg/s to 405 kg/s with pressure being directly proportional to the mass flow required from the wells. For double flash calculation, the overall required mass flow is ranging from 235 to 360 kg/s and the separator pressure correlation with mass flow is directly proportional. With Specific Steam Consumption (SSC), the pressure is inversely proportional which means that the higher the pressure, the lower the SSC. Therefore, we recommend a double flash system using 25 bara high pressure and 12.5 bara low pressure separator pressures. The second-best option is a single flash system using 25 bara. These recommendations, especially the double flash system, need to be checked in the pilot plant to gather more comprehensive information about the silica scaling index and silica scaling rates.

We make the following recommendations:

1. Other interesting impurities such as As_2S_3 (Arsenic sulfide) and Sb_2S_3 (Antimony trisulphide) can be modelled in software for geochemistry. This may be helpful to simulate behaviour of impurities in the geothermal fluids that are interesting due to high scaling potential or for other reasons. The modelling software could be WATCH, PREEQC, geochemist workbench, chiller, deposition, or one box.
2. Based on the Thermochem 2019 report, the scaling rate at a temperature of 205°C or 17.5 bara is 1-2 mm/year which can be acceptable and should be tested in the pilot plant field experiment. The Thermochem report was based on the average field data from all Unit 1 wells. The practical separator pressures and temperatures will depend on the fluid composition of the unit 2 wells. If the SST for a well is lower than the average in Unit 1, there is the possibility of operating that well at a lower separator pressure which will increase both the mass flow from the well and the steam flash ratio. Optimizing separation pressures and turbine inlet pressures will be necessary to achieve a preferred plant configuration.
3. Wellpad separators were recommended as it meant that condensate recycling was easier. However, established condensate injection is not effective as the high ammonia content means that condensate pH is high and negates the effectiveness of acid injection. Having two-phase cross-country lines and a central separator station (about 500 m from the power plant) means there would only need to be a single acid dosing system, rather than multiple systems if wellpad separators are used. This all needs further consideration.
4. In Dieng, a backpressure turbine may also be worth studying due to the opportunity to apply the direct use utilization. The proposed backpressure turbine outlet may use 1.2 bara. The discharge pressure selection is related to the exploitation and the discharge of NCGs into the atmosphere. Discharge pressure represents an energy loss associated with NCGs; if discharge pressure is below ambient value, NCGs should be extracted and re-compressed before their discharge into the atmosphere. The selected value of 1.2 bara allows to easily discharge NCGs without any extraction system.
5. Besides the technical approach, an economic approach for studying the cost difference between the single flash and double flash in Dieng will be interesting.

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to all those who provided me the opportunity to complete this report including the overall training. A special gratitude to my final report supervisor, Geir Thórólfsson and utilization Godfather, Páll Valdimarsson, who helped and encouraged me to study, and write this report.

Furthermore, I also want to acknowledge the crucial role of the GRÓ Geothermal Training Programme (GRÓ GTP), Director Gudni Axelsson, Málfrídur Ómarsdóttir, Ingimar G. Haraldsson, Vigdís Hardardóttir and Markús A.G. Wilde who facilitated all the properties and resources from the start to the end of the training. Very special thanks to PT Geo Dipa Energi (Persero), especially the Project Management Unit (PMU), Agung Wisnu Mukti, Supriadinata Marza, and all the members who supported me in this training. Other than that, thanks to my mentor Phil Lory, my Python guru Erick Jiménez and my senior Elfina.

Last but not least, full gratitude to God Almighty, Jesus Christ, for all the blessings in my life, who sent my parents, Horisman Marbun and Nurliani Samosir, also my siblings and my relatives, so I feel extremely loved. To God be the glory!

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APPENDIX I: Result of the single flash

Single flash 1300 kJ/kg
T_reservoir: 300 °C

	Separator pressure	Mass flow of wells (PYTH)	Mass flow of wells (EES)	Mass flow of steam (PYTH)	Mass flow of steam (EES)	Wells required (PYTH)	Wells required (EES)	Number of wells required (EES)	Number of wells required (PYTH)	SSC (PYTH)	SSC (EES)
	bara	kg/s		kg/s		Wells		wells		ton/h/MWnet	
0	12.5	350.29	346.70	97.32	94.11	6.01	5.94	7	6	6.4	6.2
1	13.4	350.29	349.30	95.28	92.76	6.01	5.99	7	6	6.2	6.1
2	14.4	350.29	352.10	93.32	91.54	6.01	6.04	7	7	6.1	6.0
3	15.3	352.05	355.20	91.90	90.44	6.04	6.09	7	7	6.0	5.9
4	16.3	354.98	358.60	90.83	89.43	6.09	6.15	7	7	5.9	5.9
5	17.2	358.50	362.20	89.94	88.51	6.15	6.21	7	7	5.9	5.8
6	18.2	362.01	366.00	89.06	87.65	6.21	6.27	7	7	5.8	5.7
7	19.1	366.11	370.10	88.35	86.87	6.28	6.34	7	7	5.8	5.7
8	20.0	370.21	374.30	87.64	86.14	6.35	6.42	7	7	5.7	5.6
9	21.0	374.32	378.70	86.94	85.45	6.42	6.49	7	7	5.7	5.6
10	21.9	378.42	383.40	86.24	84.82	6.49	6.57	7	7	5.6	5.6
11	22.9	383.11	388.20	85.67	84.23	6.57	6.65	7	7	5.6	5.5
12	23.8	387.79	393.20	85.10	83.67	6.65	6.74	7	7	5.6	5.5
13	24.8	393.07	398.40	84.65	83.14	6.74	6.83	7	7	5.5	5.4
14	25.7	397.75	403.90	84.06	82.65	6.82	6.92	7	7	5.5	5.4

Single flash 1600 kJ/kg
T_reservoir: 330 °C

	Separator pressure	Mass flow of wells (PYTH)	Mass flow of wells (EES)	Mass flow of steam (PYTH)	Mass flow of steam (EES)	Wells required (PYTH)	Wells required (EES)	Number of well required (EES)	Number of well required (PYTH)	SSC (PYTH)	SSC (EES)
	bara	kg/s		kg/s		Wells		wells		ton/h/MWnet	
0	12.5	257.9	259.30	95.5	94.11	4.4	4.4	5	5	6.3	6.2
1	13.4	257.9	259.40	94.1	92.76	4.4	4.4	5	5	6.2	6.1
2	14.4	257.9	259.70	92.8	91.54	4.4	4.5	5	5	6.1	6.0
3	15.3	258.5	260.10	91.8	90.44	4.4	4.5	5	5	6.0	5.9
4	16.3	259.1	260.70	90.8	89.43	4.4	4.5	5	5	5.9	5.9
5	17.2	259.1	261.40	89.9	88.51	4.4	4.5	5	5	5.9	5.8
6	18.2	260.8	262.30	89.2	87.65	4.5	4.5	5	5	5.8	5.7
7	19.1	261.4	263.20	88.3	86.87	4.5	4.5	5	5	5.8	5.7
8	20.0	262.6	264.30	87.6	86.14	4.5	4.5	5	5	5.7	5.6
9	21.0	263.8	265.50	86.9	85.45	4.5	4.6	5	5	5.7	5.6
10	21.9	264.9	266.70	86.3	84.82	4.5	4.6	5	5	5.6	5.6
11	22.9	266.1	268.10	85.7	84.23	4.6	4.6	5	5	5.6	5.5
12	23.8	267.3	269.50	85.1	83.67	4.6	4.6	5	5	5.6	5.5
13	24.8	269.0	270.90	84.6	83.14	4.6	4.6	5	5	5.5	5.4
14	25.7	270.2	272.50	84.1	82.65	4.6	4.7	5	5	5.5	5.4

PYTH: Python; EES: Engineering Equation Solver

APPENDIX II: Result of the double flash

Double flash 1300 kJ/kg
T_reservoir: 300 °C

	P_HP	P_LP	Mass flow of wells		m_dot_HP_steam_calc		m_dot_LP_steam_calc		Percentage additional steam		Msteam		Wells required		Number of wells		SSC	
			PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES
	bara	bara	kg/s		kg/s		kg/s		kg/s		kg/s		wells		wells		ton/h/MWnet	
0	21.2	12.5	317.6	319.6	73.4	71.8	14.3	14.4	19%	20%	87.70	86.23	5.4	5.5	6.0	6.0	5.7	5.6
1	21.2	13.6	323.8	326.3	74.9	73.3	12.5	12.6	17%	17%	87.39	85.92	5.6	5.6	6.0	6.0	5.7	5.6
2	21.2	14.6	330.9	332.6	76.5	74.7	10.8	11.0	14%	15%	87.29	85.70	5.7	5.7	6.0	6.0	5.7	5.6
3	21.2	15.7	337.1	339.8	78.0	76.3	9.0	9.2	12%	12%	86.99	85.52	5.8	5.8	6.0	6.0	5.7	5.6
4	21.2	16.8	344.1	347.2	79.6	78.0	7.3	7.4	9%	9%	86.89	85.38	5.9	6.0	6.0	6.0	5.7	5.6
5	21.2	17.9	351.2	354.9	81.2	79.7	5.6	5.6	7%	7%	86.77	85.30	6.0	6.1	7.0	7.0	5.7	5.6
6	21.2	18.9	359.0	362.1	83.0	81.4	3.8	3.9	5%	5%	86.83	85.27	6.2	6.2	7.0	7.0	5.7	5.6
7	21.2	20.0	366.0	370.4	84.6	83.2	2.0	2.1	2%	2%	86.67	85.27	6.3	6.3	7.0	7.0	5.7	5.6
8	21.8	12.5	316.8	318.6	72.3	70.7	15.1	15.3	21%	22%	87.47	85.96	5.4	5.5	6.0	6.0	5.7	5.6
9	21.8	13.6	323.0	325.2	73.7	72.2	13.4	13.5	18%	19%	87.16	85.63	5.5	5.6	6.0	6.0	5.7	5.6
10	21.8	14.6	329.3	331.4	75.2	73.5	11.7	11.9	16%	16%	86.87	85.39	5.6	5.7	6.0	6.0	5.7	5.6
11	21.8	15.7	336.3	338.5	76.8	75.1	10.0	10.1	13%	13%	86.77	85.19	5.8	5.8	6.0	6.0	5.7	5.6
12	21.8	16.8	342.6	345.8	78.2	76.7	8.3	8.3	11%	11%	86.48	85.04	5.9	5.9	6.0	6.0	5.7	5.6
13	21.8	17.9	349.6	353.4	79.8	78.4	6.6	6.5	8%	8%	86.37	84.94	6.0	6.1	6.0	7.0	5.7	5.6
14	21.8	18.9	357.4	360.6	81.6	80.0	4.8	4.9	6%	6%	86.43	84.89	6.1	6.2	7.0	7.0	5.7	5.6
15	21.8	20.0	364.5	368.7	83.2	81.8	3.1	3.1	4%	4%	86.28	84.86	6.2	6.3	7.0	7.0	5.6	5.6
16	22.5	12.5	316.0	317.6	71.2	69.4	16.0	16.2	22%	23%	87.24	85.67	5.4	5.4	6.0	6.0	5.7	5.6
17	22.5	13.6	322.3	324.1	72.6	70.9	14.3	14.5	20%	20%	86.94	85.31	5.5	5.6	6.0	6.0	5.7	5.6
18	22.5	14.6	328.5	330.2	74.0	72.2	12.6	12.9	17%	18%	86.65	85.06	5.6	5.7	6.0	6.0	5.7	5.6
19	22.5	15.7	334.8	337.2	75.4	73.7	10.9	11.1	14%	15%	86.36	84.83	5.7	5.8	6.0	6.0	5.7	5.6
20	22.5	16.8	341.8	344.4	77.0	75.3	9.2	9.4	12%	12%	86.26	84.66	5.9	5.9	6.0	6.0	5.6	5.5
21	22.5	17.9	348.8	351.8	78.6	76.9	7.5	7.6	10%	10%	86.16	84.53	6.0	6.0	6.0	7.0	5.6	5.5
22	22.5	18.9	355.9	358.9	80.2	78.5	5.8	6.0	7%	8%	86.03	84.46	6.1	6.2	7.0	7.0	5.6	5.5
23	22.5	20.0	362.9	366.9	81.8	80.2	4.1	4.2	5%	5%	85.89	84.42	6.2	6.3	7.0	7.0	5.6	5.5
24	23.1	12.5	315.2	316.7	70.1	68.4	16.9	17.0	24%	25%	87.02	85.44	5.4	5.4	6.0	6.0	5.7	5.6
25	23.1	13.6	321.5	323.2	71.5	69.8	15.2	15.3	21%	22%	86.72	85.07	5.5	5.5	6.0	6.0	5.7	5.6
26	23.1	14.6	327.0	329.2	72.7	71.1	13.5	13.7	19%	19%	86.22	84.79	5.6	5.6	6.0	6.0	5.6	5.5
27	23.1	15.7	334.0	336.1	74.3	72.6	11.8	12.0	16%	16%	86.14	84.55	5.7	5.8	6.0	6.0	5.6	5.5
28	23.1	16.8	340.2	343.2	75.7	74.1	10.2	10.2	13%	14%	85.86	84.36	5.8	5.9	6.0	6.0	5.6	5.5
29	23.1	17.9	347.3	350.6	77.3	75.7	8.5	8.5	11%	11%	85.76	84.22	6.0	6.0	6.0	7.0	5.6	5.5
30	23.1	18.9	354.3	357.5	78.8	77.2	6.8	6.9	9%	9%	85.64	84.13	6.1	6.1	7.0	7.0	5.6	5.5
31	23.1	20.0	361.3	365.4	80.4	78.9	5.1	5.2	6%	7%	85.50	84.08	6.2	6.3	7.0	7.0	5.6	5.5
32	23.8	12.5	314.5	315.8	69.1	67.2	17.7	18.0	26%	27%	86.80	85.20	5.4	5.4	6.0	6.0	5.7	5.6
33	23.8	13.6	319.9	322.2	70.3	68.6	16.0	16.2	23%	24%	86.29	84.80	5.5	5.5	6.0	6.0	5.6	5.6
34	23.8	14.6	326.2	328.1	71.6	69.8	14.4	14.7	20%	21%	86.01	84.50	5.6	5.6	6.0	6.0	5.6	5.5
35	23.8	15.7	332.4	334.9	73.0	71.3	12.7	13.0	17%	18%	85.73	84.24	5.7	5.7	6.0	6.0	5.6	5.5
36	23.8	16.8	339.5	341.9	74.6	72.8	11.1	11.3	15%	15%	85.65	84.04	5.8	5.9	6.0	6.0	5.6	5.5
37	23.8	17.9	345.7	349.2	75.9	74.3	9.4	9.6	12%	13%	85.36	83.88	5.9	6.0	6.0	6.0	5.6	5.5
38	23.8	18.9	352.7	356.0	77.5	75.8	7.8	8.0	10%	11%	85.25	83.77	6.0	6.1	7.0	7.0	5.6	5.5
39	23.8	20.0	360.5	363.8	79.2	77.4	6.1	6.2	8%	8%	85.30	83.69	6.2	6.2	7.0	7.0	5.6	5.5
40	24.4	12.5	313.7	315.1	68.0	66.3	18.6	18.8	27%	28%	86.58	85.00	5.4	5.4	6.0	6.0	5.7	5.6
41	24.4	13.6	319.1	321.4	69.2	67.6	16.9	17.0	24%	25%	86.07	84.59	5.5	5.5	6.0	6.0	5.6	5.5
42	24.4	14.6	325.4	327.3	70.6	68.8	15.2	15.5	22%	23%	85.79	84.28	5.6	5.6	6.0	6.0	5.6	5.5
43	24.4	15.7	331.6	334.0	71.9	70.2	13.6	13.8	19%	20%	85.52	84.00	5.7	5.7	6.0	6.0	5.6	5.5
44	24.4	16.8	337.9	340.9	73.3	71.7	12.0	12.1	16%	17%	85.24	83.78	5.8	5.8	6.0	6.0	5.6	5.5
45	24.4	17.9	344.9	348.1	74.8	73.2	10.4	10.4	14%	14%	85.15	83.61	5.9	6.0	6.0	6.0	5.6	5.5
46	24.4	18.9	352.0	354.9	76.3	74.6	8.7	8.9	11%	12%	85.05	83.48	6.0	6.1	7.0	7.0	5.6	5.5
47	24.4	20.0	359.0	362.6	77.8	76.2	7.1	7.2	9%	9%	84.92	83.39	6.2	6.2	7.0	7.0	5.6	5.5
48	25.1	12.5	312.9	314.4	67.0	65.1	19.4	19.7	29%	30%	86.36	84.79	5.4	5.4	6.0	6.0	5.7	5.5
49	25.1	13.6	318.4	320.5	68.2	66.4	17.7	18.0	26%	27%	85.86	84.37	5.5	5.5	6.0	6.0	5.6	5.5
50	25.1	14.6	324.6	326.4	69.5	67.6	16.1	16.4	23%	24%	85.58	84.04	5.6	5.6	6.0	6.0	5.6	5.5
51	25.1	15.7	330.9	333.0	70.8	69.0	14.5	14.8	20%	21%	85.31	83.74	5.7	5.7	6.0	6.0	5.6	5.5
52	25.1	16.8	337.1	339.8	72.2	70.4	12.9	13.1	18%	19%	85.04	83.50	5.8	5.8	6.0	6.0	5.6	5.5
53	25.1	17.9	344.1	346.9	73.7	71.9	11.3	11.4	15%	16%	84.95	83.31	5.9	5.9	6.0	6.0	5.6	5.5
54	25.1	18.9	350.4	353.6	75.0	73.3	9.6	9.9	13%	14%	84.66	83.17	6.0	6.1	7.0	7.0	5.5	5.4
55	25.1	20.0	357.4	361.2	76.5	74.8	8.0	8.2	10%	11%	84.54	83.05	6.1	6.2	7.0	7.0	5.5	5.4
56	25.7	12.5	312.1	313.8	66.0	64.2	20.2	20.4	31%	32%	86.14	84.63	5.4	5.4	6.0	6.0	5.6	5.5
57	25.7	13.6	318.4	319.9	67.3	65.5	18.6	18.7	28%	29%	85.85	84.19	5.5	5.5	6.0	6.0	5.6	5.5
58	25.7	14.6	323.8	325.6	68.4	66.6	16.9	17.2	25%	26%	85.37	83.84	5.6	5.6	6.0	6.0	5.6	5.5
59	25.7	15.7	330.1	332.2	69.8	68.0	15.3	15.6	22%	23%	85.10	83.53	5.7	5.7	6.0	6.0	5.6	5.5
60	25.7	16.8	336.3	338.9	71.1	69.4	13.8	13.9	19%	20%	84.83	83.28	5.8	5.8	6.0	6.0	5.6	5.5
61	25.7	17.9	342.6	345.9	72.4	70.8	12.2	12.3	17%	17%	84.56	83.07	5.9	5.9	6.0	6.0	5.5	5.4
62	25.7	18.9	349.6	352.5	73.9	72.1	10.6	10.8	14%	15%	84.46	82.92	6.0	6.0	6.0	7.0	5.5	5.4
63	25.7	20.0	356.6	360.1	75.4	73.7	9.0	9.1	12%	12%	84.34	82.79	6.1	6.2	7.0	7.0	5.5	5.4

Double flash 1600 kJ/kg
T_reservoir: 330 °C

	P_HP	P_LP	Mass flow of wells		m_dot_HP_steam_calc		m_dot_LP_steam_calc		Percentage additional steam		Msteam		Wells required		Number of wells		SSC	
			PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES	PYTH	EES
	bara	bara	kg/s		kg/s		kg/s		kg/s		kg/s		wells		wells		ton/h/MWnet	
0	21	13	237.1	237.8	77.9	76.3	9.3	9.4	12%	12%	87.23	85.73	4.1	4.1	5.0	5.0	5.7	5.6
1	21	14	240.2	241.1	79.0	77.4	8.1	8.2	10%	11%	87.06	85.55	4.1	4.1	5.0	5.0	5.7	5.6
2	21	15	243.4	244.1	80.0	78.4	6.9	7.1	**9%**	**9%**	86.91	85.43	4.2	4.2	5.0	5.0	5.7	5.6
3	21	16	246.5	247.6	81.0	79.5	5.8	5.9	**7%**	**7%**	86.78	85.34	4.2	4.2	5.0	5.0	5.7	5.6
4	21	17	249.6	251.0	82.0	80.6	4.6	4.7	**6%**	**6%**	86.67	85.27	4.3	4.3	5.0	5.0	5.7	5.6
5	21	18	253.5	254.6	83.3	81.7	3.5	3.5	**4%**	**4%**	86.83	85.24	4.3	4.4	5.0	5.0	5.7	5.6
6	21	19	256.6	257.9	84.4	82.8	2.4	2.4	**3%**	**3%**	86.73	85.23	4.4	4.4	5.0	5.0	5.7	5.6
7	21	20	259.8	261.6	85.4	84.0	1.3	1.3	**1%**	**2%**	86.63	85.26	4.5	4.5	5.0	5.0	5.7	5.6
8	22	13	236.3	236.9	77.1	75.5	9.9	9.9	13%	13%	86.92	85.41	4.1	4.1	5.0	5.0	5.7	5.6
9	22	14	239.5	240.1	78.1	76.5	8.7	8.7	11%	11%	86.76	85.22	4.1	4.1	5.0	5.0	5.7	5.6
10	22	15	242.6	243.2	79.1	77.5	7.5	7.6	**10%**	**10%**	86.61	85.08	4.2	4.2	5.0	5.0	5.7	5.6
11	22	16	245.7	246.5	80.1	78.5	6.4	6.4	**8%**	**8%**	86.49	84.96	4.2	4.2	5.0	5.0	5.7	5.6
12	22	17	248.8	250.0	81.1	79.6	5.2	5.3	**6%**	**7%**	86.38	84.89	4.3	4.3	5.0	5.0	5.7	5.6
13	22	18	252.0	253.5	82.1	80.8	4.1	4.1	**5%**	**5%**	86.27	84.85	4.3	4.3	5.0	5.0	5.6	5.6
14	22	19	255.1	256.8	83.2	81.8	3.0	3.0	**4%**	**4%**	86.18	84.84	4.4	4.4	5.0	5.0	5.6	5.6
15	22	20	259.0	260.4	84.4	83.0	1.9	1.9	**2%**	**2%**	86.35	84.84	4.4	4.5	5.0	5.0	5.7	5.6
16	22	13	235.5	236.0	76.2	74.5	10.4	10.6	14%	14%	86.62	85.05	4.0	4.0	5.0	5.0	5.7	5.6
17	22	14	238.7	239.1	77.2	75.5	9.3	9.3	12%	12%	86.46	84.84	4.1	4.1	5.0	5.0	5.7	5.6
18	22	15	241.8	242.1	78.2	76.4	8.1	8.3	10%	11%	86.32	84.69	4.1	4.2	5.0	5.0	5.6	5.5
19	22	16	244.9	245.4	79.2	77.5	7.0	7.1	**9%**	**9%**	86.19	84.56	4.2	4.2	5.0	5.0	5.6	5.5
20	22	17	248.0	248.8	80.2	78.6	5.9	5.9	**7%**	**8%**	86.09	84.47	4.3	4.3	5.0	5.0	5.6	5.5
21	22	18	251.2	252.3	81.2	79.6	4.7	4.8	**6%**	**6%**	85.99	84.42	4.3	4.3	5.0	5.0	5.6	5.5
22	22	19	254.3	255.5	82.3	80.7	3.6	3.7	**4%**	**5%**	85.90	84.40	4.4	4.4	5.0	5.0	5.6	5.5
23	22	20	257.4	259.1	83.3	81.8	2.5	2.6	**3%**	**3%**	85.81	84.39	4.4	4.4	5.0	5.0	5.6	5.5
24	23	13	234.8	235.2	75.3	73.7	11.0	11.1	15%	15%	86.32	84.77	4.0	4.0	5.0	5.0	5.7	5.5
25	23	14	237.9	238.3	76.3	74.7	9.8	9.9	13%	13%	86.16	84.54	4.1	4.1	5.0	5.0	5.6	5.5
26	23	15	241.0	241.3	77.3	75.6	8.7	8.8	11%	12%	86.02	84.38	4.1	4.1	5.0	5.0	5.6	5.5
27	23	16	243.4	244.5	78.1	76.6	7.5	7.6	**10%**	**10%**	85.63	84.24	4.2	4.2	5.0	5.0	5.6	5.5
28	23	17	246.5	247.9	79.1	77.7	6.4	6.5	**8%**	**8%**	85.53	84.14	4.2	4.2	5.0	5.0	5.6	5.5
29	23	18	250.4	251.3	80.4	78.7	5.3	5.3	**7%**	**7%**	85.70	84.07	4.3	4.3	5.0	5.0	5.6	5.5
30	23	19	253.5	254.5	81.4	79.7	4.3	4.3	**5%**	**5%**	85.61	84.04	4.3	4.4	5.0	5.0	5.6	5.5
31	23	20	256.6	258.0	82.4	80.8	3.2	3.2	**4%**	**4%**	85.53	84.02	4.4	4.4	5.0	5.0	5.6	5.5
32	24	13	234.0	234.3	74.5	72.8	11.5	11.7	15%	16%	86.02	84.46	4.0	4.0	5.0	5.0	5.6	5.5
33	24	14	237.1	237.4	75.5	73.7	10.4	10.5	14%	14%	85.87	84.21	4.1	4.1	5.0	5.0	5.6	5.5
34	24	15	240.2	240.3	76.5	74.6	9.2	9.4	12%	13%	85.73	84.04	4.1	4.1	5.0	5.0	5.6	5.5
35	24	16	242.6	243.5	77.2	75.6	8.1	8.3	10%	11%	85.34	83.90	4.2	4.2	5.0	5.0	5.6	5.5
36	24	17	245.7	246.8	78.2	76.7	7.0	7.1	**9%**	**9%**	85.24	83.78	4.2	4.2	5.0	5.0	5.6	5.5
37	24	18	248.8	250.2	79.2	77.7	5.9	6.0	**7%**	**8%**	85.15	83.69	4.3	4.3	5.0	5.0	5.6	5.5
38	24	19	252.0	253.3	80.2	78.7	4.8	5.0	**6%**	**6%**	85.07	83.65	4.3	4.3	5.0	5.0	5.6	5.5
39	24	20	255.9	256.8	81.5	79.8	3.8	3.9	**5%**	**5%**	85.25	83.61	4.4	4.4	5.0	5.0	5.6	5.5
40	24	13	233.2	233.7	73.7	72.0	12.1	12.2	16%	17%	85.73	84.21	4.0	4.0	4.0	5.0	5.6	5.5
41	24	14	236.3	236.7	74.7	73.0	10.9	11.0	15%	15%	85.57	83.95	4.1	4.1	5.0	5.0	5.6	5.5
42	24	15	239.5	239.6	75.7	73.8	9.8	9.9	13%	13%	85.44	83.77	4.1	4.1	5.0	5.0	5.6	5.5
43	24	16	241.8	242.7	76.4	74.8	8.7	8.8	11%	12%	85.06	83.60	4.1	4.2	5.0	5.0	5.6	5.5
44	24	17	244.9	246.0	77.4	75.8	7.6	7.7	**10%**	10%	84.96	83.49	4.2	4.2	5.0	5.0	5.6	5.5
45	24	18	248.0	249.3	78.4	76.9	6.5	6.5	**8%**	**9%**	84.87	83.39	4.3	4.3	5.0	5.0	5.6	5.5
46	24	19	251.2	252.4	79.4	77.8	5.4	5.5	**7%**	**7%**	84.79	83.33	4.3	4.3	5.0	5.0	5.6	5.5
47	24	20	254.3	255.8	80.3	78.9	4.4	4.4	**5%**	**6%**	84.72	83.29	4.4	4.4	5.0	5.0	5.5	5.5
48	25	13	232.4	232.9	72.9	71.2	12.6	12.8	17%	18%	85.43	83.92	4.0	4.0	4.0	4.0	5.6	5.5
49	25	14	235.5	235.9	73.8	72.1	11.4	11.6	15%	16%	85.28	83.66	4.0	4.0	5.0	5.0	5.6	5.5
50	25	15	238.7	238.7	74.8	73.0	10.3	10.5	14%	14%	85.16	83.47	4.1	4.1	5.0	5.0	5.6	5.5
51	25	16	241.0	241.9	75.6	73.9	9.2	9.4	12%	13%	84.77	83.30	4.1	4.1	5.0	5.0	5.5	5.5
52	25	17	244.1	245.1	76.5	74.9	8.1	8.3	11%	11%	84.68	83.16	4.2	4.2	5.0	5.0	5.5	5.4
53	25	18	247.3	248.3	77.5	75.9	7.1	7.2	**9%**	**9%**	84.60	83.05	4.2	4.3	5.0	5.0	5.5	5.4
54	25	19	250.4	251.4	78.5	76.8	6.0	6.2	**8%**	**8%**	84.52	82.98	4.3	4.3	5.0	5.0	5.5	5.4
55	25	20	253.5	254.8	79.5	77.9	5.0	5.1	**6%**	**7%**	84.45	82.93	4.3	4.4	5.0	5.0	5.5	5.4
56	26	13	232.4	232.3	72.3	70.5	13.1	13.2	18%	19%	85.43	83.71	4.0	4.0	4.0	4.0	5.6	5.5
57	26	14	234.8	235.3	73.0	71.4	12.0	12.1	16%	17%	85.00	83.44	4.0	4.0	5.0	5.0	5.6	5.5
58	26	15	237.9	238.1	74.0	72.2	10.9	11.0	15%	15%	84.87	83.22	4.1	4.1	5.0	5.0	5.6	5.4
59	26	16	240.2	241.2	74.7	73.1	9.8	9.9	13%	14%	84.49	83.04	4.1	4.1	5.0	5.0	5.5	5.4
60	26	17	243.4	244.3	75.7	74.1	8.7	8.8	11%	12%	84.40	82.89	4.2	4.2	5.0	5.0	5.5	5.4
61	26	18	246.5	247.6	76.7	75.1	7.6	7.7	**10%**	10%	84.32	82.78	4.2	4.2	5.0	5.0	5.5	5.4
62	26	19	249.6	250.5	77.7	76.0	6.6	6.7	**8%**	**9%**	84.25	82.70	4.3	4.3	5.0	5.0	5.5	5.4
63	26	20	252.7	253.9	78.6	77.0	5.6	5.6	**7%**	**7%**	84.18	82.64	4.3	4.4	5.0	5.0	5.5	5.4

PYTH: Python; EES: Engineering Equation Solver