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STEAM AND BRINE GATHERING SYSTEM DESIGN FOR CACHAÇOS-LOMBADAS NEW PRODUCTION WELLS IN RIBEIRA GRANDE GEOTHERMAL FIELD

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ABSTRACT

The aim of this study is the development of a conceptual design of a steam and brine gathering system for the Cachaços-Lombadas new production wells and the separation station equipment. The typical configuration in Ribeira Grande geothermal field, consisting of a vertical steam separator and a brine accumulator tank for each well, is evaluated and compared to a single horizontal gravity separator serving all wells.

This study establishes design criteria for the pipe and separation station equipment sizing to try to solve some operational difficulties of existing wells in the field. The steam and brine design flow rates are assumed to be similar to the last make up well drilled in Cachaços-Lombadas, CL7, which is the most productive well of the field, having the expected total production of around 120 ton/h of saturated steam and 450 ton/h of brine. Aiming to minimize steam and brine gathering system piping pressure losses, a maximum velocity criterion of 30 m/s for steam and 1 m/s for brine was established. It was found that the gathering system nominal pipe sizes are DN 700 for steam and DN 400 for brine. The calculated pressure loss in the estimated 1400 m pipe route from the well pad to the plant is 0.7 bar in the steam line and 0.6 bar in the brine line. Some of the wells in Cachaços-Lombadas sector are subject to wellhead pressure fluctuations which results in flow rate changes that cannot be managed by the separation station equipment, namely the brine accumulator tank. Therefore, each accumulator tank is sized to act as a buffer to accommodate possible fluctuations coming up in the well. It has also been noticed that the steam quality decreases at the outlet of the steam separators in the well field, maybe due to undersize. To minimize this occurrence, the separator annular cross section area is sized to keep the upward steam velocity below 2 m/s and so enhance the gravity role in the separation efficiency.

The common horizontal gravity separator for the three wells is sized accordingly to the criteria' established by Verkís for Icelandic geothermal power plants. Its higher volume is better suited to accommodate possible fluctuations while its efficiency is less dependent on the fluid inlet velocity which allows to operate the three wells in any combination possible. The overall project cost is estimated to be € 6,100,000

while differences between installing three individual vertical separator stations and one single horizontal gravity separator is about € 92,500, which is not relevant or decisive in the overall estimated cost but the evaluation of technical matters between both types of separation shall be developed in a later stage of the project.

1. INTRODUCTION

1.1 Project background

The Azores archipelago is an autonomous region of Portugal, located in the Atlantic Ocean, about 1,600 km from the mainland (Figure 1). The island group consists of 9 individual islands with asymmetric small-scale independent power distribution systems which makes an interconnection between islands technically unfeasible (Rangel et al., 2011).

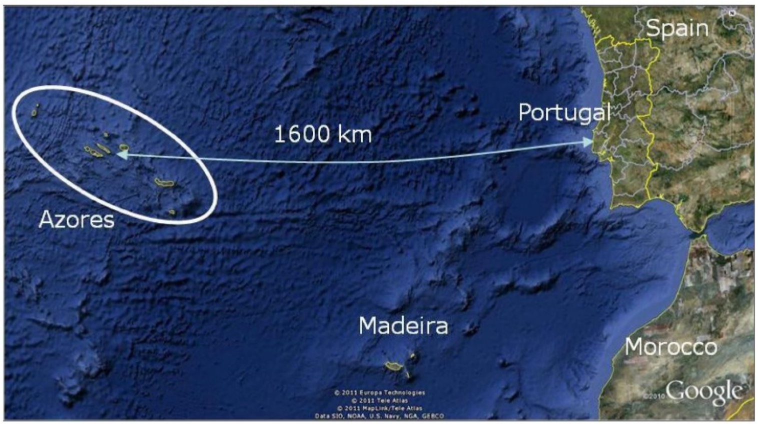

FIGURE 1: Location of Azores archipelago in the Atlantic Ocean (Google Earth)

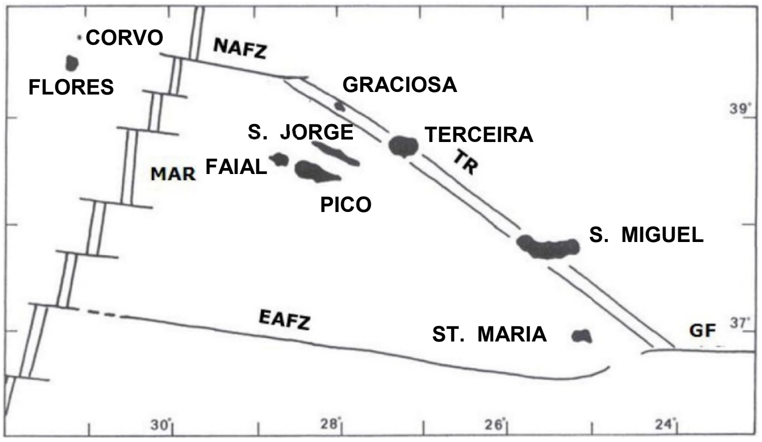

FIGURE 2: Main tectonic structures in Azores region: MAR – Mid Atlantic Ridge; NAFZ – Northern Azores Fault Zone; EAFZ – Eastern Azores Fault Zone; TR – Terceira Rift; GF - GLÓRIA Fault (Rangel et al., 2011)

The Azores islands are aligned following a WNW-ESE trend and emerge above the sea in the North Atlantic Ocean from a submarine topographic high designated as the "Azores Plateau" which is marked by the bathymetric line of 2,000 metres. The archipelago lies where the American, Euro-Asian and African lithospheric plates meet at the "Azores Triple Junction" (Figure 2). As result of this complex geotectonic setting, seismic and volcanic activity is frequent in the region (Rangel et al., 2011).

In six of the nine islands of the archipelago geothermal resources are available. However, due to the existing asymmetries between the islands in terms of population and energy demand, especially noticing that the population of São Miguel and Terceira is about 80% of the total population of the Azores, which is approximately 250,000 inhabitants, only in the largest islands the utilization of the geothermal resource for electricity production is economically feasible.

The power utility company of the Azores is Electricidade dos Açores (EDA) which manages all the production, transportation and distribution of electricity in the region. The archipelago is dependent on fossil fuel for electricity production. In 2014, the energy mix in the archipelago was 64% from fossil fuels (fuel oil and diesel) and 36% from renewable resources (geothermal, hydro, wind and biogas) of which geothermal energy has the highest percentage with 23% of the total energy production (EDA, 2014).

EDA Renováveis is a subsidiary company of EDA and exploits the Ribeira Grande geothermal field located on the north flank of the Fogo volcano in Ribeira Grande city, São Miguel Island (Figure 3) for electricity production. The Ribeira Grande high temperature geothermal field is liquid-dominated with a maximum measured reservoir temperature of up to 245°C. It is composed by three sectors: Pico Vermelho, Cachaços-Lombadas and Caldeiras.

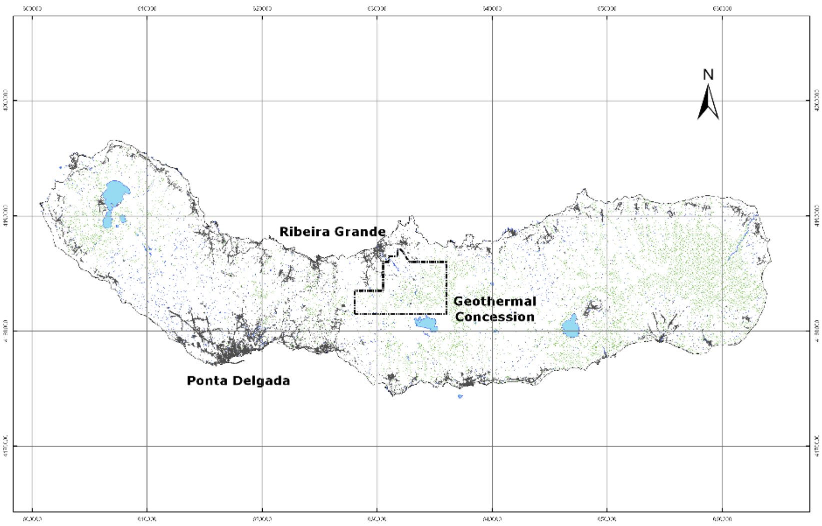

FIGURE 3: São Miguel Island (provided by EDA Renováveis)

The exploitation of the Ribeira Grande geothermal field dates back to 1980 in Pico Vermelho sector and presently only Cachaços-Lombadas and Pico Vermelho sectors are being exploited for electricity production. The concession area for the exploitation of the geothermal resource is identified in Figure 4 as a dotted line.

In the Cachaços-Lombadas sector, at the Ribeira Grande geothermal power plant, four two-phase binary units with a total rated gross power of 14.5 MWe at the generators terminals are installed which are supplied by steam and brine from 4 production wells, while all condensate and cooled brine is returned to the geothermal reservoir using 2 injection wells. After the deactivation of a back-pressure steam turbine of 3 MWe in the Pico Vermelho sector which was used from 1980 until 2005, a new two-phase binary cycle power plant was installed with one generator unit of 13 MWe gross power at the generators terminals. The steam and brine are supplied by 5 production wells and the condensate and cooled brine is completely reinjected using 3 injection wells.

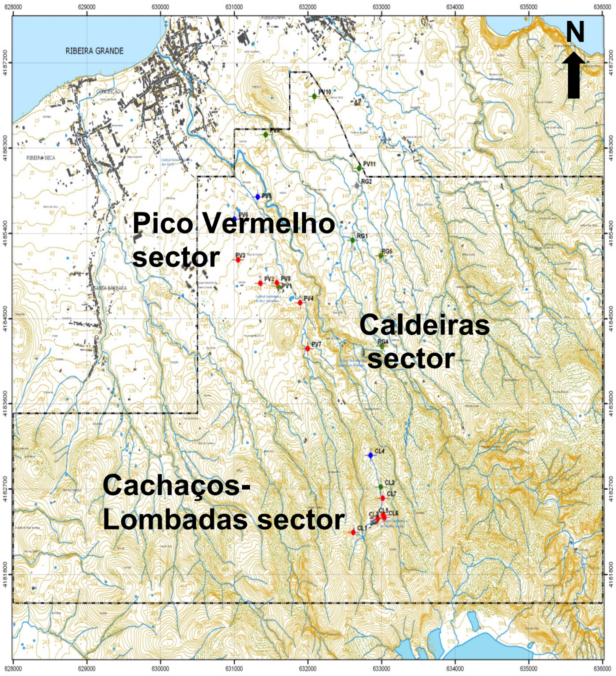

FIGURE 4: Ribeira Grande geothermal field

The combined electrical production of Pico Vermelho and Ribeira Grande plants in 2014 was 183 GWh which represented 44% of São Miguel electrical grid demand. (EDA Renováveis, 2014). These high geothermal penetration values, added to a share of 10% from wind and hydro power plants in operation in São Miguel (EDA, 2014), is an evidence of the strategy of the Regional Government to increase the contribution of renewables sources in the energy mix, while minimizing the dependency on fossil fuel and acting on the sustainable development of the Azores.

1.2 Project motivation

The Ribeira Grande geothermal plant platform is located in an area bounded by two creeks. This geographical feature has been restraining the locations for drilling make-up wells. In fact, only two production wells were drilled from 2005 until present and consequently the power plant has not been able to run continuously at the rated gross power of 14.5 MWe. Therefore, due to the lack of geothermal fluid available, the Ribeira Grande geothermal power plant has been generating energy at an average net power of 9 MWe (based on the unit's operating hours).

The present area of interest, the so-called "Mata do Botelho", has been identified as a potential upflow zone of the geothermal field in which a well pad sized to drill up to 3 make up wells is now planned to be constructed, following EDA Renováveis decision to go forward with the evaluation of this site in order to put the plant operating at the rated gross power.

To access this new drilling site important preliminary civil works have to be executed such as building a new access road to allow the mobilization of the drilling rig and all auxiliary equipment. The project includes the drilling and testing of one production well and, if found productive, two more wells will be drilled. In the second case, a bridge of 6 m width and a length of 70 m will be required to overpass a 57 m deep creek. In addition, a new access road will be constructed to access the power plant platform terrain.

The final stage of the project will be the establishment of a connection of the make-up wells to the plant's steam and brine headers, the design of the separation stations and the gathering system with optimized alternative solutions. Here the already existing solutions implemented by the plant's original designer, in terms of piping material specifications and pipe supports criteria should be kept in mind.

1.3 Project objectives

The aim of this study is the development of a conceptual design of the gathering piping systems and separation station. The project objectives are the following:

- Configuration study of the separation station and gathering piping system;
- Preliminary design of the separation station(s);
- Selection of two-phase flow and steam and brine single flow pipe diameters;
- Preliminary calculation of pipe loads, pipe supports distances and expansion loops;
- Calculation of steam and brine piping pressure losses;
- Sizing of the brine booster pumps; and
- Cost estimation of the project.

The well pad for the new production wells is expected to be located at 430 m a.s.l., while the power plant platform is at 524 m a.s.l., resulting in an elevation difference of 94 m. Figure 5 shows the location of power plant, all existing wells and the "Mata do Botelho" area of interest for drilling the new production wells.

The project objectives shall consider the rated values at the power plant steam and brine headers as follows:

- Steam: 4.1 bar(g)
- Brine: 4.6 bar(g)

The new wells' productivity and operational parameters are assumed to be similar as for well CL7 under normal operation conditions. CL7 is the most recent make-up well which was drilled in 2010 and has demonstrated a stable and productive operation regime. The well operation parameters are as follows:

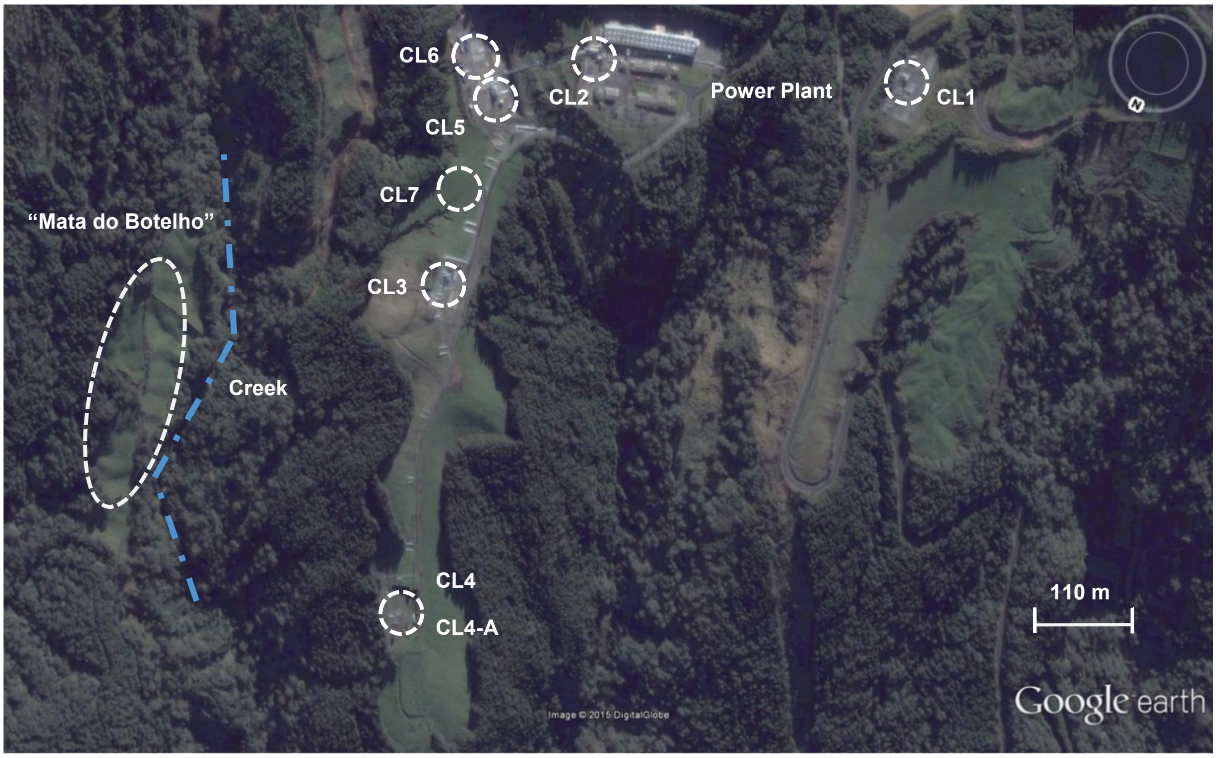

FIGURE 5: "Mata do Botelho" location (Google Earth)

- Wellhead pressure: 11 bar(g)
- Enthalpy: 1070 kJ/kg
- Steam flow rate: 11 kg/s (40 ton/h)
- Brine flow rate: 42 kg/s (150 ton/h)

The production parameters are considered to be ambitious since no other well drilled in Cachaços-Lombadas has such high production parameters as CL7.

This work presents two configurations of the separation station and gathering system piping, focused on minimizing steam and brine flow pressure losses. All the relevant sizing tasks that are to be developed in the scope of this work will be configured in order to be easily adjustable in case of varying production parameters, in the course of the testing of the first drilled well.

2. SYSTEM DESCRIPTION AND CONFIGURATIONS

Two alternative configurations for the wells' separation station and gathering system were studied and are presented in Figures 6 and 7. In both configurations, the separation will be at the well pad.

Configuration A
The solution is typical for the Ribeira Grande geothermal field wells. Each well is served by a vertical steam separator and a brine accumulator tank connected to a steam and brine header, the later through a booster pump. From the headers, one steam and one brine pipeline transports the geothermal fluids to the power plant. This configuration assures the least interference between wells and minimizes operational difficulties that may arise if the production characteristics of the wells are different while a control valve at each wellhead will allow to adjust the well to the required common separation pressure.

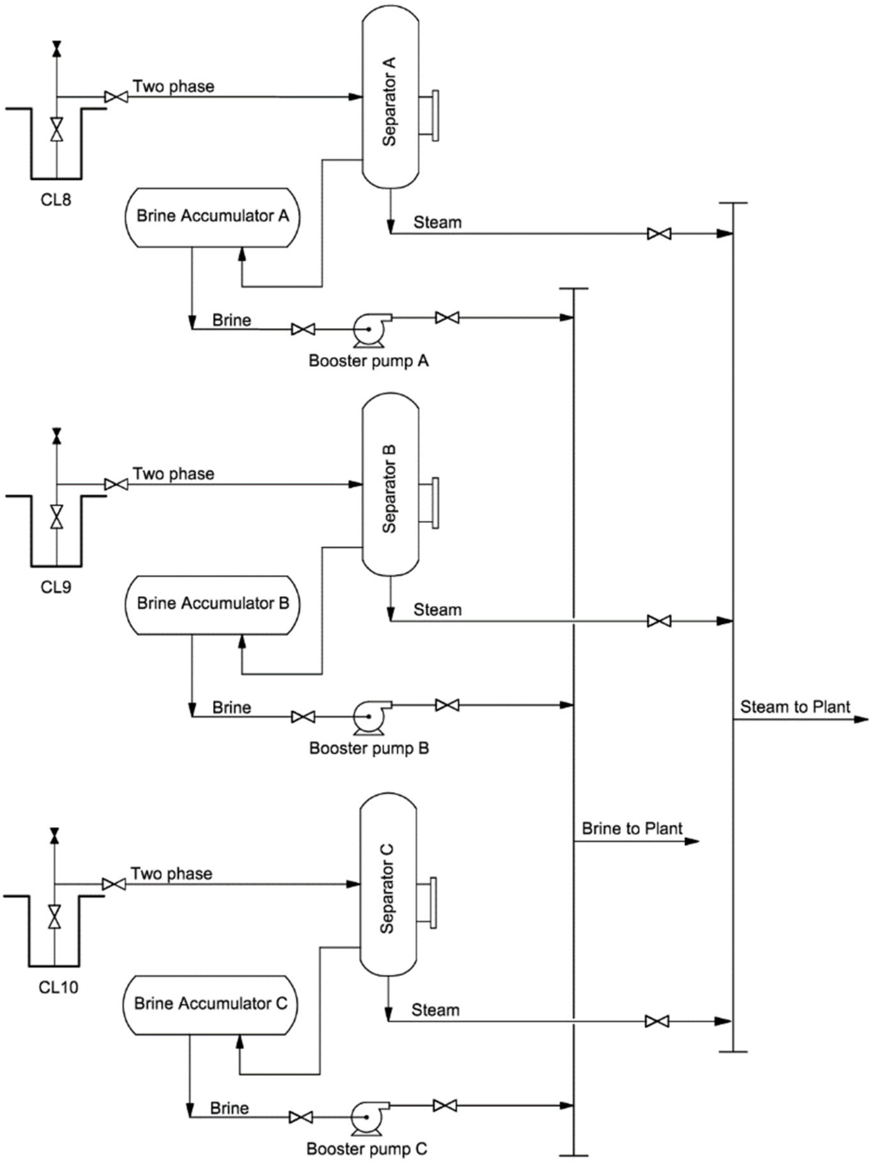

FIGURE 6: Separation station - Configuration A

The brine booster pumps principle of operation is to control the brine level in the accumulator, maintaining a buffer volume in case of sudden changes in the well operation. An important feature is the possibility to maintain continuous monitoring of the production of each well, adding flow measuring devices in each of the steam and brine lines, to satisfy the Ribeira Grande geothermal reservoir management strategy.

Configuration B

The studied solution considers the installation of one horizontal gravity separator as an alternative to the vertical cyclone separator. The operation of the wells should not have any limiting condition and be independent of each other. For a configuration that gathers the two-phase flow from the wells, the horizontal separator offers a more effective operation. It is not dependent on the flow velocity at the separator inlet compared to the vertical separator, for an efficient separation of the vapour and liquid phases.

In comparison to Configuration A, this solution lowers the materials requirements and minimizes the area required for the separation station and piping layout. The control of the separator liquid level can also be performed by the pumps although this requires a careful definition of the operation levels according to the combination of open wells. The main disadvantage of this configuration is that it does not allow a continuous monitoring of the steam and brine flow rates produced from each well. Thus it requires alternative ways to measure the flows such as chemical tracing in the two-phase piping from each well and establishing an admissible period of measurement. Flow measuring devices should also be installed after the separator in the steam and brine piping to measure the combined total flow.

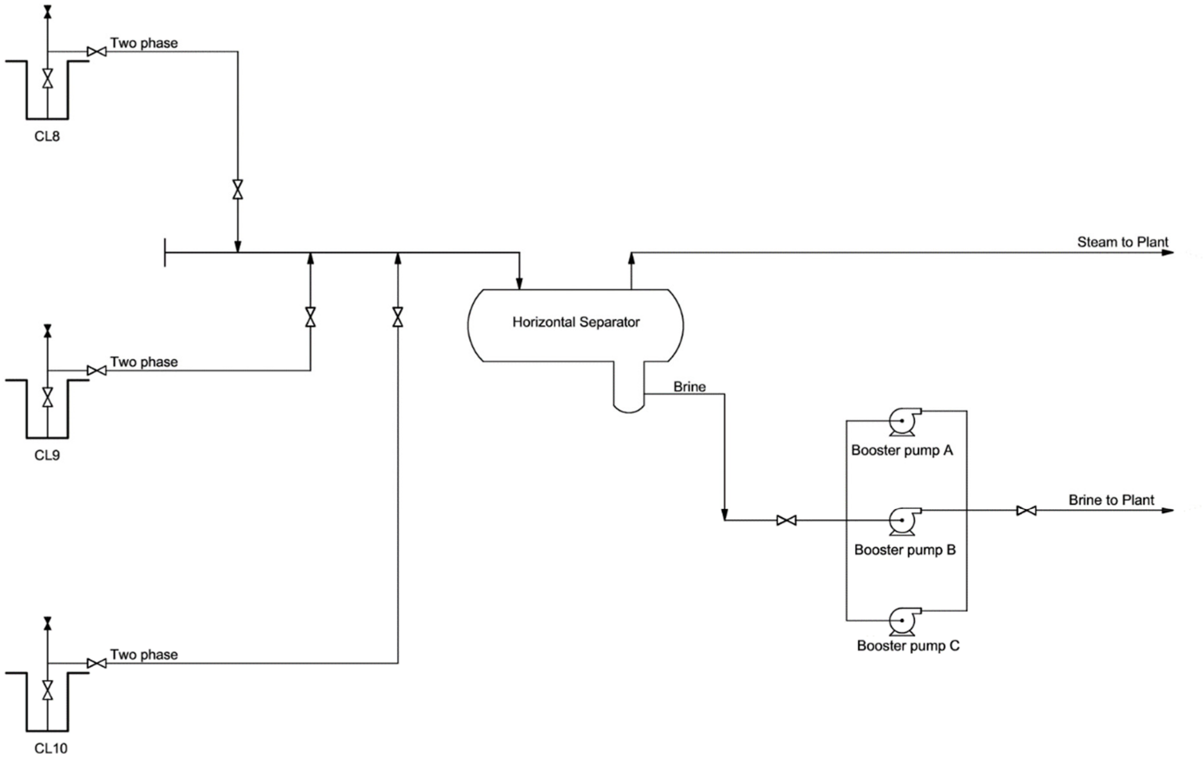

FIGURE 7: Separation station - Configuration B

3. PIPING DESIGN

3.1 Piping route selection

The steam and gathering piping route will follow the access road and bridge to connect the well pad, located at the creek's north margin, to the power plant platform at the south margin. The access road starts at an initial elevation of 430 m a.s.l. at the well pad, has a short downhill section to 428 m until it reaches the bridge section (70 m length). The next section is uphill, with two slopes of 10% and 19%, before the road ends at the final elevation of 462 m.

The steep slope and the expected high liquid fraction in the two-phase flow make it impracticable to run a two-phase flow pipe from the well pad along the access road to minimize total pipe length. Therefore, the two-phase flow will be separated at the well pad and separate steam and brine piping will transport the geothermal fluids to the power plant. From the south margin of the creek, the steam and brine pipes will follow a corridor of existing gathering system piping, duplicating the existing piping flexibility solutions until reaching the power plant platform for the final connection to the headers.

3.2 Piping specifications

The Ribeira Grande geothermal power plant piping specifications require that steam and brine piping material is carbon steel according to ASTM A106 Grade B or equivalent. The pipe thickness is according to ANSI Pipe Schedule STD with thicknesses of all fittings matching the pipe.

Piping
According to ASME B31.1 (ASME, 2007), the required properties of ASTM A106 Grade B steel pipe for the design temperature of 175°C are presented in Table 1.

Pressure vessels
For the separation station pressure vessels construction, the material required is ASTM A516 Grade 70. According to ASME B31.1, the basic allowable stress for the design temperature of 175°C is shown in Table 2.

TABLE 1: A106 Grade B pipe properties

Properties	**Values**
Modulus of elasticity (E_h) (1)	193 GPa
Basic allowable stress (S_h)	118 MPa

(1) For carbon steels: $C \leq 0.3$ %

TABLE 2: A516 Grade 70 plate properties

Properties	**Values**
Basic allowable stress (S_h)	138 MPa

3.3 Design conditions

The original design conditions both for the separated steam and brine gathering system piping, which are considered initial conditions in the scope of this study, are the following:

- Design pressure: 7.5 bar(g)
- Design temperature: 175°C
- Pressure class: 150#

The design conditions may be changed according to the calculated results that will define a preliminary separation pressure and the pump head required to boost the brine from the well pad platform to the power plant.

3.4 Pressure loss and pipe diameter selection

One of the main concerns in the design of the gathering system is the pressure losses in the steam piping from the wellhead to the power plant. The steam pressure drop is a function of the diameter, length and configuration of the steam piping as well as the density and mass flow rate of the steam. Of these, the most critical variable is the pipe diameter (DiPippo, 2007).

Two-phase flow piping
Since the separation will be done at the well pad, the length of the two-phase flow piping is reduced and therefore the expected friction losses were not considered relevant in the pipe diameter calculation. The two-phase flow pipe diameter selection was done based on the expected production of the wells, on the steam superficial velocity that should be kept around 30 m/s and on the recommended design parameters for geothermal vertical separators by Lazalde-Crabtree (Lazalde-Crabtree, 1984).

Separation station single-flow piping
The pressure loss in the single-flow piping from the separation station could not be determined at this time. However, due to its expected short length the pressure loss is not expected to be significant. The pipe diameter calculation will consider only the recommended maximum values for the steam and brine velocities.

Gathering system single-flow piping
For the gathering system single-flow piping, the diameter selection was made in a way to minimize friction losses to establish a low velocity criterion for the steam and brine flows. Also, it was evaluated how the reduction of the pipe diameter penalizes the friction losses, allowing the selection of the final diameter. The pipe length from the well pad to the power plant platform is found to be about 1410 m with 90 bends including expansion loop legs.

In this scenario, a first calculation of the pipe diameters and friction losses for several steam and brine flow velocities was carried out and two alternatives of pipe diameters were identified for steam and brine. In order to calculate the friction head losses, either fluid velocity or pipe diameter should be chosen, using Equations 1 or 2:

$$v = \frac{4\dot{Q}}{\pi d^2} \tag{1}$$

where v = Fluid velocity (m/s);
$\dot{Q}$ = Volumetric flow rate (m^3/s);
d = Inside diameter of pipe (m).

or

$$v = \frac{4\dot{m}}{\pi \rho d^2} \tag{2}$$

where $\dot{m}$ = Mass flow rate (kg/s);
ρ = Fluid density (kg/m^3).

The friction head loss (h_{loss}) in straight pipes, expressed in meter of fluid height, is calculated by the Darcy-Weisbach which is introduced as Equation 3:

$$h_{loss} = \frac{fL}{d}\frac{\bar{v}^2}{2g} \tag{3}$$

where f = Friction factor;
L = Pipe length (m);
$\bar{v}$ = Average fluid velocity (m/s);
g = Gravitational constant (m/s^2).

The friction factor is dependent on the Reynolds number which distinguishes the laminar or turbulent nature of the flow.

The Reynolds number is defined in Equation 4:

$$Re = \frac{\rho v d}{\mu} \tag{4}$$

where μ = Fluid dynamic viscosity (kg/(m s)).

The flow is considered to be laminar when $Re \leq 2100$ and turbulent when $Re > 5000$. The friction factor can then be calculated by the relations given by Equations 5 and 6.

Laminar flow

$$f = \frac{64}{Re} \tag{5}$$

Turbulent flow

The friction factor for turbulent flow is calculated by the Colebrook-White equation:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\epsilon}{3.7d} + \frac{2.51}{Re\sqrt{f}}\right) \tag{6}$$

where ϵ = Pipe absolute roughness (m);
= 0.005 (m).

Pipe fittings like bends and connections, valves and others induces friction head losses that are added to Equation 3, resulting in Equation 7:

$$h_{loss} = \frac{fL}{d}\frac{\bar{v}^2}{2g} + \sum_{i=1}^{n} n_i k \frac{\bar{v}^2}{2g} \tag{7}$$

where k = Loss coefficient of each type of pipe fittings and valves;
n = Number of pipe fittings and valves.

In this study it was not considered relevant to add valves and connections such as t-joints and others for the evaluation of the head loss because of its low number compared to the existing bends. The loss coefficient considered for 90° bends is 0.15 (Krex, 1986).

The recommended steam and brine flow velocities should be according to the following:

$v_{steam} \leq 30$ m/s
$v_{brine} \leq 1$ m/s

The selected diameters where then used to perform a more detailed analysis of the steam pressure loss. The variation of the steam density caused by the pressure drop on the way from the separation station to the plant steam header is analysed, allowing also a prediction of the separation pressure for each steam gathering system pipe diameter.

3.5 Brine booster pumps

Due to the 94 m elevation difference between the well pad and the power plant, pumps are required to boost the brine from the accumulator tank at the well pad to the header at the power plant platform. The pump power P is calculated using the Equation 8:

$$P = \frac{\rho g H Q}{\eta} \tag{8}$$

where H = Head (m);
Q = Volumetric flow rate (m^3/s);
η = Overall efficiency of pump and motor = 0.70.

The pump head can be estimated by applying the Bernoulli Equation between the pump inlet at 1 and the plant brine header at 2, resulting in Equation 9, expressed in height of fluid:

$$\frac{p_1}{\rho g} + \frac{v_1^2}{2g} + z_1 + H - h_{loss_{1-2}} = \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + z_2 \tag{9}$$

where p = Static pressure (Pa);
z = Elevation (m).

The term $\left(\frac{v_2^2}{2g} - \frac{v_1^2}{2g}\right)$ is comparably small because the velocities are similar and can be neglected. Thus Equation 9 can be simplified, resulting in Equation 10:

$$H = \left(\frac{p_2 - p_1}{\rho g}\right) + (z_2 - z_1) + h_{loss_{1-2}} \tag{10}$$

3.6 Pipe thickness

The minimum wall thickness t_m of the gathering system piping for straight pipe is determined under internal pressure in accordance with Equation 11:

$$t_m = \frac{P D_0}{2(SE + Py)} + A \tag{11}$$

where P = Internal design gauge pressure (Pa);
D_0 = Outside diameter of pipe (m);
S = Basic allowable stress (Pa);
E = Weld joint efficiency factor;
y = Temperature coefficient dependence;
A = Additional thickness (m).

For ferritic steels and temperatures of 482°C or below, the *y* coefficient value is 0.4. The weld joint efficiency factor E is included in the allowable stress values given by ASME B31.1 and presented in Tables 1 and 2. Table 1 is applied for a seamless pipe. The additional thickness for corrosion is 3 mm.

The pipe nominal thickness t_n should be chosen according to the power plant piping specifications with a wall thickness corresponding to the STD schedule for each pipe diameter selected.

3.7 Pressure vessel thickness

The thickness of the pressure vessels with internal pressure will also be evaluated through Equation 11. The temperature dependent coefficient y is 0.4, taking the steel and the design temperature in consideration. The weld joint efficiency factor E is assumed to be 1 and the additional thickness for corrosion is 3 mm.

4. SEPARATION STATION DESIGN

4.1 Separation station design

As presented in the possible configurations for the separation station, there are two types of separators, the vertical Webre separator and the horizontal gravity separator. One of the identified operational difficulties of the wells at the Cachaços-Lombadas sector are the fluctuations caused by different inflow zones with different enthalpies. These fluctuations cause changes in the steam and brine flow that has to be dealt by the separation station equipment. The main concern is to avoid dumping brine from the vessels to the surroundings during high peak production periods of brine. The design of the vessels is studied in order to accommodate these excesses and provide the control system the time for the brine booster pumps to react accordingly to the fluctuations.

4.2 Webre separator

Most geothermal fields in the world, like the Ribeira Grande field, are water dominated, producing liquid and steam. The steam can be separated and removed from the mixture before feeding the power plant equipment such as steam turbines where the steam is expanded, or two-phase binary plant heat exchangers.

The most popular steam-water separator is the Webre type. The Webre steam-water separator design is widely used in New Zealand, Philippines, Indonesia, Kenya and elsewhere in the world. It has been very successful with a separation efficiency claimed to be as high as 99.97% (Foong, 2005). In 1961, Bangma ran a series of experiments with a spiral inlet separator. By progressively increasing the inlet velocity of the separator, he demonstrated that the separation efficiency increases until a breakdown velocity is reached. Above this velocity the efficiency deteriorates rapidly. His spiral inlet separator achieves the highest efficiency

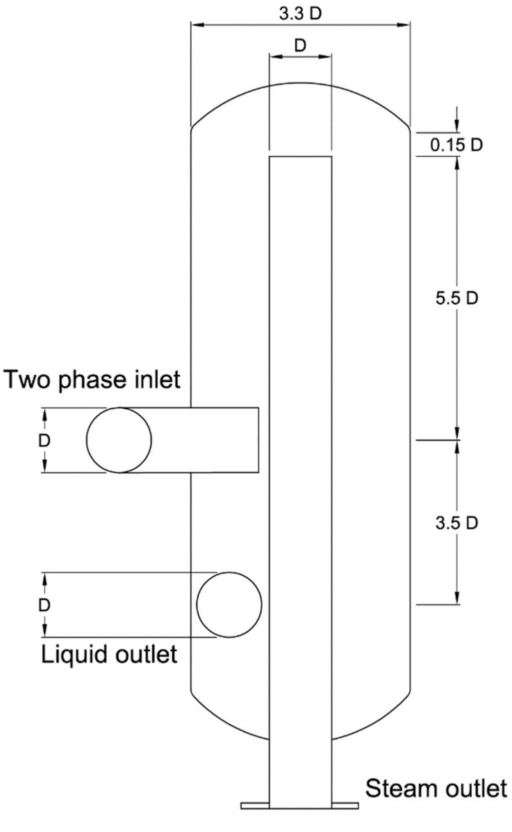

FIGURE 8: Webre separator design parameters (Lazalde-Crabtree, 1984)

when the steam inlet velocity is between 30 and 40 m/s. The breakdown velocity is approximately 45 m/s (Foong, 2005). The Webre type separator is also used in both Pico Vermelho and Ribeira Grande geothermal power plants since 1980.

Lazalde-Crabtree recommended several design parameters for geothermal separators as guidelines. Both geometrical and flow parameters are shown in Figure 8 and Table 3.

TABLE 3: Recommended design parameters for geothermal separators (Lazalde-Crabtree, 1984)

Parameter	Value
Maximum steam velocity at inlet of two-phase inlet pipe	45 m/s
Recommended range of steam velocity at the two-phase inlet pipe	25-40 m/s
Maximum annular upward steam velocity inside cyclone	4.5 m/s
Recommended range of upward annular steam velocity inside cyclone	2.5-4.0 m/s

From operation experience of the Ribeira Grande geothermal field power plants, it was verified that the design of the vertical separator differs from the design parameters recommended by Lazalde-Crabtree. These are the vessel diameter, promoting a lower annular upward steam velocity and the distance between the two-phase inlet and liquid outlet nozzles which are higher in practice.

Based on the experience of operation of the installed separators and considering its more recent design, the parameters for the vertical separators for the new Cachaços-Lombadas wells were adjusted according to Figure 9. The separator general design was according to the following criteria:

1. The inside diameter of the separator is optimized for the annular upward steam velocity inside the cyclone and does not exceed 2 m/s;
2. The brine outlet diameter is selected in order to keep the free flow from the separator to the accumulator in the velocity range from 0.3 to 0.4 m/s. It is calculated for a full cross-sectional flow, thus providing the additional cross-section area for peak brine flow due to well fluctuations.

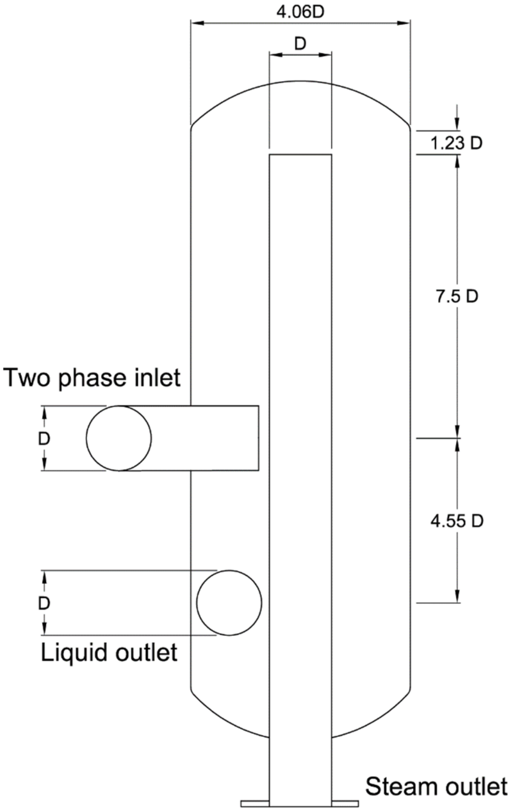

FIGURE 9: Webre separator design parameters for Cachaços-Lombadas

4.3 Brine accumulator tank

The task of the brine accumulator tank is to receive the liquid phase of the mixture after separation, including all salts and other solids of the fluid. In the Ribeira Grande geothermal field, the brine is pumped to the plant main header to feed the binary unit's preheaters. The use of a brine accumulator promotes a stable flow, acting as a buffer to accommodate wells fluctuation to a certain extent. By maintaining its level, it keeps the accuracy of the control of the process within certain limits.

The sizing of the brine accumulator tank, respectively, its approximate volume and initial inside diameter, should be chosen according to the following guidelines:

1. The tank normal operation level corresponds to 120 s of the well brine flow when connected to a single well;

2. The high level of operation is defined as 85% of the full tank height filler. The time required to fill the vessel from normal to high level should be at least 180 seconds;
3. The length of the tank is $L = 4D$, where D is the inside diameter.

4.4 Submergence of pumps and outflow diameter selection for water from a tank with a free surface

The minimum level of brine in the accumulator tank for safe pump operation can be found by the submergence depth S. Submergence of pumps is one parameter which may affect the swirl entering the pump and is certainly important with regard to the formation of strong vortices. The criterion to calculate the minimum submergence depth generally involves the parameter F_B, according to Equation 12, which is akin to the Froude number based on the bell mouth diameter D_B (Clark, 2002):

$$F_B = \frac{V_B}{\sqrt{gD_B}} \qquad (12)$$

where V_B = Average velocity through the plane of the bell mouth (m/s).

The bell mouth diameter corresponds to the brine outlet nozzle inside diameter. The minimum submergence depth to satisfy the criterion is presented in Equation 13:

$$\frac{S}{D_B} > 2.3F_B + 1.0 \qquad (13)$$

4.5 Horizontal gravity separator

A typical illustration of a horizontal gravity separator is shown in Figure 10. The main principle of separation here is gravity, augmented by a set of vane baffle plates fitted to the bottom of the vessel and a horizontal perforated droplet removal plate, or wire mesh screens, at the entrance to the steam exit chamber. The design of the horizontal gravity separator, represented in Figure 11, should be done according to the following requirements given by Jóhannesson and Gudmundsson (2014).

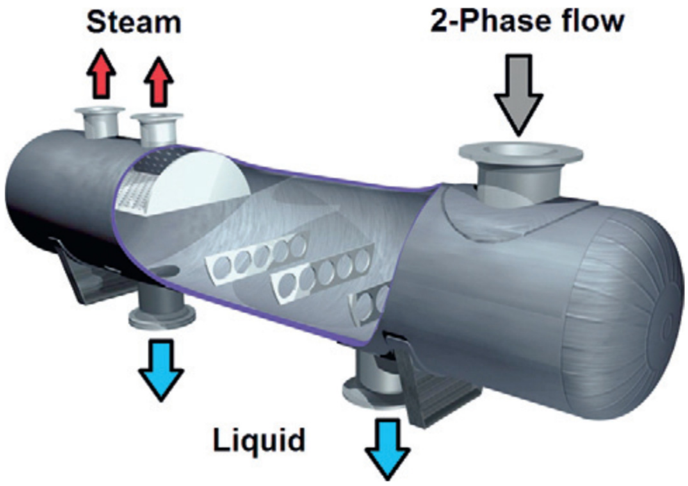

FIGURE 10: Horizontal gravity separator (DiPippo, 2007)

The main design requirements of the horizontal gravity separator are the Chevron type filter cross-section and the vessel bottom brine section. The separated steam will be channelled to the vessel outlet through a Chevron type filter. The filter cross-section area and the steam velocity through the filter are calculated according to Equations 14 and 15:

$$K_f = U_d\sqrt{\frac{\rho_g}{(\rho_l - \rho_g)}} \qquad (14)$$

where K_f = Souders-Brown velocity (m/s) – (0.18 - 0.2 m/s for FLEXCHEVRON);
U_d = Steam velocity through filter (m/s);
ρ_g = Density of the steam phase (kg/m^3);
ρ_l = Density of the liquid phase (kg/m^3).

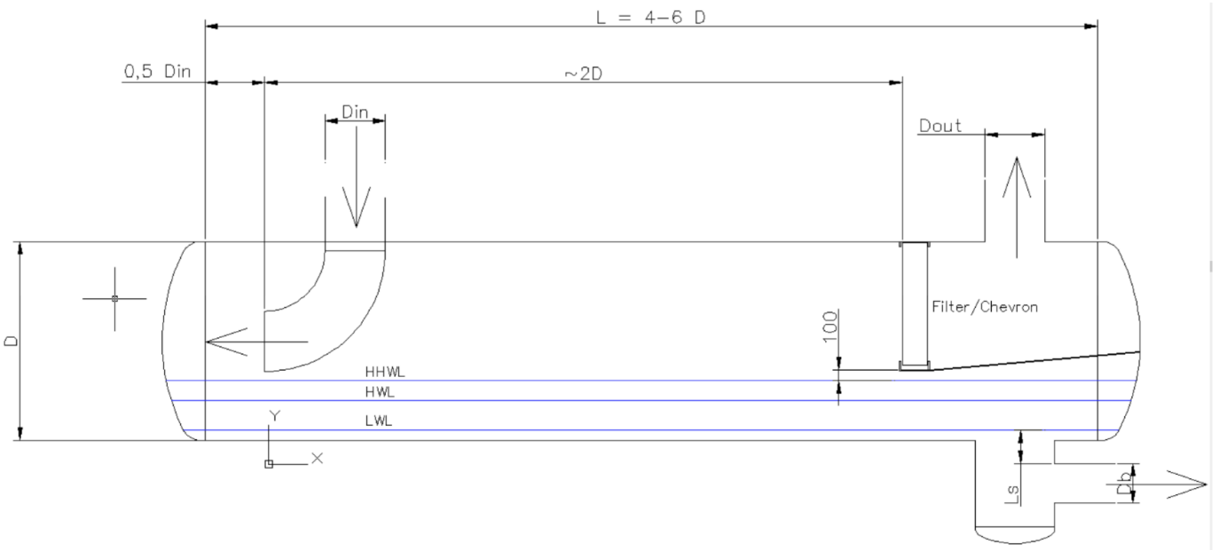

FIGURE 11: Horizontal gravity separator design requirements (Jóhannesson and Gudmundsson, 2014)

$$\dot{V}_g = A_s U_d \tag{15}$$

where ($\dot{V}_g$) = Volumetric steam flow rate (m^3/s);
A_s = Cross-section area of the filter (m^2).

The design of the separator should comply with the following requirements:

1. A_s = 50-60 % of the total cross section;
2. $L = 4 - 6D$;
3. The level of the brine section allows a stable level control. The volume corresponds to the amount of fluid equivalent to 40-120 s of the brine flow, depending on how many wells are connected to the separator. For this study the selected time is 120 s.
4. The high tank should be kept at least 100 mm below the filter section assembly;
5. The time required to fill the vessel from normal to high level should be at least 60 s;
6. Low brine level should correspond to the submergence depth;
7. Brine outflow drip leg diameter should not be less than D/4.

Horizontal separator nozzle schedule
The definition of the horizontal separator nozzles diameters will be done by calculating the inlet and outlet inside diameters that satisfy the established criteria for the maximum steam and brine velocities. Rewriting Equation 2 as a function of the inside diameter, results in Equation 16:

$$d = \sqrt{\frac{4\dot{m}}{v\pi\rho}} \tag{16}$$

The steam and brine velocities should be according to the following:

v_{steam} ≤ 30 m/s
v_{brine} ≤ 1 m/s

4.6 Flow measurements

In the Ribeira Grande geothermal field, the steam and brine flows are continuously monitored by the power plants *Scada* control system. The flow measurement is done by a *pitot tube* type sensor inserted in each well's steam and brine line after the separator. This condition is also satisfied during a simultaneous operation of the wells since each well has its individual separation station. Vortex flowmeters have been found giving good results in the brine service in the Ribeira Grande geothermal power plant. They are considered a valid alternative to the *pitot tube* type which is sensitive to solids that are present in the geothermal fluids.

In the case of a single separator which can be found in all of the wells, the measurement of the steam and brine flow from each well is not possible, only the combined measurement for all wells can be done. Nevertheless, this situation can be surpassed if temporarily only a single well is in operation what allows the measurement of flows produced by this well.

Flow tracer testing can also be an alternative for measuring the steam and brine flows of each well.

5. MECHANICAL STRESS ANALYSIS

5.1 Loads acting on piping

The loads and stresses acting on the piping are separated into two types depending on their duration. The first type is called sustained loads, or loads which can be expected to be present virtually at all times of the plant's operation. Examples would be weight and pressure loadings associated to the piping normal operating conditions. The second type is called occasional loads, or loads which are present during only a small period of the piping system operating time. Examples of occasional loads are high winds, fluid hammer, relief valves discharge, earthquakes and high-energy pipe break (Smith and Van Lann, 1987). The sustained loads to be considered in the frame of this work are the pipe medium and insulation weights. As representatives of the occasional loads wind and seismic activity are analysed.

Most of the formulas presented in this chapter are from Jónsson (2015): *Mechanical design of geothermal power plant*, unless referenced otherwise.

5.1.1 Sustained loads

According to ASME B31.1, the sum of the longitudinal stresses (S_L) due to pressure, weights and other sustained loads does not exceed S_L, as seen in Equation 17:

$$S_L = \frac{PD_0}{4t_n} + \frac{0.75iM_A}{Z} \leq 1.0S_h \tag{17}$$

where t_n = Selected nominal wall thickness (m);
M_A = Sustained bending resulting moment (Nm);
S_h = Basic material allowable stress at maximum (hot) temperature (Pa);
i = Stress intensity factor (the product 0.75i shall never be taken less than 1);
Z = Section modulus $m^3 = \pi/32\ (D_0^4 - d^4)/D_0$.

Vertical sustained loads

The vertical sustained loads are designated as q_{vs} and calculated by Equations 18, 19, 20 and 21:

$$q_{vs} = q_p + q_e + q_v \tag{18}$$

$$q_p = \pi g \rho_s \left(\frac{D_0^2 - d^2}{4}\right) \tag{19}$$

$$q_e = \pi g \rho_e \left(\frac{D_e^2 - d^2}{4}\right) \tag{20}$$

$$q_v = \pi g \rho_v \left(\frac{d^2}{4}\right) \tag{21}$$

where q_p = Pipe weight (N/m);
q_e = Insulation weight and cladding (N/m);
q_v = Medium weight (N/m);
ρ_s = Density of steel (kg/m^3) = 7850 kg/m^3 for carbon steel;
ρ_e = Density of thermal insulation (kg/m^3) = 100 kg/m^3 for mineral stone wool;
D_e = Outside diameter of insulation (m).

The insulation thickness to be considered is 100 mm.

5.1.2 Occasional loads

As per ASME B31.1, the effects of pressure, weight, other sustained loads, and occasional loads must meet the following requirement in Equation 22.

$$\frac{PD_0}{4t_n}+\frac{0.75iM_A}{Z}+\frac{0.75iM_B}{Z}\leq kS_h \tag{22}$$

where M_B = Occasional bending resulting moment (Nm);
k = 1.15 for occasional loads acting no more than 8 hours at any time and no more than 800 hour/year;
= 1.20 for occasional loads acting far no more than 1 hour at any one time and no more than 80 hour/year;
= 1.00 in other cases.

The k factor considered is 1.

The occasional loads acting on the pipe can be divided in vertical and horizontal:

Vertical occasional loads

The vertical occasional load q_{vo} is calculated according to Equations 23, 24 and 25.

$$q_{vo} = q_s + q_{sv} \tag{23}$$

$$q_{sv} = 0.5eq_g \tag{24}$$

$$q_g = q_v + q_p + q_e \tag{25}$$

where q_s = Snow weight (N/m);
q_{sv} = Seismic load (N/m);
e = Seismic factor = 0.30

Snow weight q_s is not a load that needs to be considered at the Ribeira Grande geothermal power plant site. So, the vertical occasional load consists only of seismic load q_{sv}.

Horizontal occasional loads

The horizontal occasional load q_{ho} is the maximum value of wind and seismic load calculated through Equations 26-29.

$$q_{ho} = max\left[q_{w,}\, q_{sh}\right] \tag{26}$$

$$q_w = CpD_e \tag{27}$$

$$p = \frac{v_w^2}{1.6} \tag{28}$$

$$q_{sh} = eq_g \tag{29}$$

where q_w = Wind load (N/m);
q_{sh} = Seismic load (N/m);
C = Form factor, C=0.6 for round pipe;
p = Wind pressure (N/m^2);
v_w = Wind speed (m/s) = 36 m/s (130 km/h).

The seismic factor and wind speed v_w are empirical values based on recent geothermal power plant projects in São Miguel Island by EDA Renováveis.

5.2 Bending moments

The bending moments of the pipeline are calculated making the assumption that the pipe is a simple supported beam with a length L_s between supports and with uniform load over the entire span. This will give us a conservative figure for distance evaluation between supports. In this case, the bending moment is maximal in the middle of the pipeline and so the resulting sustained and occasional moments are according to Equations 30 and 31 (Krex, 1986).

$$M_A = \frac{1}{8} q_{vs}\, L_s^2 \tag{30}$$

This study does not consider the existence of sustained concentrated loads between supports such as valve weight that should be analysed case by case in a later more detailed design stage. Nevertheless, the installation of valves increases the resultant sustained bending moment M_A, therefore the length between supports should be reduced in the sections where valves are installed.

$$M_B = \frac{1}{8} \sqrt{q_{vo}^2 + q_{ho}^2}\, L_s^2 \tag{31}$$

where L_s = Length between supports (m).

5.3 Deflection criteria

The length between supports can also be determined by the deflection criterion of the pipeline. For a simple supported beam with the support distance L_s the maximum deflection δ is in the middle of the beam and it is given by Equation 32.

$$\delta = \frac{5}{384} \frac{q L_s^4}{EI} \tag{32}$$

where q = Uniform load (N/m) = q_g;
E = Modulus of Elasticity (Pa);
I = Moment of Inertia (m^4) = π/64 (D_0^4-d^4).

The maximum deflection should be less than $L_s/500$ (Jóhannesson, Th., personal communication) for both steam and brine piping.

5.4 Length between supports L_s

The length between supports L_s is calculated for sustained and occasional loads according to the deflection criterion and the minimum result is selected. For the sustained and occasional loads, the length between supports is the maximum solution of Equations 17 and 22. The final length between supports can be then defined according to the designer criteria and the final sum of the longitudinal stresses S_L can be recalculated.

The calculated length corresponds to a maximum value that satisfies the criteria and the designer is free to choose shorter lengths.

5.5 Thermal expansion of pipeline

Geothermal gathering systems pipelines carry high temperature fluids such as brine and steam. Due to the temperature variations that occur in the piping between installation and operation, materials will be subject to expansion and contraction, designated in general terms as thermal expansion. The expansion ΔL (m) in a pipe with a length L (m) due to a temperature change is given by Equation 33:

$$\Delta L = \alpha L \Delta T \tag{33}$$

where α = Thermal expansion coefficient (1/°C)
ΔT = Temperature variation (°C);

According to ASME B31.1, the thermal expansion coefficient for carbon and low alloy steels in the temperature range of 20-175ºC is 12.5×10^{-6} (1/ºC). A temperature variation of 165ºC is considered, assuming an installation temperature of 10ºC.

Since every piping system has restrictions that prevent free expansion, thermal expansions will always create stresses but, if the system if flexible enough, the expansion may be absorbed without creating undue stresses that may damage the piping system, the supports and the equipment to which the pipes are connected (Smith and Van Lann, 1987). It is then necessary to design a piping system with enough flexibility to absorb the thermal expansion, adding solutions like changes of direction and U shape pipe loop which comprises the expansion loops.

5.6 Flexibility and expansion loops

In the scope of this work two types of expansion loops will be considered that assure the required gathering system piping flexibility, a change in direction and U shaped loops. According to ASME B31.1, all piping should meet the following requirements with respect to flexibility:

1. The piping system duplicates a successfully operating condition or replaces a system with a satisfactory service record;
2. The piping system can be adjudged adequate by comparison with previously analysed systems;
3. The piping system is of uniform size, has not more than two anchors and no intermediate restraints, is designed for essentially noncyclic service (less than 7,000 total cycles), and satisfied the following criterion (Equation 34):

$$\frac{D_0 Y}{(L-U)^2} \leq 208.3 \tag{34}$$

where Y = Resultant displacement between the anchors to be absorbed by the piping (mm);
L = Developed length of pipe along the longitudinal axis (m);
U = Anchor distance (straight line between the anchors) (m).

The gathering system piping of the new wells can be divided into two sections in respect to the flexibility analysis. The first section is new and has a length of almost 400 m. It is located between the well pad and the south margin, where the second section starts in a corridor of existing gathering system piping. The first section meets requirement 3 and the second section meets requirement 1, meeting the empirical values of the existing piping system.

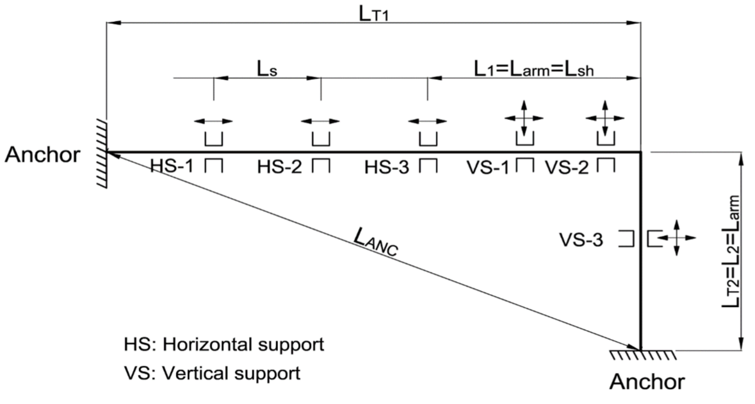

FIGURE 12: Change of direction expansion loop

Change of direction expansion loop

The change of direction expansion loop is exemplified in Figure 12 and meets the requirements of Equation

39 with respect to the arm length. In Jónsson, (2015), the variables of Equation 34 are calculated as follows:

$$Y = \alpha \Delta T \sqrt{L_{T1}^2 + L_{T2}^2} \tag{35}$$

$$L_{ANC} = \sqrt{L_{T1}^2 + L_{T2}^2} \tag{36}$$

$$L = L_1 + L_2 \tag{37}$$

$$U = \sqrt{L_1^2 + L_2^2} \tag{38}$$

Assuming $L_1 = L_2 = L_{arm}$ and substituting the above variables in Equation 34 results in:

$$L_{arm} \geq \sqrt{\frac{D_0 \alpha \Delta T L_{ANC}}{71.48}} \tag{39}$$

The criterion is applied assuming a distance L_{ANC} between the anchors calculated from the expansion arm length L_{arm}.

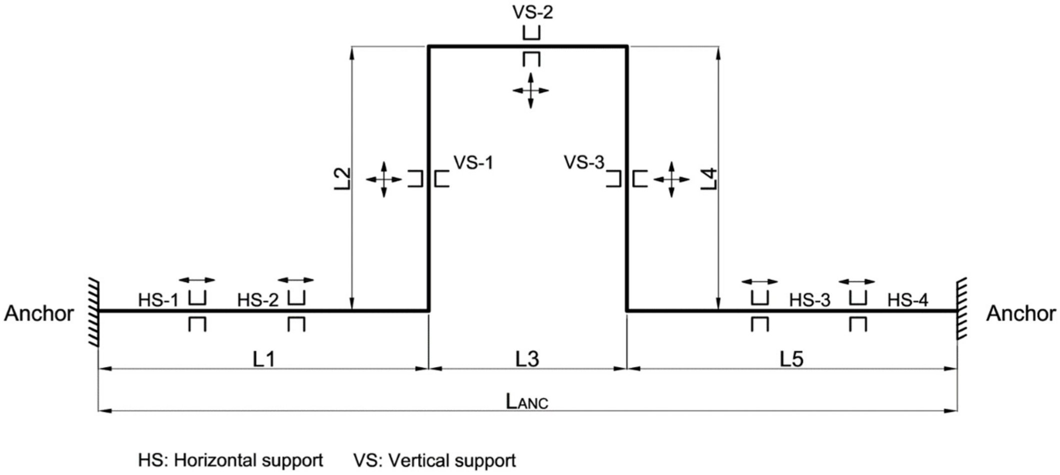

FIGURE 13: U-shape expansion loop

U-shape expansion loop

U-shape expansion loop as shown in Figure 13 can be positioned either vertically or horizontally, depending on the land topology and land use restraints, in the second case for instance, to give passage to animals in the neighbouring pastures. According to Jónsson (2015), U-shape loop sizing can be according to Equation 40:

$$L_2 = \sqrt{\frac{3ED_0\Delta}{S_A}} \tag{40}$$

where Δ = Resultant displacement between anchors (m);
S_A = Allowable stress range (Pa).

Also:

$$L_3 = L_2 \text{ or } L_3 = \frac{L_2}{2}$$

And:

$$S_A = f(1.25S_c + 0.25S_h) \tag{41}$$

where f = cyclic stress range factor ($f \leq 1$), assumed 1;
S_c = Basic material allowable stress at the minimum metal temperature expected (Pa);
S_h = Basic material allowable stress at the maximum metal temperature expected (Pa).

As per ASME B31.1, when S_h is greater than S_L, the difference between them may be added to the term $0.25S_h$ in Equation 41. In this case, the allowable stress range S_A is calculated by Equation 42:

$$S_A = f(1.25S_c + 1.25S_h - S_L) \tag{42}$$

However, this was not considered here.

From Equations 39 and 40 it can be concluded that larger diameter pipes require longer arm loops to accommodate the expansion stresses between anchors, indicating that it is the steam pipe that defines the geometry of the piping system. Typically, vertical loops are limited by the bend leg length since long loops are subject to undesirable wind loads and therefore the distances between anchors have to be shorter. Horizontal loops, if not limited by the land topography and use, have longer bend legs, requiring more supports but allowing longer distance between supports which reduces the total number of loops required.

6. COST ESTIMATE OF IMPLEMENTATION

In the following, the cost estimate of implementation of the steam and brine gathering system piping and separation stations, considering three vertical separators and accumulator tanks or one common horizontal gravity separator, will be presented. All prices presented are in Euro (€). Since the gathering system piping is part of both alternatives, the difference in total cost is the result from the cost of the pressure vessels. We compare three vertical separators and brine accumulator tanks or one horizontal gravity separator.

The cost estimate is based on unit prices of piping, valves and pumps, indicators for steel construction, piping and equipment erection works at site as well as anticorrosion protection using paint coating and thermal insulation works, including aluminium cladding. All prices and indicators are those of Portugal mainland materials suppliers and mechanical contractors for the construction and erection works.
Civil works for foundations of piping and equipment were estimated based on the associated mechanical works. In the total combined costs of mechanical and civil works, the mechanical works corresponds to 70% while civil works reflect only 30%, including steel hardware for pipe supporting (Jóhannesson, Th: personal communication). The electrical, control and instrumentation works were estimated to be 15% of the referred combined costs.

Detailed design and supervision works are empirical values based on EDA Renováveis' experience in similar projects in the past and are assumed to be 7.5% of the referred combined costs.

6.1 Materials

Piping
The most representative piping for the separation stations and gathering systems were pipes with 28", 16" and 10" diameter. The unit prices of pipe and 90° long radius bends are presented in Table 4.

The 28" pipe is not seamless but longitudinal welded.

TABLE 4: Piping and bends unit prices

Material description	Unit price
28" pipe API 5L Gr. B ERW Sch. STD	275 €/m
16" pipe A106 Gr. B 16" Sch. STD	150 €/m
10" pipe A106 Gr. B 16" Sch. STD	90 €/m
28" long radius bend A234 WPB Sch. STD	1055 €/EA
16" long radius bend A234 WPB Sch. STD	285 €/EA
10" long radius bend A234 WPB Sch. STD	105 €/EA

Valves
The valves considered for the estimate are the 28”, 16” (for the gathering system piping) and 8” (for the separation station brine piping) in diameter and their costs are presented in Table 5.

TABLE 5: Valves unit prices

Material description	Unit price
28” A216 WCB gate valve Trim 5	10,000 €/EA
16” A216 WCB gate valve Trim 5	5000 €/EA
8” A216 WCB gate and check valves Trim 5	1750 €/EA

Pumps
The unit price for a brine booster centrifugal pump including duplex stainless steel impeller and casing, double mechanical seal shaft sealing, coupling and a 60 kW electrical motor, with pump and motor installed in a steel frame, is estimated to be € 35,000.

6.2 Mechanical construction and erection works

The delivery time of the project was calculated to be between 8 and 9 month or about 200 days. It is important to mention that the climatic conditions at the construction site are very variable, with wind and precipitation typically influencing the works execution, causing the extension of the delivery time.

Piping
In past projects at the Ribeira Grande geothermal power plant, an experienced welder could completely execute two 12” Sch. STD pipe weldings during a work day. The estimated time for the 28”, 16” and 10” weldings were evaluated based on this indicator and on the pipe diameter. In these conditions, it was calculated that a total of 5 welders are required to execute both the setup of the separation station and gathering the system piping within the delivery time of 200 days.

The cost of the supporting team of welders and other workers required is estimated to be 5,300 €/day, based on prices from similar projects of EDA Renováveis. For erection works, a crane is needed, a forklift and also scaffolding for the final painting and insulation works of piping and separation station equipment. These costs, based on the Portuguese market, can be considered to be around 1.8 €/kg.

Separators and accumulator tanks
For separators and accumulator tanks steel fabrication works and erection a unit price of 5.5 €/kg is estimated.

6.3 Anticorrosion protection, insulation and cladding

The anticorrosion protection by paint coating and the insulation and cladding works unit prices are as follows. For anticorrosion protection by paint coating (high-temperature specification):

- 20 €/m^2 for shop painting;
- 15 €/m^2 for final painting and touch up at site.

For insulation and cladding:

- 150 €/m^2 for separators and accumulators;
- 100 €/m^2 for piping.

7. RESULTS

The results presented in this section were obtained utilizing *Engineering Equation Solver* software (F-Chart Software, 2015) and *Excel*. The drawings were produced by Autodesk’s *AutoCad LT 2013* software unless mentioned otherwise.

7.1 Pipe diameter results

This section presents the results for the nominal pipe size selection for the separation station piping, the two-phase flow and the gathering system single flow piping. The pressure values presented herein are bar absolute (bar) unless stated otherwise.

Separation station single flow piping
For the expected steam and brine flow rates and the defined maximum flow velocities for each fluid, the calculated inside pipe diameters are presented in Table 6.

TABLE 6: Pipe inside diameter for maximum velocity

Fluid	Flow rate (kg/s)	Maximum velocity (m/s)	d (mm)
Steam	11	30	390.1
Brine	42	1	242.4

Selecting the next nominal diameter pipe from ANSI pipe schedule with a thickness corresponding to schedule STD, the final results are presented in Table 7.

TABLE 7: Calculated velocity for nominal pipe size

Fluid	Flow rate (kg/s)	Nominal pipe size (inch)	Nominal pipe size (mm)	d (mm)	Calculated velocity (m/s)
Steam	11	18”	457.00	437.94	23.80
Steam	11	16”	406.40	387.34	30.42
Brine	42	10”	273.10	254.56	0.91

The brine nominal pipe size selected is 10” (DN 250) while for steam it is 16” (DN 400), exceeding marginally the velocity of 30 m/s. Due to the reduced length, there is no decisive advantage in choosing the next pipe size (18”).

Two-phase flow piping
For the expected total production of a well, considering the maximum superficial steam velocity established and observing the recommendations of Lazalde-Crabtree for the vertical separator design, the two-phase flow nominal pipe size selected is 16” (DN 400).

Gathering system single flow piping
The gathering system piping initial pipe diameter analysis, pressure loss and fluid velocity calculations are presented in Tables 8 and 9 for steam and brine total flows:

- Total steam flow rate: 33 kg/s (120 ton/h);
- Total brine flow rate: 126 kg/s (450 ton/h).

TABLE 8: Calculated steam pressure loss and flow velocity for nominal pipe sizes

Option	Nominal pipe size (inch)	Nominal pipe size (mm)	d (mm)	Steam velocity (m/s)	Pressure loss, line (bar)	Pressure loss, bends (bar)	Total pressure loss (bar)
1	30"	762.0	742.94	24.8	0.32	0.13	0.45
2	28"	711.0	691.94	28.6	0.47	0.17	0.64
3	24"	610.0	590.94	39.2	1.07	0.32	1.39
4	20"	508.0	488.94	57.3	2.87	0.68	3.55

TABLE 9: Calculated brine pressure loss and flow velocity for nominal pipe sizes

Option	Nominal pipe size (inch)	Nominal pipe size (mm)	d (mm)	Brine velocity (m/s)	Pressure loss, line (bar)	Pressure loss, bends (bar)	Total press. loss (bar)
1	18"	457.0	437.94	0.9	0.25	0.05	0.30
2	16"	406.4	387.34	1.2	0.48	0.08	0.57
3	14"	355.6	336.54	1.6	1.01	0.15	1.15
4	12"	323.9	304.84	1.9	1.69	0.22	1.91

From the calculated values, two nominal pipes sizes are selected to develop a detailed pressure loss analysis comparison for the transport from the well pad to the plant, which are the 28” (DN 700) and 24” (DN 600) pipe. The 28” pipe keeps the steam velocity below 30 m/s, minimizing the pressure losses while the 24” exceeds that value and results in a pressure drop 2 times higher than the 28” pipe.

The brine pump’s technical characteristics are presented in Table 10 for each nominal pipe size evaluated.

TABLE 10: Brine pump technical characteristics

Option	Pump head (m)	Pump discharge pressure (bar)	Pump driver power (kW)
1	97	14.7	172
2	100	15.0	177
3	107	15.5	189
4	115	16.3	204

For these results, the separation pressure is considered to be 5.8 bar. The 18” and 16” nominal pipe sizes minimize the pressure losses and the pump driver power, noticing that there is only a 5 kW difference between both nominal pipe sizes, hence not presenting a decisive operational cost. Option 2 marginally exceeds the velocity of 1 m/s but the value of 1.2 m/s is acceptable. Considering also the economic benefit of selecting a smaller pipe diameter and maintaining the pumps operational costs low, the selected nominal pipe size for the brine gathering system is 16” (DN 400). The calculated pump driver electrical power is required to boost the total brine flow of the three wells. Therefore, the electrical power to drive one pump is 60 kW for the selected pipe size.

Pressure loss along the pipe route

The steam pressure drop along the pipe route from the well pad to the plant header can be better evaluated by pipe sections for 24” and 28” nominal pipe sizes. The analysis allows evaluating the separation pressure for each pipe size considering that the steam plant header pressure should be kept at 5.1 bar. The results are presented in Tables 11-14 for 24” and 28” nominal pipe sizes, respectively. Section 0 corresponds to the well pad location and separation pressure while Section 10 is at the plant platform and plant steam header pressure.

The estimated separation pressure for the 24” steam pipe gathering system is 6.6 bar while for 28” it is 5.8 bar, assuming the same steam header pressure at the plant. The average flow velocity is 30 m/s in the 28” pipe and 40 m/s in the 24” pipe.

Brine piping design pressure

The pump discharge pressure lies above the original brine piping design pressure; therefore, it should be increased. It is not in the scope of this work to simulate transient flow regimes to characterize the maximum pressure reached in the piping system caused for example by closing a valve upstream the pump discharge or a sudden increase of flow. To account for the transient regimes a design pressure of 20 bar(g) was selected.

TABLE 11: Pressure loss pipe route for 24” nominal pipe size

Section	**Pipe length (m)**	**No. bends**	**p (bar)**	**v (m/s)**	**Pressure loss, line (bar)**	**Pressure loss, bends (bar)**	**Pressure loss, total (bar)**
0	0	1	6.60	35.8	0.102	0.003	0.106
1	141	20	6.49	36.4	0.104	0.068	0.172
2	282	8	6.32	37.3	0.107	0.028	0.134
3	423	6	6.19	38.0	0.109	0.021	0.130
4	564	10	6.06	38.8	0.111	0.036	0.147
5	705	9	5.91	39.7	0.114	0.033	0.147
6	846	6	5.76	40.7	0.116	0.023	0.139
7	987	9	5.63	41.6	0.119	0.035	0.154
8	1128	11	5.47	42.8	0.122	0.044	0.166
9	1269	10	5.31	44.0	0.126	0.041	0.166
10	1410	-	5.14	-	-	-	-

TABLE 12: Average velocity and total pressure loss values for 24” nominal pipe size

Average velocity (m/s)	**Pressure loss, line (bar)**	**Pressure loss, bends (bar)**	**Pressure loss, total (bar)**
39.5	1.13	0.33	1.46

TABLE 13: Pressure loss along pipe route for 28” nominal pipe size

Section	**Pipe length (m)**	**No. bends**	**p (bar)**	**v (m/s)**	**Pressure loss, line (bar)**	**Pressure loss, bends (bar)**	**Pressure loss, total (bar)**
0	0	1	5.80	28.6	0.047	0.002	0.049
1	141	20	5.75	28.8	0.047	0.038	0.085
2	282	8	5.67	29.2	0.048	0.015	0.063
3	423	6	5.60	29.6	0.048	0.012	0.060
4	564	10	5.54	29.9	0.049	0.020	0.068
5	705	9	5.47	30.2	0.049	0.018	0.067
6	846	6	5.41	30.5	0.050	0.012	0.062
7	987	9	5.35	30.9	0.050	0.018	0.069
8	1128	11	5.28	31.3	0.051	0.023	0.074
9	1269	10	5.20	31.7	0.052	0.021	0.073
10	1410	-	5.13	-	-	-	-

TABLE 14: Average velocity and total pressure loss values for 28” nominal pipe size

Average velocity (m/s)	**Pressure loss, line (bar)**	**Pressure loss, bends (bar)**	**Pressure loss, total (bar)**
30.1	0.49	0.18	0.67

Flange class rating

The pump and valves flange pressure rating class needs to be increased. The design temperature of 175ºC is limited to 14 bar(g) for 150# class carbon steel flanges so 300# class flanges should be selected.

7.2 Pipe thickness

The gathering system steam and brine pipe minimum thickness t_m and nominal thickness t_n results are presented in Table 15.

TABLE 15: Steam and brine pipe thickness

Fluid	**Nominal pipe size (inch)**	**Design pressure (bar(g))**	**t_m (mm)**	**t_n (mm)**
Steam	28”	7.5	5.25	9.53
Brine	16”	20	6.42	9.53

7.3 Mechanical stress analysis

The results of the mechanical stress analysis are resumed in Table 16. For the calculation of the applied loading, the brine density was considered to be 1000 kg/m^3 which represents the worst case scenario. The load due to the steam weight is negligible.

TABLE 16: Sustained and occasional loads

Fluid	Vertical sustained load (N/m)				Vertical occasional load (N/m)			Horizontal occasional load (N/m)		
	q_p	q_e	q_v	q_{vs}	q_s	q_{sv}	q_{vo}	q_{sh}	q_w	q_{ho}
Steam	1617	250	0	1867	0	327	327	654	443	654
Brine	915	156	1156	2227	0	390	390	779	295	779

The results for pipeline length between supports are presented in Table 17. It shows that 16” brine piping requires shorter lengths between supports due to the higher sustained load, resulting from the greater medium weight when compared to the 28” steam pipe.

TABLE 17: Length between supports

Pipe size	L_s (m)		
	Sustained loads	Sustained and Occasional loads	Deflection criteria
28” (steam)	40	35	27
16” (brine)	20	17	15

7.4 Flexibility and expansion loops

The results from the expansion loops calculations are presented in Tables 18 and 19.

TABLE 18: U-shape expansion loop design

Pipe size	L_{ANC} (m)	Δ (mm)	L_2 (m)	L_3 (m)	L_1 (m)	S_A (MPa)
28”	30	62	12	6	12	177
16”	30		9	5	13	

U-shape expansion loop
It is evaluated that 7 horizontal expansion loops are required for the new pipeline section of 400 m length.

Change of direction expansion loop
At least two changes of direction expansion loops should be considered for the new section piping according to the results of this study.

TABLE 19: Change of direction expansion loop design

Pipe size	L_{ANC} (m)	L_{arm} (m)	L_{T1} (m)	L_{T2} (m)
28”	32	27	23	27
16”	32	20	29	20

The topography of the area must be included later in the design, taking advantage of the natural opportunities provided by the land elevation for change of direction loops to minimize the number of U-shape loops. The bridge section should be analysed better since an anchor point is typically placed in the middle of the bridge which allows the pipe to expand in both directions.

The main objective of the flexibility analysis was to estimate a maximum number of expansion loops for the new section, to calculate the additional length of pipeline and the number of bends required, to estimate the gathering system piping pressure drop and select the pipe diameter for steam and brine flow. The method used for the flexibility analysis of the new pipe section is conservative and should not be considered final for the implementation of the gathering piping system. Therefore, computer stress analysis should be done in the final piping design which is a normal procedure at EDA Renováveis.

The expected pipe route between the well pad and the power plant platform is included in Appendix I.

7.5 Separation station results

This section presents the design results of the separation station with three vertical separators and brine accumulators, and one single horizontal gravity separator serving the three wells.

Vertical separator

The conceptual design of the vertical separator is presented in Figure 14 and the general characteristics and main design parameters of the separator are presented in Tables 20-22. All calculated values, with the exception of the separator inside diameter, which is a design assumption, should be considered approximate values. An additional nozzle is identified in the drawing which is the balance pipe. The balance pipe allows gas which forms by degassing of the brine to be vented to the separator, keeping the pressure of the two vessels balanced.

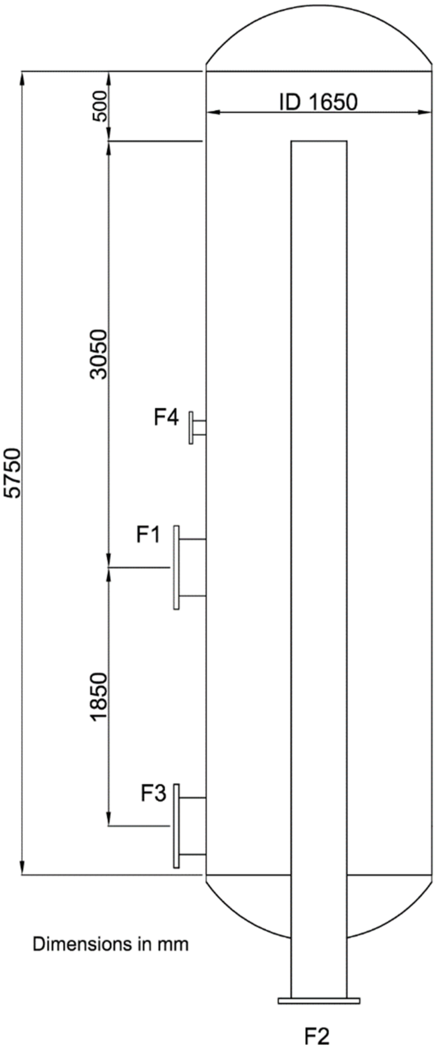

FIGURE 14: Vertical separator design

TABLE 20: Separator general parameters

Parameter	Value
Volume	13.5 m^3
Inside diameter	1650 mm
Vessel weight	4415 kg
Height between head welds	5750 mm
External surface area	40 m^2
Calculated thickness	7.6 mm
Nominal thickness	14 mm

TABLE 21: Separator nozzles schedule

Nozzles schedule		
No.	**Description**	**Size**
F1	Two-phase flow inlet	16”
F2	Steam outlet	16”
F3	Brine outlet	16”
F4	Balance pipe	4”

TABLE 22: Steam and brine design velocities

Parameter	Value
Steam velocity at two-phase inlet pipe (approximate)	30.4 m/s
Annular upward steam velocity inside cyclone	1.8 m/s
Brine outlet velocity	0.4 m/s

Brine accumulator tank

The design of the brine accumulator tank is presented in Figure 15, while the general characteristics of the brine accumulator tank are presented in Tables 23-24.

All calculated values, with the exception of the accumulator tank inside diameter, which is a design assumption, should be considered as approximate values. Low level for safe pump operation is considered to be 35%.

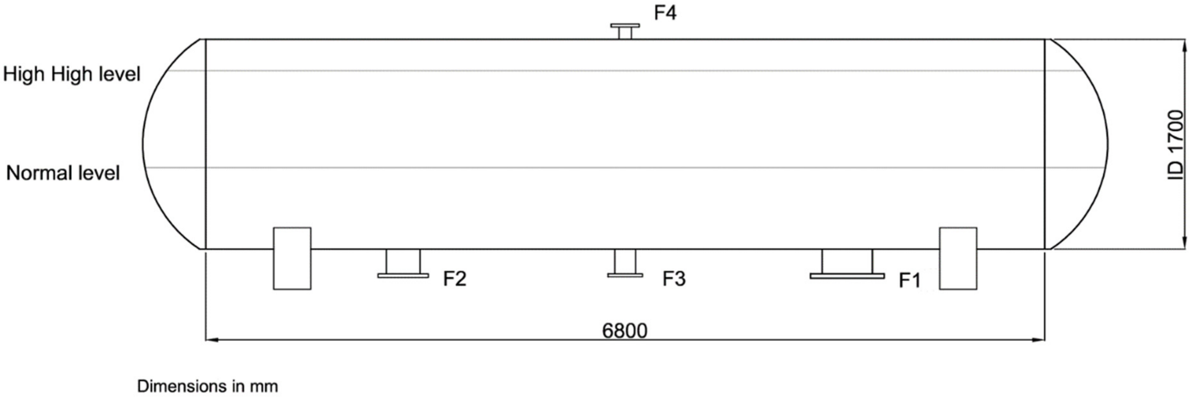

FIGURE 15: Brine accumulator tank

TABLE 23: Accumulator tank general parameters

Parameter	Value
Volume	16.7 m^3
Inside diameter	1700 mm
Vessel weight	5281 kg
Length between head welds	6800 mm
External surface area	47 m^2
Calculated thickness	7.7 mm
Nominal thickness	14 mm
Submergence depth (low level %)	600 mm (35%)
Brine outlet velocity	0.91 m/s

TABLE 24: Accumulator tank nozzles schedule

Nozzles schedule		
No.	**Description**	**Size**
F1	Brine inlet	16”
F2	Brine outlet	10”
F3	Brine drain outlet	6”
F4	Balance pipe	4”

The brine accumulator main nozzles control a brine drain outlet which in case of brine excess flow caused by operational reasons such as a pump failure, can be diverted and disposed adequately.

Horizontal gravity separator

The design of the horizontal gravity separator is presented in Figure 16. The general characteristics of the horizontal gravity separator are presented in Tables 25-27.

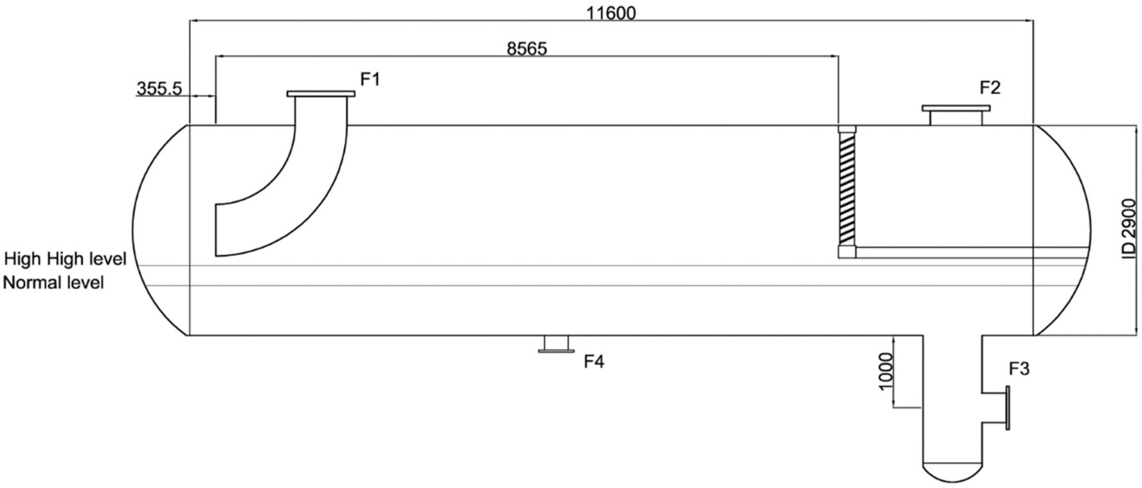

FIGURE 16: Horizontal gravity separator

TABLE 25: Horizontal separator general parameters

Parameter	Value
Volume	76.6 m^3
Inside diameter	2900 mm
Vessel weight	15,270 kg
Length between head welds	11,600 mm
External surface area	135 m^2
Calculated thickness	11 mm
Nominal thickness	14 mm

TABLE 26: Horizontal separator nozzles schedule

Nozzles schedule		
No.	**Description**	**Size**
F1	Two-phase flow inlet	28”
F2	Steam outlet	28”
F3	Brine outlet	16”
F4	Brine drain outlet	12”

TABLE 27: Horizontal separator design values

Parameter	Value
Sounders-Brown velocity K_f	0.182 m/s
Steam trough filter velocity U_d	3.13 m/s
Filter cross section area A_s	3.44 m^2
Brine outflow drip leg diameter	762 mm
Volumetric steam flow rate $\dot{V}_g$	10.8 m^3/s
Steam velocity at two-phase inlet pipe (approximate)	28.6 m/s
Submergence depth	1000 mm
Brine outlet velocity	1.2 m/s

The Sounders-Brown velocity K_f is within the design range of 0.18 to 0.2; the cross-section area of the filter type Chevron selected is 60% of the vessel cross section area. The steam velocity is below 30 m/s and the brine outlet velocity is slightly above 1 m/s. The brine outflow drip leg diameter is 725 mm and the next nominal diameter is 762 mm which corresponds to 30”. The calculated submergence depth relative to the central line of the brine outlet nozzle was 925 mm, which is increased to 1000 mm.

The results from each separation station type are resumed in Table 28, considering three vertical separators and accumulator tanks and one horizontal gravity separator, showing the most significant parameters for a cost evaluation.

TABLE 28: Separation station type parameters comparison

Type	Volume (m^3)	Weight (kg)	External surface area (m^2)
Vertical separators and accumulator tanks	90.6	29,100	261
Horizontal gravity separator	76.6	15,270	135

Selected thickness for pressure vessels

The selected thickness for all pressure vessels is 14 mm, allowing a direct comparison between the vertical and horizontal separators. It is also in accordance with the existent pressure vessels in the Ribeira Grande and Pico Vermelho power plants.

7.6 Cost estimate of the project

The estimated overall breakdown cost of the project is presented in Table 29 for Configuration A and in Table 30 for Configuration B of the separation stations.

TABLE 29: Configuration A project estimated breakdown cost

Activity description	Cost (€)
Design and supervision works	377,200
Gathering system piping	
Piping materials	747,000
Construction and erection works	1,744,500
Anticorrosion protection by painting coating	188,500
Thermal insulation and cladding	538,500
Pumps and valves	165,750
Vertical separators and accumulator tanks	
Construction and erection works	160,000
Anticorrosion protection by painting coating	9,135
Insulation and cladding	39,150
Equipment and piping foundations	1,468,500
Electrical, control and instrumentation	754,500
Total	**6,192,735**

TABLE 30: Configuration B project estimated breakdown cost

Activity description	Cost (€)
Detailed design and supervision works	369,700
Gathering system piping	
Piping materials	747,000
Construction and erection works	1,744,500
Anticorrosion protection by painting coating	188,500
Thermal insulation and cladding	538,500
Pumps and valves	165,750
Horizontal gravity separator	
Construction and erection works	90,900
Anticorrosion protection by painting coating	4,725
Insulation and cladding	20,250
Equipment and piping foundations	1,428,850
Electrical, control and instrumentation	739,300
Total	**6,037,975**

The overall estimated cost of the project is found to be about € 6,100,000. The total costs of Configuration A separation station is € 208,285 while for Configuration B it is €115,875, making the difference € 92,500. In the overall estimated cost of the project this is not decisive and the evaluation and pondering of technical matters have to be considered at a later stage of the engineering detailed design. The percentage of the costs of each project activity is summarised in Table 31.

TABLE 31: Cost weight per project activity

Activity description	Cost weight per activity
Design and supervision works	6%
Gathering system piping	53%
Pumps and valves	3%
Separation station equipment's	3%
Equipment and piping foundations	24%
Electrical, control and instrumentation	12%

The break-down cost per project activity shows that the gathering piping system works is about half of the overall project costs while the civil works for equipment and piping foundations is about a quarter.

8. CONCLUSIONS AND RECOMMMENDATIONS

The main conclusions and recommendations of this study are the following:

- Two configurations of the separation station for the new Cachaços-Lombadas sector wells CL8, CL9 and CL10 were evaluated. Configuration A comprises the installation of individual vertical separators, associated with brine accumulator tanks for each well; Configuration B considers the installation of a single common horizontal gravity separator, receiving the total flow of the three wells. In either of the alternatives, the separation of the two-phase flow is done at the well pad.
- The gathering system pipe sizes selected are 28” (DN 700) for steam and 16” (DN 400) for brine, considering the expected total flow of 33 kg/s (120 ton/h) of steam and 126 kg/s (450 ton/h) of brine. However, 24” can be considered an economical choice, penalizing the piping pressure drop and requiring to operate the wells at a higher separation pressure and therefore at lower wellhead pressure.
- The total electrical power required to boost the three wells brine flow from the well pad to the plant brine header is 177 kW.
- The two-phase flow pipe size should be 16” (DN 400) for each well, considering the steam superficial velocity of 30 m/s and following Lazalde-Crabtree (1984) design criteria; the vertical separator steam and brine outlets are 16” in diameter.
- The vertical separator preliminary design assures that the annular upward steam velocity is below 2 m/s.
- The brine accumulator tank was designed to offer a reasonable buffer volume to accommodate well fluctuations. The volume corresponds to a total of 300 s of the nominal brine flow, 120 s for nominal normal level while 180 s corresponds to the difference from normal to high level.
- In using a single vertical separator in a cluster of wells, the design needs to consider that all wells are operating at the design steam flow rate conditions, otherwise the steam inlet velocity will be lower, reducing the efficiency and therefore the quality of the outlet steam. It is improbable that in coming years the new Cachaços-Lombadas wells will operate simultaneously, therefore a single vertical separator to separate the wells combined two-phase flow is not the best technically solution at the present time, as it can be offered by the horizontal gravity separator.
- The advantage of operation of a horizontal gravity separator serving multiple wells, in contrast to the individual separation station, is that its performance is less dependent of the two-phase inlet flow rate and, due to its large volume, is better adjusted to serve as a buffer to compensate the fluctuations of the wells.
- The flexibility analysis was carried out to estimate a maximum number of expansion loops for the new pipeline section, establishing the additional length of pipe and number of bends required to calculate the gathering system piping pressure losses and to select the pipe diameter for steam and brine flow.
- The method used for the flexibility analysis of the new pipe section from the well pad to the existing piping corridor is conservative and should not be considered final for the implementation of the gathering piping system. Therefore, computer stress analysis should be done in the final piping design what is normal procedure in EDA Renováveis.
- The cost estimate of the project is about 6.1 m€.
- The cost of Configuration A separation station is € 208,285 while for Configuration B it is € 115,875, differing about 92,500 €, which in the overall estimated cost of the project is not relevant. It is recommended that the evaluation and pondering of technical matters between both configurations should be developed at a later stage of the project engineering detailed design.

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REFERENCES

ASME, 2007: *ASME B31.1-2007. Power piping. ASME code for pressure piping, B31.* The American Society of Mechanical Engineers (ASME), 336 pp.

Clark, P.B., 2002: Some observations on the hydraulics of pumping stations. *Proceedings of the 2nd International Conference on Water and Wastewater Pumping Station Design, Cranfield, United Kingdom*, 9-22.

DiPippo, R., 2007: *Geothermal power plants. Principles, applications, case studies and environmental impact* (2nd edition). Butterworth Heineman, 493 pp.

EDA, 2014: *Demand and supply of electricity.* Electricidade dos Açores (EDA), *PLCOR (Planeamento, Controlo, de Gestão e Regulação)* Ponta Delgada, São Miguel, Azores, Portugal, internal report (in Portuguese), 36 pp.

EDA Renováveis, 2014: Annual Report. EDA Renováveis, Ponta Delgada, São Miguel, Azores, Portugal, (in Portuguese), 103 pp.

F-Chart Software, 2015: *EES, Engineering Equation Solver.* F-Chart Software internet website, *http://www.fchart.com/ees/ees.shtml.*

Foong, K.C., 2005: Design concept for a more efficient steam-water separator. *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey,* 7 pp.

Jóhannesson, Th., and Gudmundsson, Y., 2014: *Mechanical design of geothermal power plants. Lecture 2: Drilling and gathering systems*. Reykjavík University, Reykjavík, Iceland, 82 pp.

Jónsson, M.T., 2015: *Mechanical design of geothermal power plant*. UNU-GTP Iceland, unpublished lecture notes, 25 pp.

Krex, H.E., 1986: *Maskin ståbi* (6th ed.). Nyt Teknisk Forlag, Cph, Denmark, 472 pp.

Lazalde-Crabtree, H., 1984: Design approach of steam water separators and steam dryers for geothermal applications. *Geothermal Resources Council, Bulletin, 13*, 11-20.

Rangel, G., Franco, A., Cabeças, R., Bicudo da Ponte, C., 2011: Use of geothermal resources in the Azores Islands: A contribution to the energy self-sufficiency of a remote and isolated region. *Geothermal Resources Council, Transactions, 35,* 1209-1214.

Smith. P.R., and Van Lann. T.J., 1987: *Piping and pipe support systems*. McGraw-Hill Book Company, New York, NY, US, 334 pp.

APPENDIX I: Gathering system pipe route

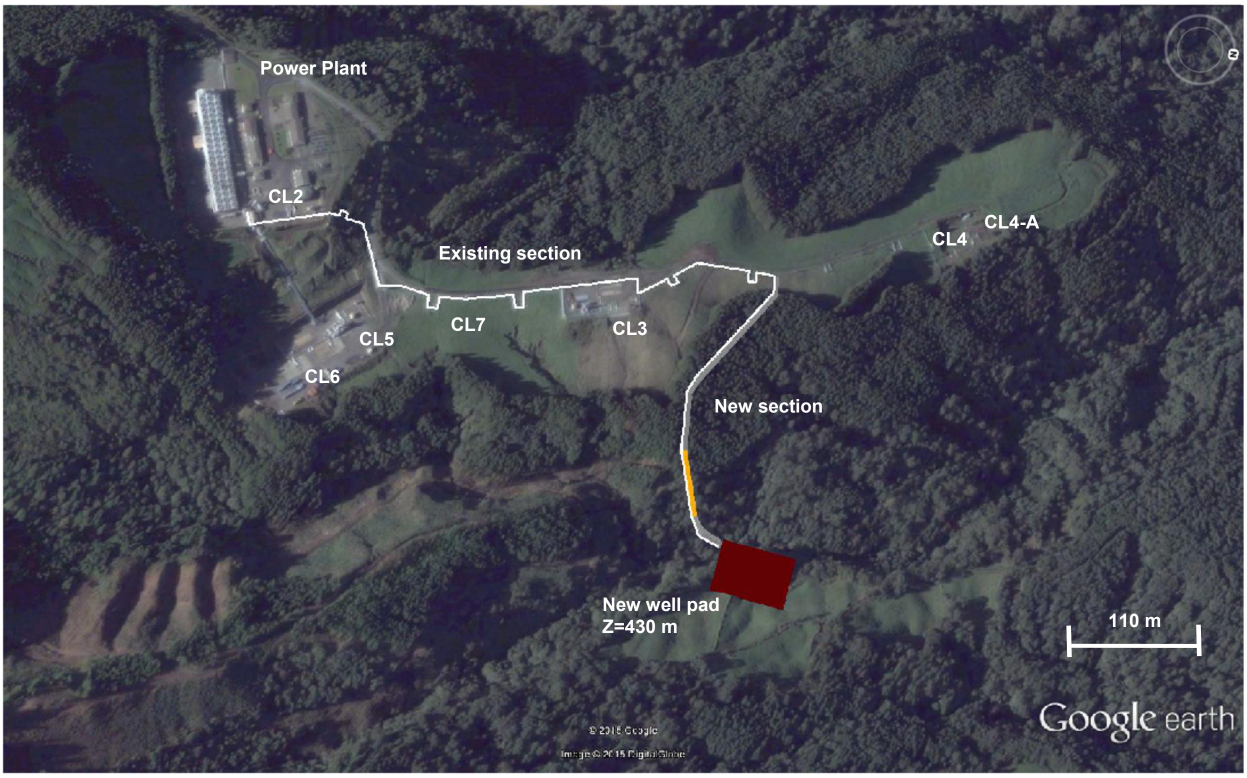

FIGURE 1: Gathering system pipe route from well pad to the plant (Google Earth)