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WELL FLOW TESTING IN SOL DE MAÑANA GEOTHERMAL FIELD IN BOLIVIA

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ABSTRACT

The Sol de Mañana geothermal field is located in Bolivia in the area of Potosí, Sud Lipez province. In the field 5 wells have already been drilled. The capacity of the field, based on information from existing wells and superficial studies, is estimated to be 100 MWe. Approximately 25 additional wells are to be drilled to produce this amount of energy. The first power plant will be installed as soon as energy, sufficient for 50 MWe is available at wellhead. Interference tests will be carried out to determine if there is any connection between the wells and to gain more information about the reservoir. Drilling of new wells and testing of the previously drilled wells will be carried out simultaneously. Caution will be exercised to minimize interference of the involved wells. When flow testing production wells, the Russel James method will be used to measure the well capacity. Orifice plates (Sizes 4, 6 and 8 inches in diameter) will be used to maintain the head pressure, the lip pressure will be measured in the lip pressure spool while the amount of brine produced will be measured in the weir box. The old wells will also be monitored for changes in pressure and static water level. Three wells are located on drilling pad 3; SM-3 (old), SM-31(new) and SM-32 (new). SM-31 will be the first well to be tested while wells SM-1, SM-2 and SM-3 are monitored for interference. Thereafter, the simultaneous testing will be started, whereby all the aforementioned wells will be opened using an 8 "orifice plate for a period of 5 days. Both the individual and simultaneous tests take approximately 40 days. The objective of the tests is to obtain the production capacity, the pressure and the temperature of the wells and to establish if interference exists between the wells. The test results together with geological studies can be used to revise the conceptual model of the reservoir.

1. INTRODUCTION

The geothermal prospect "Sol de Mañana" is located in Bolivia in the department of Potosí, province of Sud Lípez (Figure 1). In the years from 1988 to 1994 pre-feasibility studies were carried out to identify the geothermal potential of the area. The studies were carried out by ENDE (National Electricity Company). Furthermore, 5 exploration wells were drilled (Table 1). The drilling campaign was developed by ENEL (Italian Electricity Company) and YPFB (Bolivian oil field company). After the tests of the wells, a reservoir temperature of 250°C on average and a potential of 100-150 MWe was

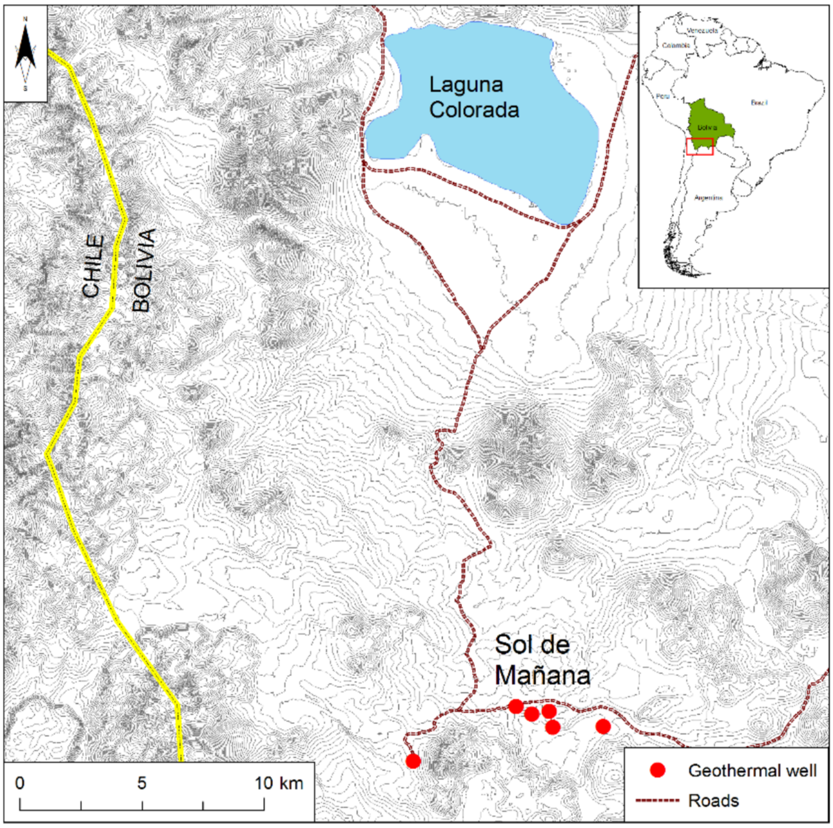


FIGURE 1: Location of the Sol de Mañana field (Ramos, 2015)

estimated.

In 1997, CFE (Mexican Electricity Company) conducted further production tests to determine interference between the wells and to check the capacity of the reservoir, identifying a potential of 120 MWe.

In 2008, feasibility studies developed by JETRO (Japan Foreign Trade Organization) and West JEC (Engineering Consultants of Western Japan) for the potential installation of a geothermal plant 100 MWe were carried out.

In 2013, based on the study results, the government of Bolivia applied for funding to develop the project to the JICA (Japan International Cooperation Agency). This additional study confirmed the potential of 100 MWe, sustainable for 30 years.

TABLE 1: Geothermal wells in Sol de Mañana field (JICA, 2013)

Well	**Altitude (m a.s.l.)**	**Depth (m)**	**Type**
SM-1	4,858.84	1,180	Production well
SM-2	4,905.57	1,486	Production well
SM-3	4,884.77	1,406	Production well
SM-4	4,840.54	1,726	Injection well
SM-5	4,903.54	1,705	Production well

Based on these above mentioned studies, ENDE plans to develop a 100 MWe power plant in two 50 MWe modules. In 2019, a drilling campaign comprising 25 geothermal wells (16 production and 9 injection wells) was launched. Prior to implementation of the first 50 MWe module, well flow tests will be carried out to demonstrate the capacity of each well and whether the interconnection exist in the reservoir (JICA, 2013).

At the end of the drilling of each well, flow tests will be carried out to determinate capacity, temperature and pressure. When it has been confirmed that the existing wells are sufficient to generate the first 50 MW, the simultaneous test will be started which aims is demonstrate the connection between the wells and determine the capacity of the reservoir. The main objective of this report is to design a procedure for the well testing, considering that drilling is continued at the same time.

2. WELL FLOW TESTING

2.1 Introduction

The development of a geothermal field consists of different stages.

- *First stage:* Implementation of pre-feasibility and feasibility studies based on surface studies
- *Second stage:* Drilling of geothermal wells and determination of the reservoir capacity by production well tests and installation of the geothermal plant
- *Third stage:* Monitoring of the geothermal resource.

Within the stages of development, the first stage is surface exploration that includes geological, geophysical and geochemical studies. The part that represents the greatest risk is the second stage when geothermal wells are drilled to measure the thermally gradient, monitor the production and reinjection capacities etc. The wells are an essential part of the development and the information gained is used to update the conceptual model of the reservoir.

After drilling the wells, traditional well tests must be carried out to determine the production capacity of the reservoir. Based on the pressures, temperature, enthalpy and the type of flow the limits of the reservoir can be estimated.

The tests can be short, stepwise or long, either by discharging or by pumping. Interference tests may also be carried out if needed. These tests can last from days to months when several wells are involved. Tracer tests may as well be of help to determine the connection between the reinjection wells and the production wells and thus determine the cooling of the reservoir (Axelsson, 2013).

A well test procedure to determine the interference has to be developed months before the discharge by selecting the appropriate method of discharge (Figure 2) and ensuring that the necessary equipment, permits and safety procedures are available.

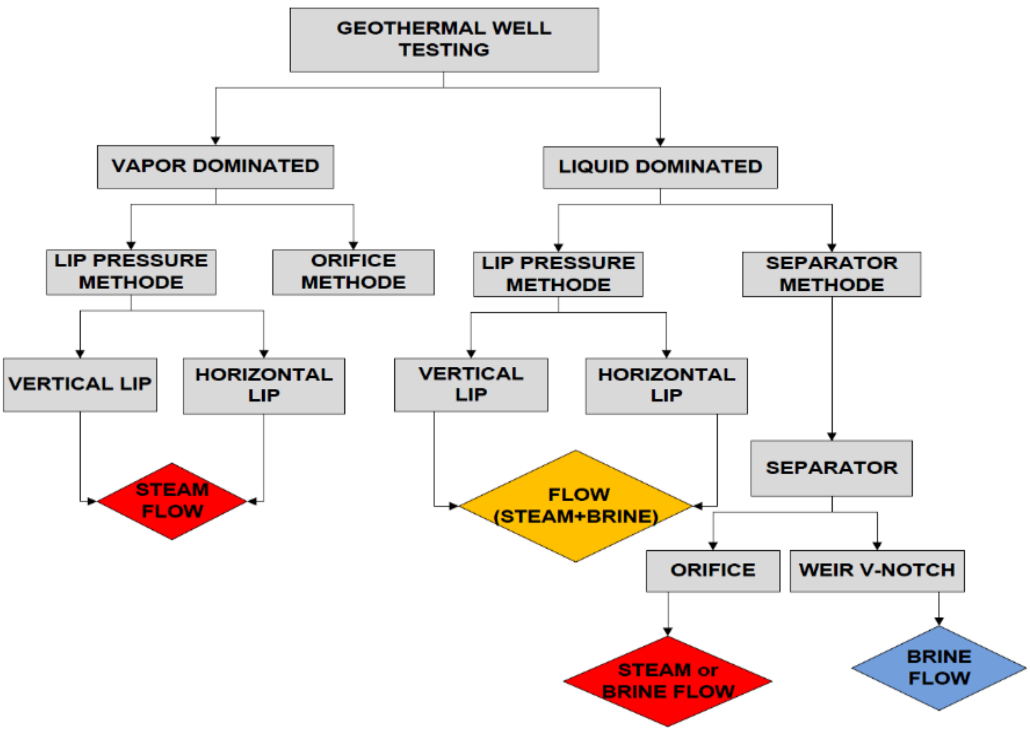


FIGURE 2: Production test methods (Mohamad et al., 2015)

The methods to realise the discharge are selected depending on the type of flow. In the case of Sol de Mañana the flow is liquid dominated and therefore the lip pressure method or the use of steam separator are possible options. The lip pressure method is most commonly used for initial well testing while the separator is typically used to connect the well to the geothermal power plant.

For the tests conducted in Sol de Mañana the conventional method of lip pressure will be applied. The equipment is portable, can be used repeatedly over a long time, is easy to install, low cost, and was successfully used before.

2.2 Conventional discharge

The lip pressure method with conventional discharge has the following objectives: Clean all the waste from the well, collect data for the design of the steam supply system and the plant, and to obtain information to update the conceptual model of the field. All these objectives are supported by data obtained from the wells such as wellhead pressures, total flow, enthalpy of the fluid, and fluid chemistry (components concentrations, pH and content of gases).

To determine the total flow, the Russell James method is applied where constant wellhead pressure (WHP) has to be achieved using orifice plates of different dimensions (2", 4", 6", 10") which are installed at the wellhead outlet. Based on the data that will be obtained, the mass flow curve (MF) and enthalpy (H) as a function of head pressure (WHP) can be estimated (Figure 3).

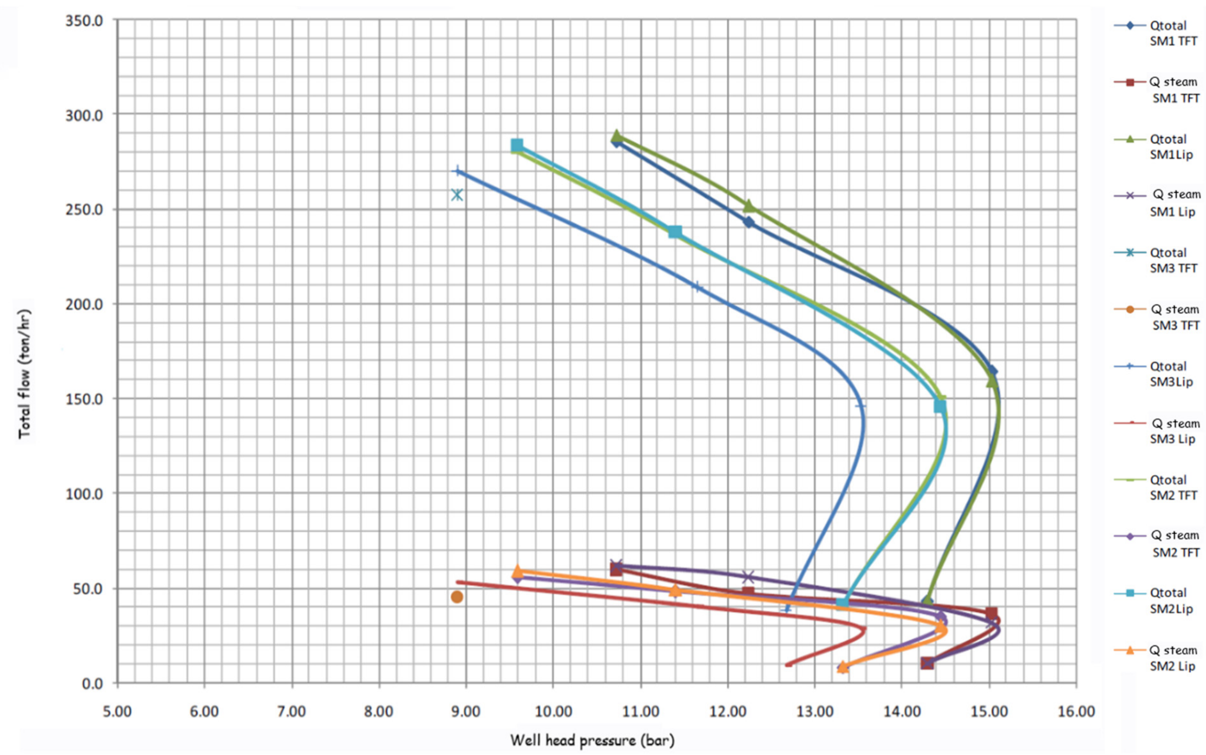


FIGURE 3: Typical production curves for production wells (JICA, 2013)

2.2.1 Description of the tests

Prior to the production tests, it is necessary to pressurize the wells to reach the necessary head pressure for discharge. The two-phase fluid is transported to the shaft of the valves of the well and through the lateral valve to the silencer where boiling of the fluid (flashing) occurs when the gaseous and liquid phases of the biphasic fluid are separated at atmospheric pressure. The steam rises to the atmosphere through the silencer and the brine (separated liquid phase) is initially conducted to a channel (where the brine flow is measured in the weir box) and then transported through a high-density polyethylene pipeline by gravity or pumping up to the valve shaft of the reinjection well. For estimate of the capacity of all the wells, the method of Russell James is used (Axelsson, 2013).

Russell James lip pressure method
For measuring the well capacity, the James lip pressure method is applied that includes the pressure and the temperature under dynamic or static conditions and thus characterizes both the liquid and gaseous phases of the fluids of the different wells. The normal condition of the geothermal fluid in the casing is 2-phase flow. This requires that the enthalpy of the steam and water mixture, or the ratio of steam and water, is measured as well as the total mass of fluid.

This method is based on an empirical formula developed by James in 1966. For production wells with large biphasic flows, this method is the most versatile and economic for testing. Its advantages over other methods are the simplicity of both the needed equipment (hardware) and instrumentation as well as the ability to measure large flows with inexpensive equipment.

The equipment consists of a shaft of valves, a pipe from the well to the silencer, a silencer, a pipe for the injection of the brine and the orifice plates as shows in Figure 4.

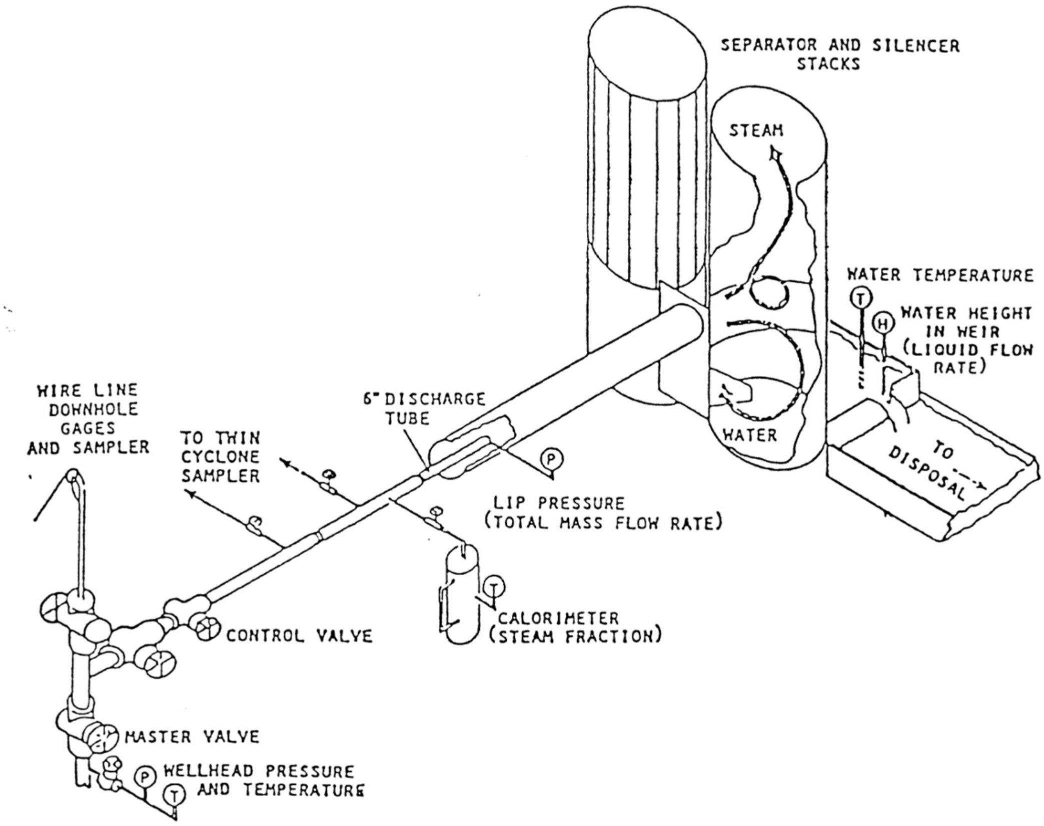


FIGURE 4: Equipment for Russell James method (Cheng, 1980)

According to Grant (2011) it may take some time (days and even weeks) for the wells to be stabilized during the test period. With this method results are achieved within 5% error for measurements of mass flow and enthalpy. The lip pressure is a measure of the pressure that is present at the end of the well discharge pipe when entering what is known as the expansion chamber of the silencer. The flow of separated brine in the silencer is measured in the weir box while the steam is discharged into the atmosphere. With these two measurements (lip pressure and discharge in the weir box), the enthalpy of the fluid and the mass flow of the well can be calculated (Grant, 2011).

The Russell James's formula relates the mass flow, the enthalpy, the area of the discharge pipe and the lip pressure as follows in Equations 1 and 2:

$$\frac{G * H^{1.102}}{P^{0.96}} = 184 \quad (1)$$

where

$$G = \frac{W}{A} \quad (2)$$

and W = Mass flow (kg/s);
H = Enthalpy (kJ/kg);
A = Area of the pipe (cm^2);
P = Lip pressure (bar).

According to Porras Mendieta (1991), the first valve at the wellhead is the kill valve that allows the evacuation of fluid at the time of testing or simply relieve pressure in the valve shaft, then comes the master valve (rating of configuration is class 600 – 1500) that is responsible for allowing the passage to the system or blocking it in case of pipe damage.

The pipe that connects the well to the silencer must withstand high temperatures so carbon steel pipes suited for elevated pressure and temperature are used. For the reinjection pipe HDPE high-density polyethylene is commonly used since it transports the brine from a discharge pond which is not high in temperature.

Auditory contamination caused by fluids at high pressure can be detrimental for the workers. For this reason, it is necessary to install a silencer at the outlet of the wellhead system to reduce the noise that is around 100 dBA (Ortiz, 2012).

Temperature and pressure measurements
Measuring temperature and pressure in the wellbore can be done either under static (with the well closed) or flowing conditions (with the well in production). In geothermal wells where the temperatures are between 150 and 380°C we have to use a K10G (Kuster Company) or similar (Steingrímsson, 2013). These instruments are of small diameter and can be used in virtually all wells that do not have serious problems in the pipeline and have no obstructions (Steingrímsson, 2013).

The measuring tools are reliable and require limited maintenance for the measurement of temperatures up to 300°C. With good calibrations and field procedures, the precision achieved is of the order of +/- 1°C for the measurement of temperature and +/- 0.2% for pressure measurements, but in practice the precision of the field data is frequently lower (ENDE, 2017).

Chemical sampling
For the sampling of both the geothermal steam and the geothermal liquid, samples are taken before the orifice plates using a portable separator. Samples may as well be taken at the weir box to check for the composition of the brine. The components that must be analysed both in the steam and the brine/geothermal liquid, in the Sol de Mañana field are:

1. *In vapour (gas phase):* CO_2, H_2S, NH_3, N_2, H_2, CH_4, O_2, Ar and He, which will be sampled with a mini-separator during the production test of the wells. Pressure and/or temperature.
2. *In condensate:* pH, Cl, SiO_2, $\delta^{18}O$ and δD.
3. *In brine (liquid phase):* pH, Na, K, Ca, Mg, SO_4, HCO_3, Br, I, HBO_2, As, CO_2, H_2S, SiO_2, NH_3, δD (H_2O) and δ18O (H_2O). Trace elements and metals should also be analysed. Pressure and/or temperature.

Sampling and preservation of samples require special care and established procedures to correctly obtain the concentrations of all these elements and compounds. The preservation of the samples is necessary to be able to establish the original concentrations of the samples.

3. PRODUCTION WELL TESTING FOR "SOL DE MAÑANA"

3.1 Background

The production tests were carried out in the "Sol de Mañana" field in 2011-2013 with the objective of determining the capacity of the reservoir and the interconnection that may exists between the wells. The instrumentation that was used during the last test are shown in Figure 5.

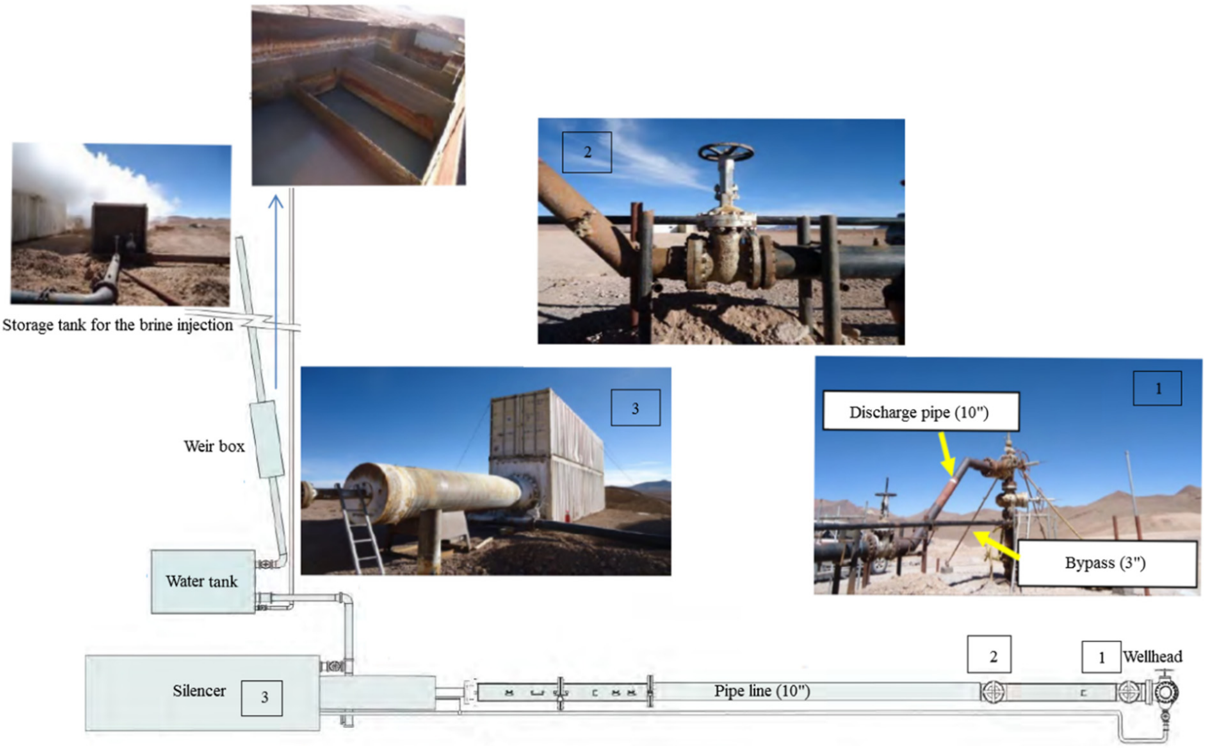


FIGURE 5: Equipment for the production test in the "Sol de Mañana" field (JICA, 2013)

Before starting the tests, an inspection showed small leaks at wellhead in all the wells, but it was concluded that these would not affect the execution of the tests. The wells showed high pressure, 9-15 bar-g, at the wellhead (Villaroel, 2014), therefore, it is very likely that when the valves of the wells will be opened, it will be possible to start production.

It was decided to install a 20,600 m^3 big pond because it was presumed that well SM-4 well would not have the capacity to inject all the brine from the production wells. The injection is driven by gravity due to the difference of height between the wells. Results of the well testing are described in the following chapters.

3.1.1 Production wells

Well SM-1
Several measurements were carried out during and after the well was drilled in 1988, including temperature and pressure profiles, thermometry and injectivity tests. A mass flow of 370 ton/h was determined with a pressure of 45 bar, a temperature of 230°C, an enthalpy of 1,060 kJ/kg and with the water level below 850 m as shown in Figure 6 (ENEL, 1989a).

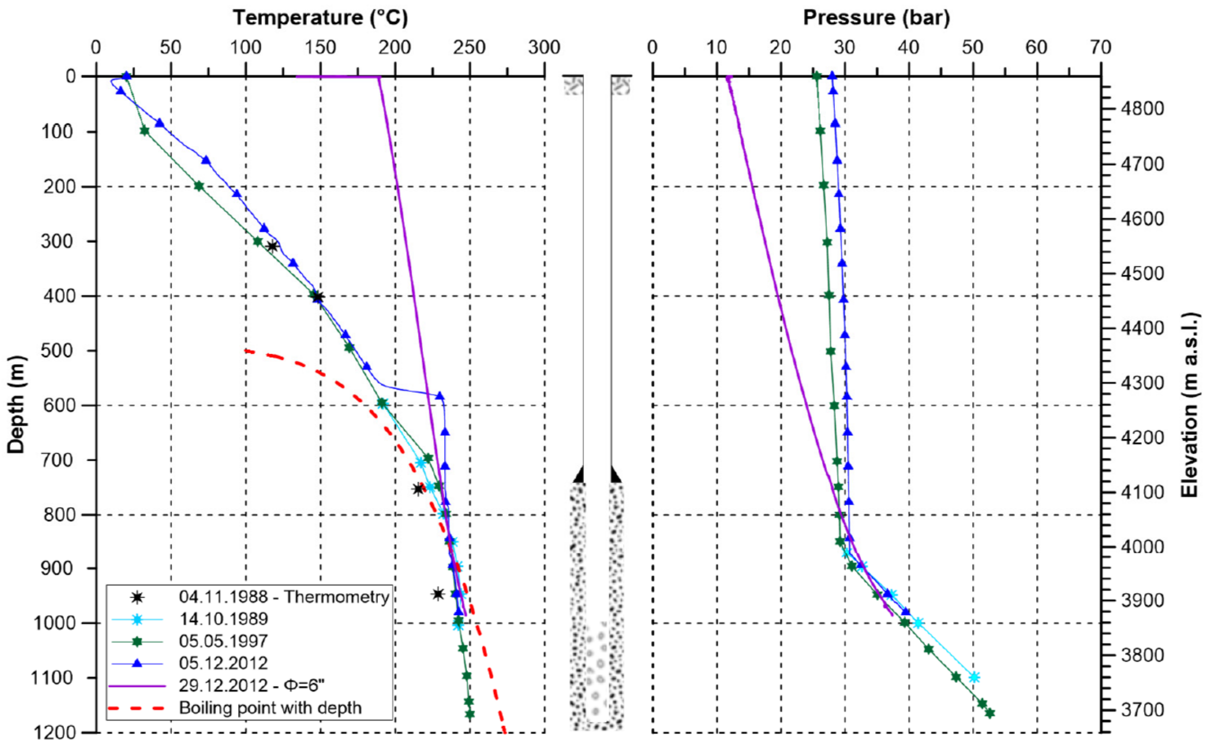


FIGURE 6: Temperature and pressure logs in well SM-1 (Ramos, 2015)

Well SM-2
This production well was drilled down to 1,486 m depth in 1988-1989. In the post-drilling tests, it was determined that the well has a reservoir temperature of 250°C and a pressure of 55 bar (Figure 7). In the following test during the evaluation of the well, the pressure and temperature of the well were registered, flowing through a regulated valve equivalent to a 2"diameter hole towards the silencer.

The fluid feed from the reservoir to the well is compressed liquid and the evaporation point is located at approximately 1,000 m depth (ENEL, 1989b).

Well SM-3
This production well has a TVD (true vertical direction) of 1,406 m, drilled in 1989. The well has two permeable zones from 950 to 1,000 m depth and from 1,200 to 1,400 m depth. With a reservoir pressure of 55 bar and a temperature of 260°C (Figure 8), different production tests determined a mass flow of 250 tons/h with a head pressure of 8 bar and an enthalpy of 1,050 kJ/kg (ENEL,1989c). Records of pressure and temperature were made in static conditions determined that the water level is at 900 m depth. The pressures between the SM-1, SM-2 and SM-3 wells were monitored and an apparent connection between the SM-1 and SM-3 wells was determined with a pressure change in the SM-2 well (JICA, 2013).

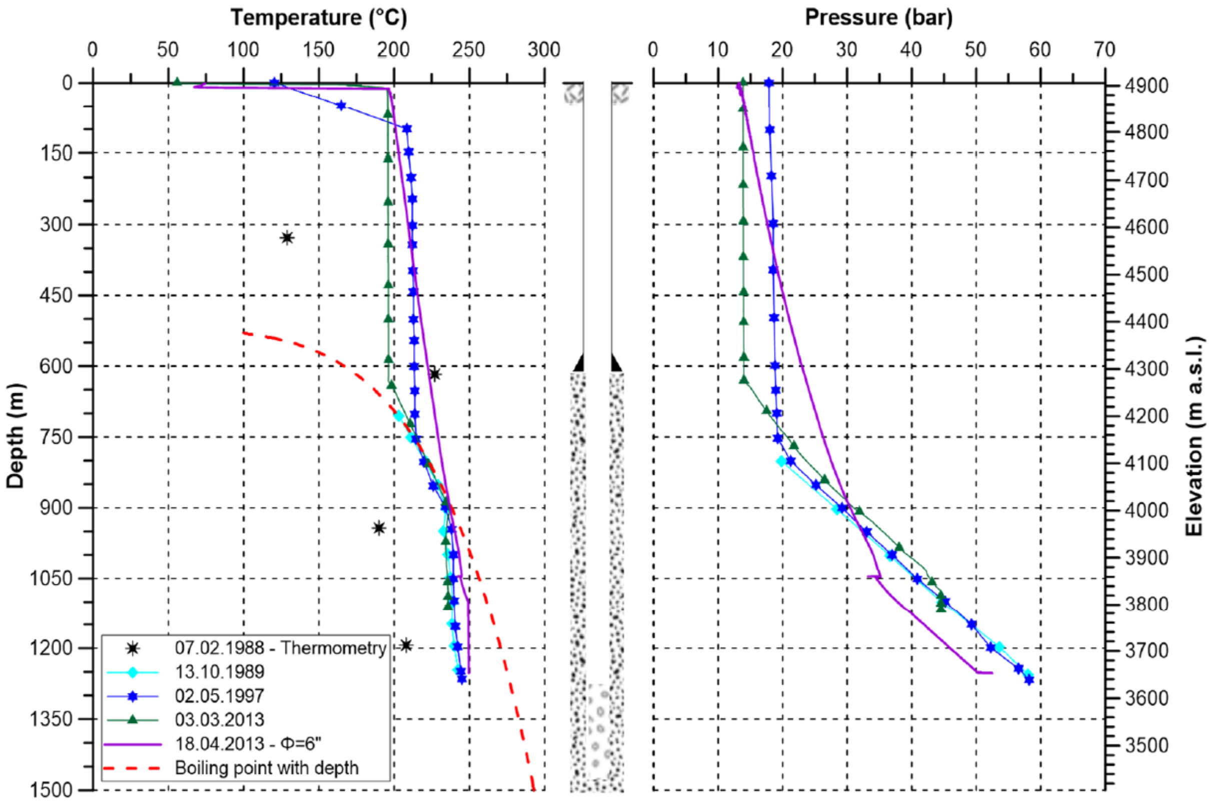


FIGURE 7: Temperature and pressure logs in well SM-2 (Ramos, 2015)

Well SM-5

The SM-5 well is a production well, drilled in 1992, to a total depth of 1,705 m, a reservoir pressure of 55 bar, temperature of 262°C and wellhead pressure of 2.82 bar. The water level in this well is at 400 m

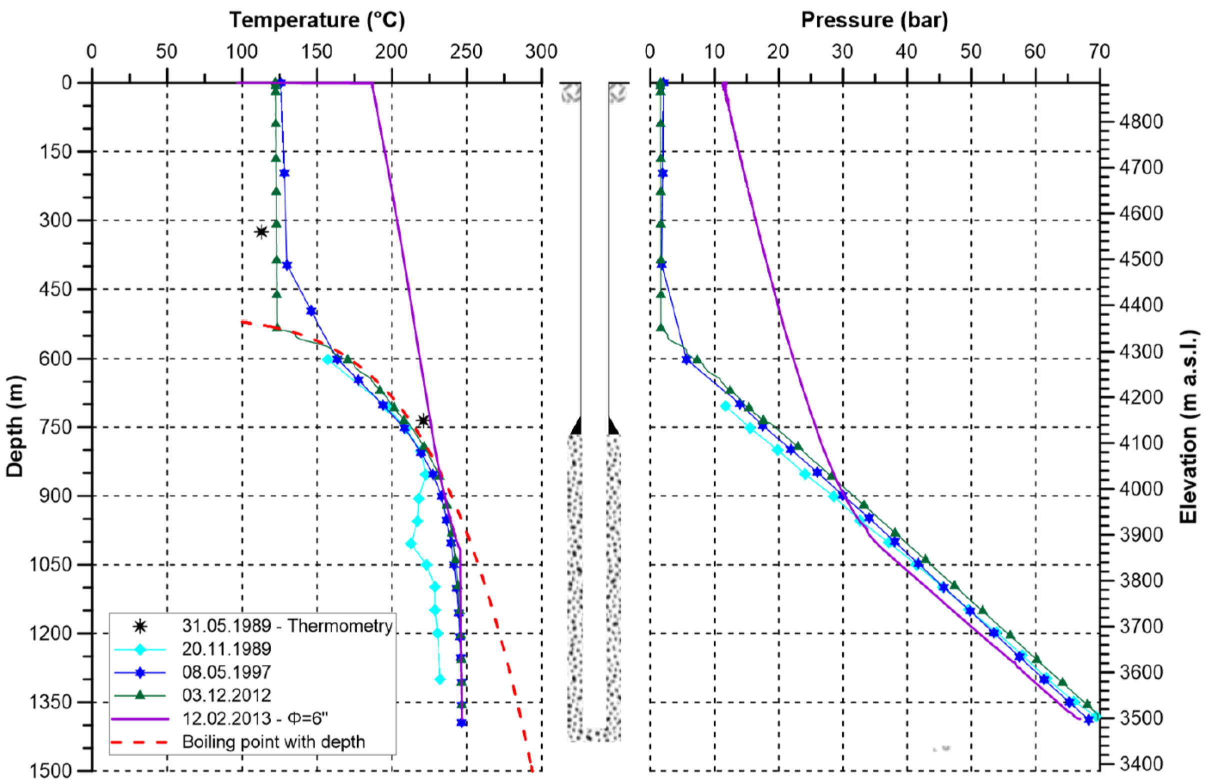


FIGURE 8: Temperature and pressure logs in well SM-3 (Ramos, 2015)

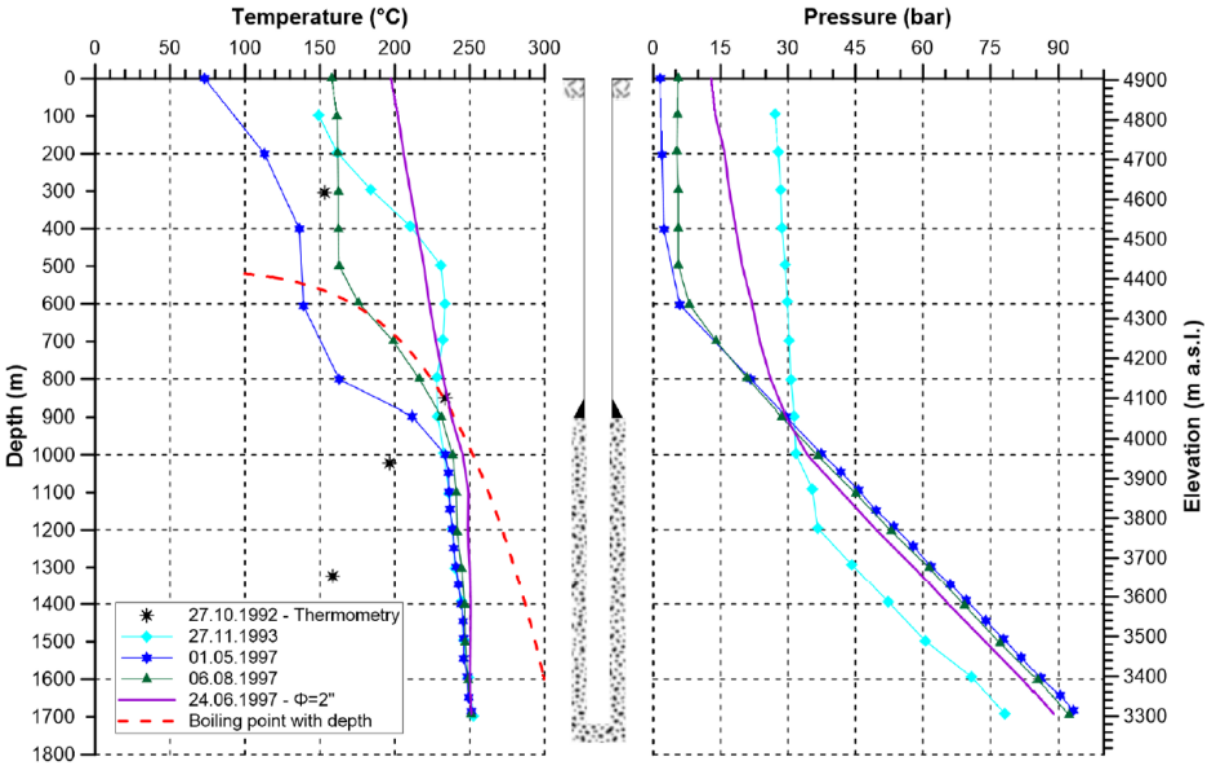


FIGURE 9: Temperature and pressure logs in well SM-5 (Ramos, 2015)

FIGURE 10: Well SM-5, teschemacherite coats the well (JICA 2013; Villarroel, 2014)

depth and the curves for the recovery of the well is shown in Figure 9 (ENEL, 1989d).

The first tests determined a mass flow of 230 tons/h and an enthalpy of 1,060 kJ/kg. When initiating operations for the well testing in 2013 it became evident that the well was embedded with scaling. teschemacherite (bicarbonate of ammonia - NH_4HCO_3) was found during the last well testing in well SM-02 and it is presumably also present in well SM-05 as shown in Figure 10.

Based on all the results obtained using the Russell James method, the mass flow of steam and brine and the enthalpy for wells SM-1, SM-2 and SM-3 was determined as shown in Table 2 (Villarroel, 2014). For more details, see Appendix I.

After the production tests, chemical analysis of steam and brine were carried out, finding the following:

- The chemical characteristics of the fluids differ between the wells;
- The production brine shows neutral pH (approximately 7) and has no corrosive element except for chlorite (Cl). It is suitable for the operation of the generation plant.
- Salinity is relatively high (Cl = 5,100-5,800 ppm-wt).

TABLE 2: Results of flow rate measurements and enthalpy calculations using the Russel James method (Villarroel, 2014)

Well	Opening (“)	WHP (bar-g)	Total flow (tons/h)	Enthalpy (tons/h)	Steam flow (tons/h)
SM-1	2	14.3	43.2	1,160.1	15.2
	4	15.0	159.4	1,076.2	50.1
	6	12.2	251.5	1,120.0	83.9
	10	10.7	289.0	1,112.6	95.5
SM-2	2	13.2	41.1	1,102.9	13.4
	4	14.4	145.7	1,088.0	46.6
	6	11.4	237.7	1,091.8	76.4
	10	9.6	283.7	1,092.8	91.3
SM-3	2	12.7	38.1	1,186.6	13.8
	4	13.5	146.7	1,071.3	45.8
	6	11.7	208.7	1,058.5	64.0
	10	8.9	270.0	1,068.6	84.0

- The concentration of boron (< 0.3 mg/l) and arsenic (< 0.01 mg/l).
- The concentration of non-condensable gases in the steam is very low (~ 0.4 l / kg condensate (Villarroel, 2014)) reducing the load on equipment for extracting these gases from the condenser.
- The concentration of H_2S in the vapour is also very low (< 9 mg / kg of reservoir liquid).
- With the exception of non-condensable gases, no great difference is observed in the chemical characteristics measured during the past production tests and those of the present study.
- The incrustation in the wellheads of SM-2 and SM-5 is teschemacherite (NH_4HCO_3), soluble in water (JICA, 2013).

3.1.2 Injection wells

Well SM-4

Well SM-4 is a reinjection well with a TVD (true vertical direction) of 1,726 m, a pressure of 90 bar and a temperature of 260°C in the bottom of the well. The water column inside the well reaches to 550 m depth. Three different injectivity tests were carried out during the first test and determined an index of 2 tons/h/bar and a capacity of 130 tons/h to inject by gravity. It is presumed that this well is located in the outer limits of the reservoir and during this test, 41 tons/h were injected over the period of one month without showing indications of increased wellhead pressure (ENEL, 1989e).

The second test was conducted with the siphon method which uses two types of pipes, one inside of the well and the other one for the siphon. The injected water dissipates into the soil trapping air and causing a vacuum inside the well. The greater the permeability of the well, the greater the degree of vacuum. When the predetermined degree of vacuum is achieved, the pipe valve (which functions as a siphon) opens. A large amount of water can be injected by this method, depending on the water level and the height of the pipes.

The injection was carried by the siphon method (see Figure 11). The reinjection capacity of SM-4 well was estimated to be 59 m^3/hour based on water level changes (from 135.5 (318 m^3) to 122 cm (266 m^3) in 53 minutes). Therefore, it is expected that the reinjection capacity of SM-4 well could exceed 100 m^3/hour, according to the results of the previous test.

During the injection into SM-4, it is observed that the temperature increases gradually from 82°C at surface to 89°C at a depth of 1,650 m. In case that the injection water level is increased to zero meters/surface, the pressure inside the well at a depth of 1,500 m is estimated to be 128 bar. According to the PTS data acquired during the injection (Figure 12), a difference was identified in the relationship between injected flow and the dynamic pressure for small (less than 25 t/h) and larger flow rates.

FIGURE 11: Set up for the siphon method (JICA, 2013)

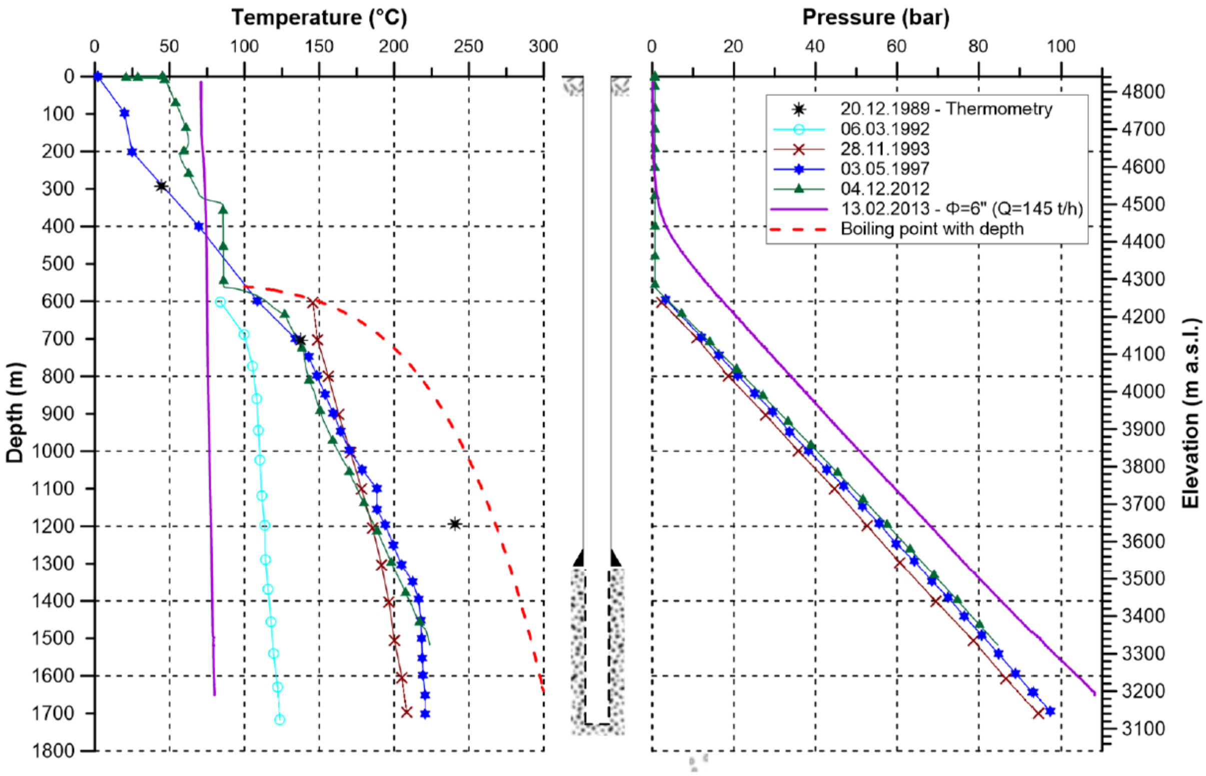


FIGURE 12: Temperature and pressure logs in well SM-4 (Ramos, 2015)

This difference can be caused by friction in the 7" slotted pipe since the gradient of the PTS pressure inside the well was found to be higher than estimated with the smooth surface. In this case, the SM-4 injectivity exceeds 600 tons/h (JICA, 2013).

3.2 Test equipment for production and reinjections wells

In the following section the equipment necessary for well testing and for monitoring of the geothermal wells will be described. Firstly, a 10" ANSI 900 master valve and two 3" ANSI 900 side valves (Geological and Mining Institute of Spain, 1981) are needed. Due to the high temperatures during the tests, thermal expansion will occur which requires the well to be anchored using guide wires or rods that are attached to the 10" flange and to the floor of the well pad.

From the master valve runs a straight steel pipe with a 10" diameter and a length of at least 25 meters. The connections of the sections of the pipeline need to sustain a two-phase fluid with a pressure of up to 20 bar-g and a temperature of approximately 200°C.

TABLE 3: Parameter of the flow and environment in Sol de Mañana (JICA, 2013)

Field parameters	Values
Wind velocity	25 m/s
Max. noise permitted	68 dB
Tmin	-17 °C
Tmax	12 °C

The silencers to be used will be those of conventional portable type, constructed of steel plates and with a tangential inlet to ensure spiral flow of the geothermal fluid which, unless overloaded, will ensure sufficient separation capacity (OLADE, 1980). The basis of the test realised before estimated a flow of steam at 125 tons/h with a velocity of 3.7 m/s of steam upwards the silencer to open air, and 260 tons/h of brine. Field parameters like noise level are shown in Table 3 (JICA, 2013).

After the separation of the fluid in the silencer the brine will be deposited in the weir box. The capacity of this equipment has to match the amount of brine produced which was estimated to be 260 tons/h with a velocity of 0.6 m/s. From the weir box the brine will be transported to a pond and afterwards to the injection wells using a HDPE pipe with a diameter of 10" or 12" (JICA, 2013).

3.3 Procedure for discharge

After demobilization of the rig starts the installation of the equipment for the well testing, that is the discharge wellhead, the silencer, the weir box, pipes and valves. All parts must be correctly and safely installed to start the production tests.

On well pad 3 are three production wells, SM-3 which is an old well and two new well SM-31 and SM-32. The well pad for injection is well pad 4 on which well SM-4 (old well) and 3 new wells are located. When the test starts, two older wells SM-1 and SM-2 are monitored. Location of the wells can be seen in Figure 13 (ENDE, 2017).

During the well testing, the drilling campaign continues. The distance between SM-1 and SM-3 is 0.67 km, and between SM-2 and SM-3 is 0.72 km. For the initial flowing of the SM-31 well, the distance of the adjacent drilling will be considered to verify that the noise and wind do not affect the personnel working on the drilling rig and the well tests (Figure 16) (JICA, 2013).

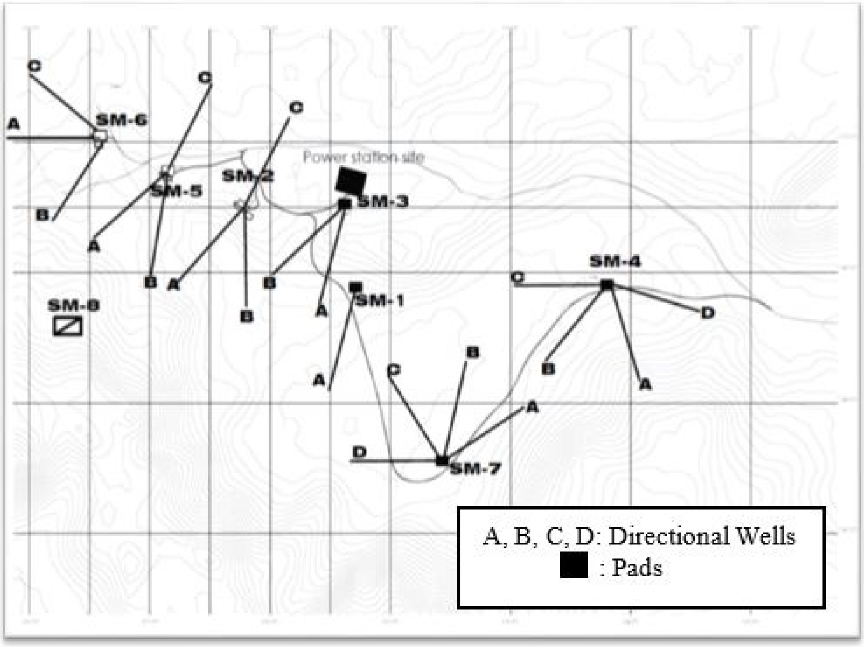


FIGURE 13: Production and injection wells in Sol de Mañana field (ENDE, 2017)

After the final cleaning of the well, the master valve is connected and the manometers and thermometers installed. The elongation of the anchor casing is evaluated based on the heating of the well.

When the water level reaches the wellhead the heating phase starts, but if this does not happen within a reasonable waiting time of 30 days, the column is stimulated. In the case of the Sol de Mañana field, stimulation has to start immediately because drilling activities have to be continued and the interconnection studies of the wells carried out (Geological and Mining Institute of Spain, 1981).

For stimulation the airlift method is used. To initiate the stimulation, a 2" diameter pipe is introduced into the well below the water level. A compressor feeds air under pressure into the water column to achieve lightening. During the process the water temperature must be monitored once this operation is carried out. More air is introduced until the well begins to flow on its own and the production flow can be monitored by the regulating valve.

Because the flow is primarily biphasic, the Russel James method is applied. Its installation is simple, it has the capacity to accommodate high and long-lasting flows and has been used successfully in previous tests.

The operation will be carried out for a period of 30-40 days. The results will be evaluated according to the different flow rates to be controlled by the control valves, which are located in the well flow line which goes to the silencer and later to the master valve (Geological and Mining Institute of Spain, 1981).

The operation will be carried out for a period of 30 to 40 days. In this time the well will be tested with different orifice plates estimating the pressures and the mass flow to generate the well production curve. The output will be monitored as shown in Figure 14.

a) Well head pressure (WHP);
b) Critical pressure (Pc); and
c) Water level in the weir box.

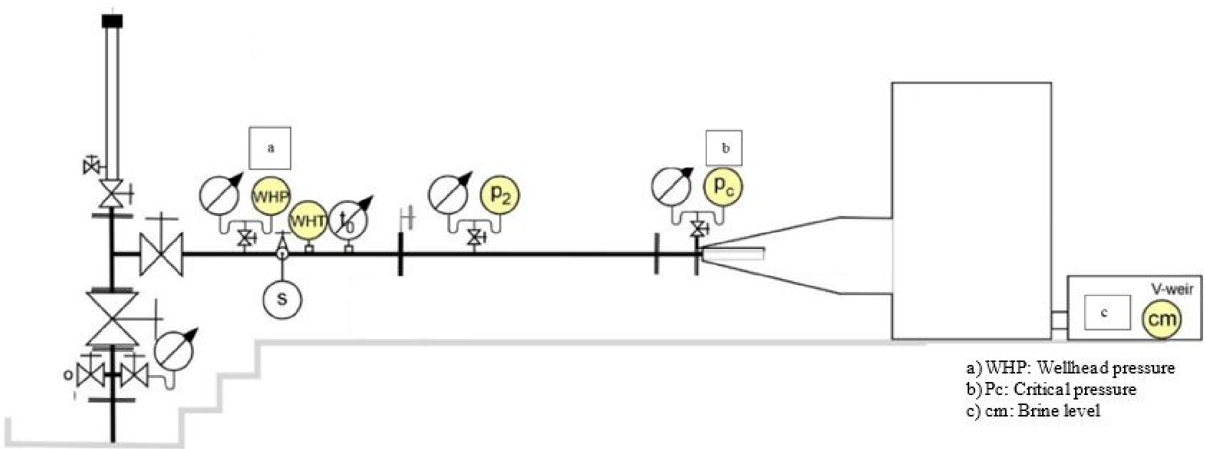


FIGURE 14: Monitored points during the well testing (ENDE, 2017)

The data obtained is necessary to calculate the mass flow (kg/s) and the enthalpy (kJ/kg) for each stage of the flow test at different wellhead pressures (WHP).

One of the results of the tests is the amount of brine to inject into the injection wells. Knowing that the one of the main problems during the well testing is the injection of the brine because it can cause scaling of teschemacherite. The minerals saturation index is closely monitored in the fluids.

The well pad number 4 will be used for the injection. On this well pad is an older well and three more wells are planned. For the well test SM-4 (old well) and SM-41 (new well) are used. The existing well has a capacity of 600 tons/h, assuming that the additional well will have the same capacity the total injection capacity is approximately 1,200 tons/h. The simultaneous well tests will be carried out between 4 open wells. The production of the three existing wells is 842.7 tons/h (data taken from Table 2 in this report) and estimating that the SM-31 well will have a capacity similar to that of the existing wells, total production would be approximately 1,112.7 tons/h, so the injection capacity would be sufficient.

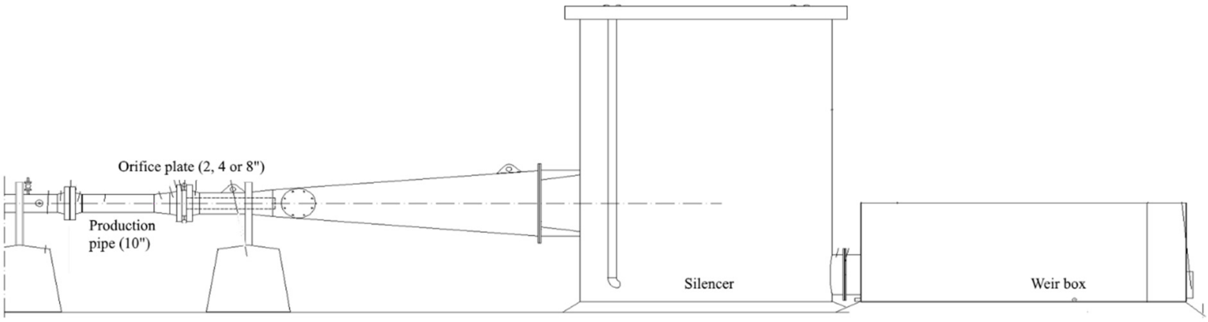


FIGURE 15: Equipment for well testing (ENDE, 2017)

Optionally, the brine can be used to support the water supply during drilling in the second stage (9⅝ anchor casing) when a special additive called attapulgite (clay) is used which has the ability to adapt and create the same gel and viscosity conditions in the brine that has the bentonite in fresh water.

The equipment used for the well testing is shown in Figure 15. The installation will start at the existing wells SM-1 and SM-2. For the testing of the other wells the drilling of well SM-31 has to be finished before the installation of equipment (ENDE, 2017).

The first activity on the well pad of SM-3 will be the workover for the installation of the new arrangements of the wellhead. The subsequent drilling of the SM-31 well is estimated to take approximately 60 days and completion of the well will take about 3 days. Pressure and temperature tests to analyse if stimulation is required is the last step.

If the well requires stimulation the airlift method will be applied pumping compressed air into the well to lower the water table through the side valves and with the master valve closed. The wellhead pressure (WHP) has to monitored to ensure that the collapse pressure in the shoe of the production casing due the air compression is not reached. In most of the wells drilled in the Sol de Mañana filed to date this is around 20 bar, but must be confirmed for each well in the pressure records (ENDE, 2017).

When well SM-31 is ready for well testing, all of the equipment for the method of Russell James using the initial orifice plates with diameters of 4", 6" and 8" will be installed. The diameters were selected based on the results obtained in the last production tests. The first discharge opening the well will be with a 4” orifice plate lasting approximately 5 days or until the well stabilizes. Wellhead pressure and critical pressure are monitored and samples of the steam and condensate taken. Afterwards the same procedure will be carried out with a 6" orifice plate and finally with an 8" plate.

This discharge will be carried out for a period of 5 days or longer until stability is reached (constant wellhead pressure). During the opening, the pressure, temperature and steam and brine flow are monitored to obtain the first production curves. To perform the PT in dynamic conditions pressure and temperature surveys will be re-performed after finding the well balance. These measurements have a duration of half a day. The results of the measurements are shown in Figure 16.

At the end of the test using the 8"orifice plate, the tests continue using the 6" and 4" orifice plate for 5 days with the aim to obtain the production curves and determinate the potential of the well. During the test the temperature and pressure and the height of the water column in static conditions are monitored in wells SM-1, SM-2 and SM-3 to observe potential changes to prepare for the simultaneous well testing.

After finishing the test of the SM-31 well that will last approximately 30 days, the simultaneous tests will be started by opening the 4 wells (SM-1, SM-2, SM-3 and SM-31) at the same time for an estimated period of 5 days, using 8" orifice plates. The interference between the wells will be identified to verify the reservoir's production capacity. The parameters that are monitored during the test are the wellhead

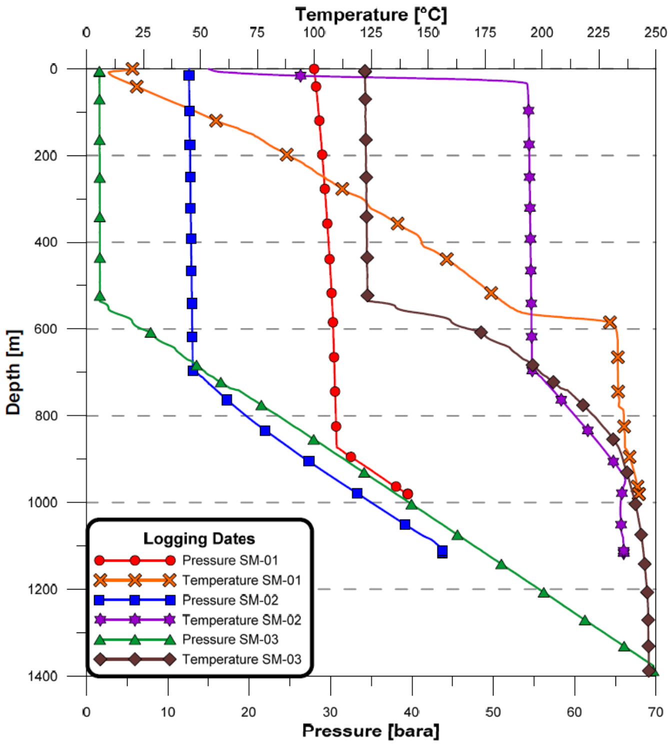


FIGURE 16: Pressure-temperature profiles (Villarroel, 2014)

pressure, the temperature and the height of the water column. This data is used to update the conceptual model of the field.

During the tests, sampling of both brine and steam is carried out. The samples are taken from the pipe line that connects the well head to the silencer by using a single cyclone separator at line pressure. Both gas and water samples will be collected at this point. Water samples are also taken from the weir box at atmospheric pressure (ENDE, 2017).

From the samples taken, the pH, chloride, silica, sulphate and the CO_2/H_2S content will be analysed. Throughout the duration of the tests for each orifice plate, a sample will be taken every 8 hours of both brine and steam. Some of the tests can be performed on site and other samples will be taken to be analysed in a laboratory (JICA, 2013).

3.4 Safety during the production testing - handling gas from the well

The initial release of gas from the well to the atmosphere requires special safety measures. It is a cold gas and should be handled in the following manner:

- When the well opens, the gas flows out that has accumulated above the water table in the well (or compressed air).
- The site must be evacuated before the opening of the well and only personnel with defined roles and equipped with the necessary personal protective equipment will be allowed on the site.
- Only a person using a self-contained breathing apparatus should open the well. Additional breathing equipment must be on site to be used in emergencies. The person opening the well should be ready to close the well immediately in case of emergencies or signs of insufficient air quality on and around the site.
- A pole with a plastic band or a flag (wind sleeves) must be in place to observe the predominant direction of the wind. Preferably, the well should not open when the prevailing wind is toward the nearest home or camp, if applicable.
- Because CO_2 is heavier than N_2 and O_2 in the atmosphere, it is likely to accumulate and spread through valleys or depressions. The areas where CO_2 accumulation can be expected must be identified before the opening of the well and evacuated and/or monitored with a gas meter.
- The risk of exposure to the gas is greater when the potential cold gas from the well is released at the start of the discharge. Once the steam reaches the surface, the hot steam that rises to the sky takes the gas with it. Depressions around the well site may contain CO_2 pockets that must be monitored.
- The most dangerous gas found in the steam is hydrogen sulphide (H_2S) but in comparison with other geothermal fields, its concentration is very low (50 ppm in total NCG) in the Sol de Manana field. Therefore, no harmful exposure to H_2S is expected, but for prevention workers will carry multi-gas personal safety monitors (ENDE, 2017).

3.5 Content of the test report for the production wells

After the production tests, a report will be prepared which includes the measurements made in the wells for each change of diameter of the orifice plates, and the contents of the fluid samples taken during each stage. The minimum data to be included is the following:

- The measurements made in the wells during the completion and recovery of the well, the pressure and temperature profiles identifying the permeable zones (Grant and Bixley, 2011).
- A summary of all the production tests carried out to date, to verify if there are any changes in the enthalpy, the mass flow, the geochemistry of the fluid and to verify that there is no teschemacherite (NH_4HCO_3) present to avoid fouling in the well and the valves (Villarroel, 2014).
- All the manoeuvres carried out during the opening of the well, all the changes of the orifice plates and obtained wellhead pressure curves and the lip pressure (measurements made at the entrance of the silencer) depending on the opening time and mass flow. The results of all these tests are shown in the Figure 17. The volume of brine produced that is determined in the weir box and based on the data the steam curve and the brine flow as a function of head pressure (JICA, 2013).

In the simultaneous test we will verify how the wells are connected by geological structures, the mass flow changes will be identified as well as the enthalpy and the wellhead pressure (Figure 18).

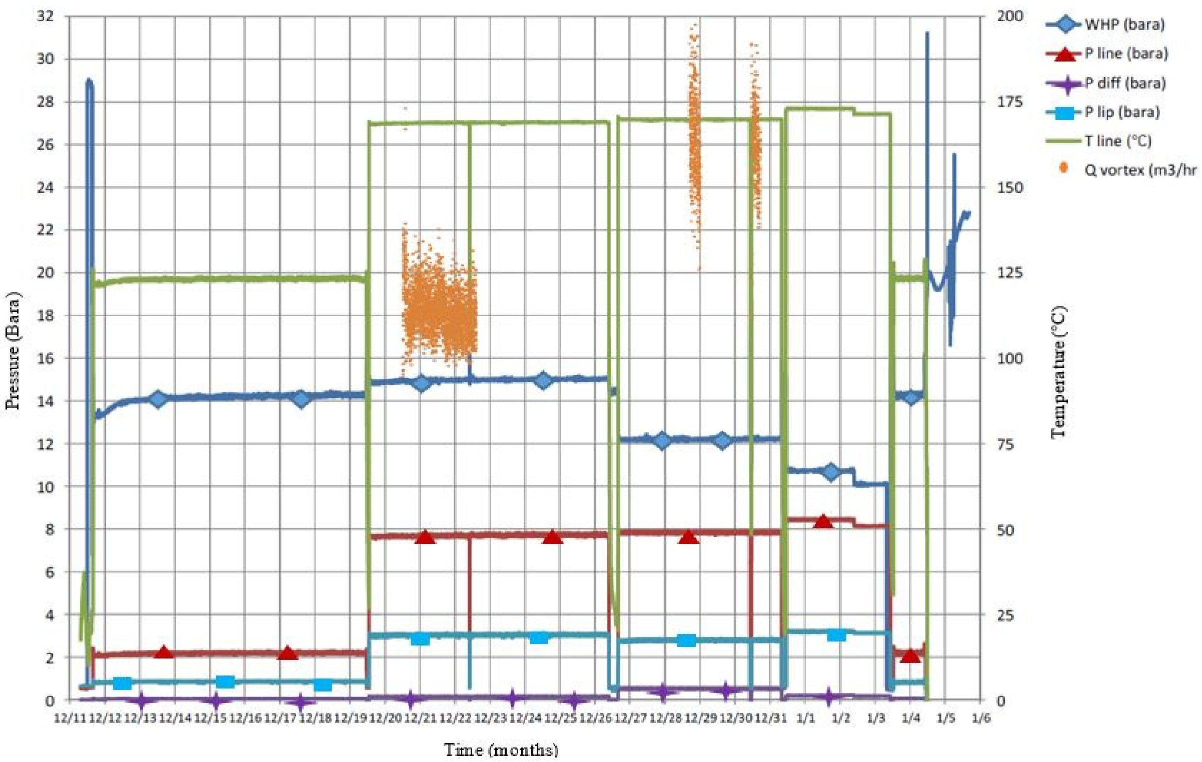


FIGURE 17: Measurements with the different sizes of orifice plates (3", 4", 6" and 10") in Sol de Mañana field (JICA, 2013)

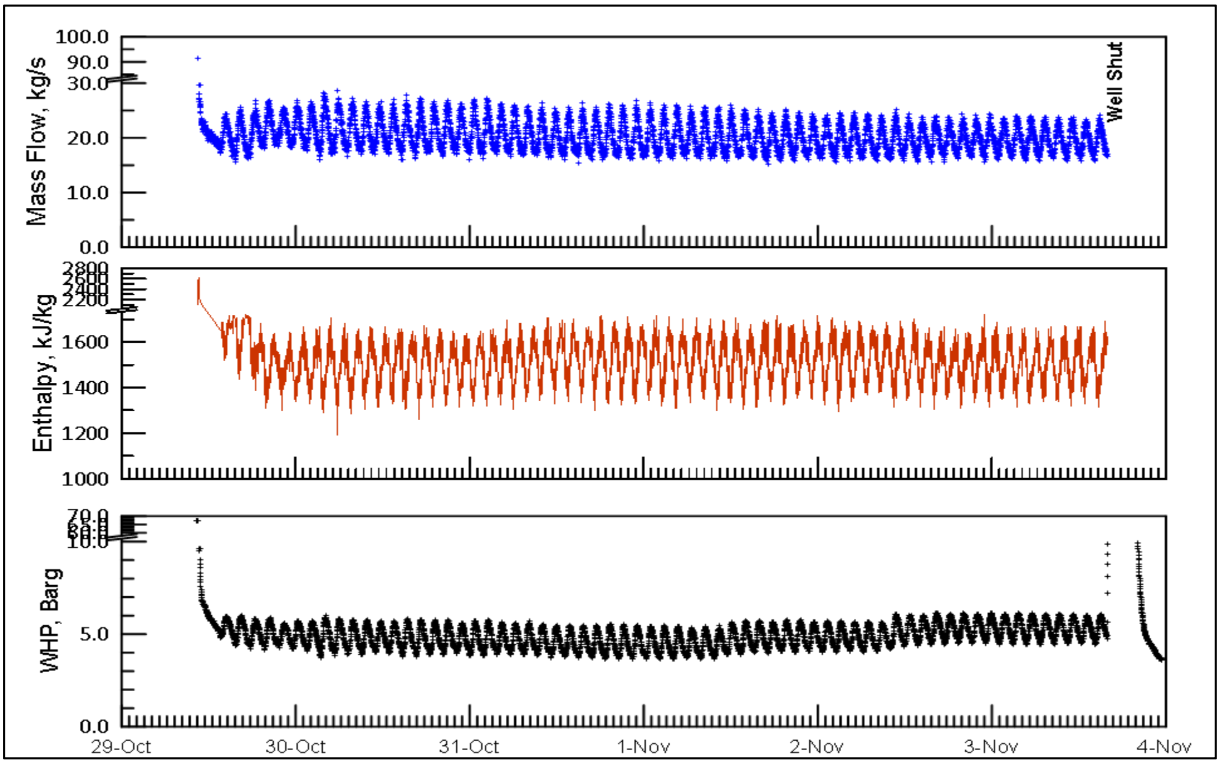


FIGURE 18: Simultaneous discharge output trends (ENDE, 2017)

3.6 Schedule for testing production wells

The production tests will be carried out in parallel with the drilling. Table 4 shows the scheduled activities.

TABLE 4: Activities for well testing and drilling

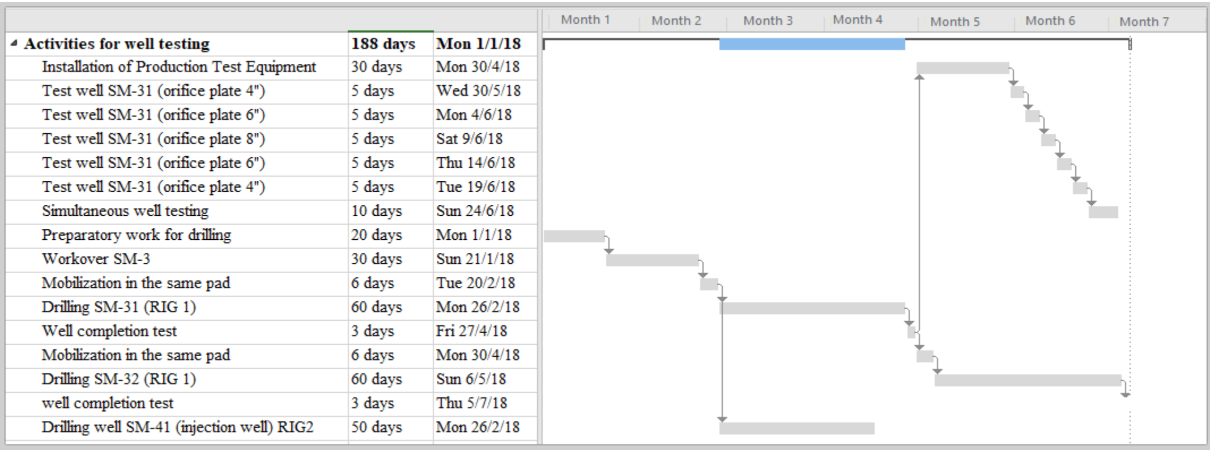
Activities for well testing	Duration (days)
	188
Installation of production test equipment	30
Well test SM-31 (orifice plate 4")	5
Well test SM-31 (orifice plate 6")	5
Well test SM-31 (orifice plate 8")	5
Well test SM-31 (orifice plate 6")	5
Well test SM-31 (orifice plate 4")	5
Simultaneous well testing	10
Preparatory work for drilling	20
Workover SM-3	30
Mobilization on the same pad	6
Drilling SM-31 (RIG 1)	60
Well completion test	3
Mobilization on the same pad	6
Drilling SM-32 (RIG 1)	60
Well completion test	3
Drilling well SM-41 (injection well) RIG 2	50

During the first activity, the final design of the drilling programme will be reviewed. Meetings will be held before drilling; the two rigs will be mobilized and the drilling equipment will be prepared for the climatic and height conditions.

The next activity is the workover of the SM-3 well (first platform to be evaluated during the tests). The well will be cleaned and the production liner will be installed. After that the drilling of SM-31, which will last 60 days, and the drilling of SM-41 reinjection well will start.

After completing the drilling, the production equipment for the SM-31 well will be installed and the testing of this well and the simultaneous tests will be started.

After the installation of the heads and performance of the final tests, the rig will be mobilized and moved to the next well which is in 60 m distance to continue drilling. The distance is sufficient to ensure no effect on any of the other activities. Figure 19 shows all the activities (ENDE, 2017).



Activities for well testing	188 days	Mon 1/1/18
Installation of Production Test Equipment	30 days	Mon 30/4/18
Test well SM-31 (orifice plate 4")	5 days	Wed 30/5/18
Test well SM-31 (orifice plate 6")	5 days	Mon 4/6/18
Test well SM-31 (orifice plate 8")	5 days	Sat 9/6/18
Test well SM-31 (orifice plate 6")	5 days	Thu 14/6/18
Test well SM-31 (orifice plate 4")	5 days	Tue 19/6/18
Simultaneous well testing	10 days	Sun 24/6/18
Preparatory work for drilling	20 days	Mon 1/1/18
Workover SM-3	30 days	Sun 21/1/18
Mobilization in the same pad	6 days	Tue 20/2/18
Drilling SM-31 (RIG 1)	60 days	Mon 26/2/18
Well completion test	3 days	Fri 27/4/18
Mobilization in the same pad	6 days	Mon 30/4/18
Drilling SM-32 (RIG 1)	60 days	Sun 6/5/18
well completion test	3 days	Thu 5/7/18
Drilling well SM-41 (injection well) RIG2	50 days	Mon 26/2/18

FIGURE 19: Schedule for well testing

4. CONCLUSIONS AND RECOMMENDATIONS

The geothermal field Sol de Mañana is located in Bolivia in the department of Potosí Sud lipez Province. Surface studies and 5 wells are suggested enough to confirm a potential of 100 MWe. ENDE has decided to drill 25 geothermal wells and install two units of 50 MW_e capacity. To obtain the number of wells required for 50 MWe it is necessary to perform simultaneous tests of the geothermal wells to confirm their geothermal potential.

The most suitable for production tests depends on the type of fluid that occurs in the reservoir. In the Sol de Mañana field the dominant fluid phase is liquid and it is necessary to make an interference tests to quantify the connection between the wells that will be drilled for the generation of 100 MWe. Based on the need it was decided to use the Russell James conventional method. Necessary equipment is economic and easy to install. The equipment is portable and can be used without any activity being affected.

The equipment used during the tests is the surface arrangement, that is the master valve, the side valves, a steel pipe from the well head to the silencer (10") to the silencer, a HDPE pipe for the injection, 4", 6" and 8 "orifice plates, a weir box and a pond. It was tested how much brine can be injected.

All wells located on well pad SM-3 will be tested. The tests will be carried out on the new SM-31 well while monitoring the SM-1, SM-2 and SM-3 wells. Subsequently, simultaneous test will be carried out between the previously mentioned wells while SM-4 and SM-41 will be initiated as injectors. The test will last approximately 40 days.

For safety in the area of drilling and testing the speed and direction of the wind must be monitored continuously to control the emission of H_2S and CO_2 into the environment and as well as the noise. A nose limit of 68 dB must not be exceeded.

Brine content must be monitored to identify potentially present teschemacherite (NH_4HCO_3) to avoid fouling in the valves and in the production wells.

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APPENDIX I: Production well test result (SM-1 and SM-3) (JICA, 2013)