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ENVIRONMENTAL CONSIDERATIONS IN PRODUCTION TESTS AND GEOTHERMAL WELL STIMULATION

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ABSTRACT

The production test is one of the most important activities in geothermal development because through the production test the properties of a reservoir become known, and in this way, the amount of energy that can be extracted from it, can be evaluated. However, these tests involve certain environmental aspects that will have to be managed, such as the emission of gases and wastewater, generation of noise, etc. During well production tests in the Hengill geothermal field, environmental aspects involved in well discharges were investigated for well HE-58, using a 35-day data period with records of water amount, steam discharge, and gas emissions to the atmosphere and the ground. For well HE-21 the amount of Fluoride (as KF) discharge into the water and the amount sulphur hexafluoride (SF_6) is discharged in the steam was monitored.

Another important activity is stimulation which is used when there is a decline in pressure in the well. This activity, though necessary, may have undesirable environmental effects.

In this report discharge tests using lip pressure, tracer flow, and stimulation through matrix acidification, are analysed. For environmental analysis, the DASI method for identifying effects is used, and the RIAM method to evaluate the magnitude of the impacts. Finally, activities to minimize environmental effects are considered such as: using of a muffler, mitigation of H_2S emissions, designing and planning a monitoring system for air and water, checking equipment and leakage, and other considerations for the minor impacts.

1. INTRODUCTION

Well tests are important for field development decisions, because this is the first step in evaluating the amount of energy that can be extracted. Discharge tests after warm up of the well are a key to the estimation of the capacity and the success of the well. During energy production from a geothermal reservoir, monitoring data is collected to continuously upgrade the model of the reservoir. All this information is essential for a successful assessment of a reservoir. The capacity of a geothermal field can be determined from its size, heat content and production response. The first assessment of a geothermal field capacity is usually done by a volumetric method (Muffler and Cataldi, 1978).

In this paper, two different methods for evaluating the flow of a well are analysed: lip pressure and tracer flow tests, in wells HE-58 and HE-21, respectively. These wells are a part of a production well system in the Hellisheidi and Hverahlíd areas in the Hengill geothermal field.

Production tests are important to obtain knowledge of the potential energy and other characteristics of a reservoir. However, this activity involves different environmental aspects: such as gas emission, noise, wastewater, etc., so it is necessary to establish the possible environmental effects and actions to be taken when performing a production test in order to prevent possible negative environmental and social impacts on different environmental components such as water, air, soil, flora, wildlife etc.

One activity that may be important during production tests is stimulation, because it involves the injection of different chemicals in quantities that need to be considered in the environmental study. Stimulation is needed when flow has declined because of scaling or for other reasons. Sometimes it is not possible to discharge a well, because some wells develop scales or encounter other ways of flow restriction. Different methods of well stimulation exist, such as the use of chemicals that are injected into the well and upon discharge the fluid composition changes, because of reactions in the well. In this paper, an environmental analysis will be conducted to define environmental effects to be monitored.

2. OVERVIEW OF DRILLING

2.1 Short description of drilling

Well drilling is a vital component of geothermal exploration and the future utilization of a geothermal field. Well studies provide information such as enthalpy, steam fraction and chemical composition of the fluid that permits the estimation of the amount of energy that can be extracted from the reservoir. The main characteristics of the reservoir are size, temperature and permeability.

There are three different types of wells, production wells that are used for power generation, reinjection wells that contribute to the sustainability of the resource, and monitoring wells that are used to study the behaviour of the geothermal reservoir.

In general, geothermal wells are controlled by a main valve system that is used to ensure the stability of the well. A geothermal well is connected to the geothermal reservoir through feed-zones of open sections or intervals. Feed-zones are either particular open fractures or permeable aquifer layers. In volcanic rocks, feed-zones are often fractures or permeable layers such as interbeds (layers between different rock formations) while in sedimentary systems, feed-zones are most commonly associated with thin aquifer layers or thicker permeable formations. Fractures can also play an important role in sedimentary systems. In some instances, a well is connected to a reservoir through a single feed-zone while in other cases several feed-zones may exist in the open section, but often one of these is the dominant one; see Figure 1 (Axelsson and Franzson, 2012).

2.1.1 Classification of geothermal wells

Different types of geothermal wells with different roles are drilled into geothermal fields such as described by Axelsson and Franzson (2012): temperature gradient, exploration, production, step out, make up, reinjection, monitoring and unconventional wells. These are all important at different stages of the development of a new or existing geothermal field. The three principal types for environmental considerations are: production, reinjection and monitoring wells.

Production wells: Their main purpose is to enable the production of geothermal energy (such as hot liquid, two-phase mixture, or steam) from a specific target, or a geothermal reservoir. Production wells are designed either for spontaneous discharge through boiling (high-temperature reservoirs) or for the application of downhole pumps (low temperature reservoirs).

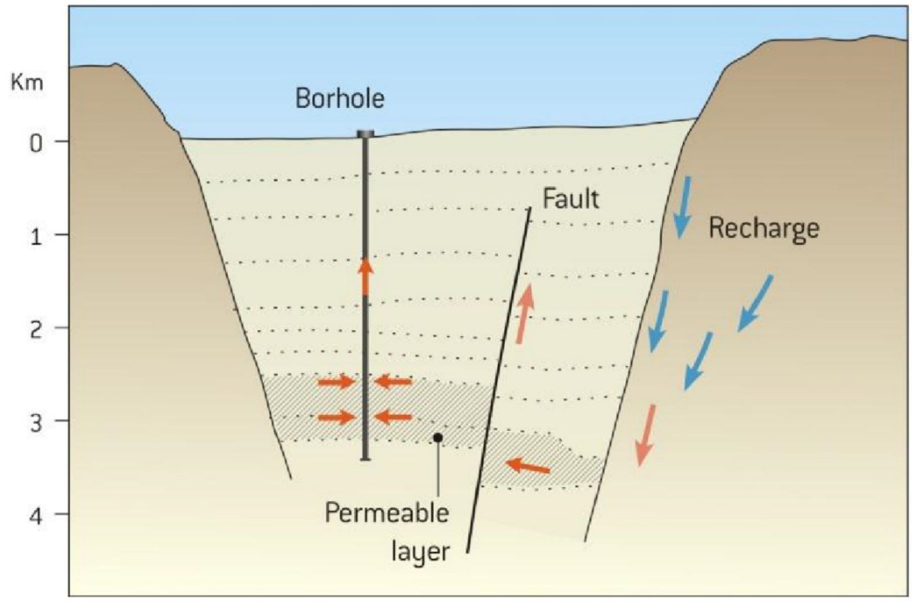

FIGURE 1: Schematic representation of a reservoir
(Axelsson and Franzson, 2012)

Reinjection wells: Reinjection wells are used to return fluid to the geothermal system or to inject water of a different origin as supplemental recharge. The location of reinjection wells is variable. Reinjection can be applied inside a production reservoir, on its periphery, below or above it or outside the main production field, depending on conditions and the purpose of the reinjection.

Monitoring wells: These are used to monitor changes in geothermal systems, mainly after utilization starts, mostly pressure and temperature changes. These are in most cases already existing wells, such as exploration wells or abandoned production wells.

Production wells can also be classified into three principal types depending on fluid enthalpy:

1. **Dry-steam high-temperature wells** where the flow from the feed-zone(s) to the well-head is steam-dominated.
2. **Two-phase high-temperature wells** where the flow from the feed-zone(s) is liquid or two-phase but the wells produce a two-phase mixture.
3. **Liquid-phase low temperature wells**, which produce liquid water at the well-head

3. PRODUCTION TESTING

The information obtained through production tests is needed to confirm whether a well was satisfactorily drilled and to decide how to utilize the reservoir. Some important reservoir and wellbore parameters are: temperature, permeability, formation storage (storability), type of reservoir (porous or fractured). Skin factor and location of the reservoir boundaries are also important. Based on the well test objectives, several kinds of tests may be designed to determine these parameters and reservoir properties. Grant et al. (1982)

3.1 Description of study area for production testing

The Hengill mountain is one of the highest mountains in the region east of Reykjavík, Iceland's capital. It is located in the centre of the western volcanic zone in Iceland, on the plate boundary between the North American and the European crustal plates; this boundary runs from Reykjanes in a north easterly direction towards Langjökull. The plates are diverging at a relative rate of 2 cm/year. Hengill mountain is on the triple junction of the Reykjanes Peninsula volcanic zone, the Western volcanic zone and the South Iceland Seismic Zone.

Within the Hengill complex, several potential geothermal fields can be distinguished. Two of these have been developed where Reykjavík Energy operates co-generation geothermal plants at Nesjavellir and Hellisheidi. The installed capacity at Nesjavellir power plant is 120 MWe and 290 MWth. The Hellisheidi power plant is also a co-generation plant with 303 MWe and 133 MWth installed. The Nesjavellir power plant is located on the northern side of the Hengill Mountain and the Hellisheidi power plant on the southern side. Other possible production fields on the southern side of the Hengill Mountain are Bitra, Hverahlíd, Gráuhnúkar, and Meitill (Figure 2).

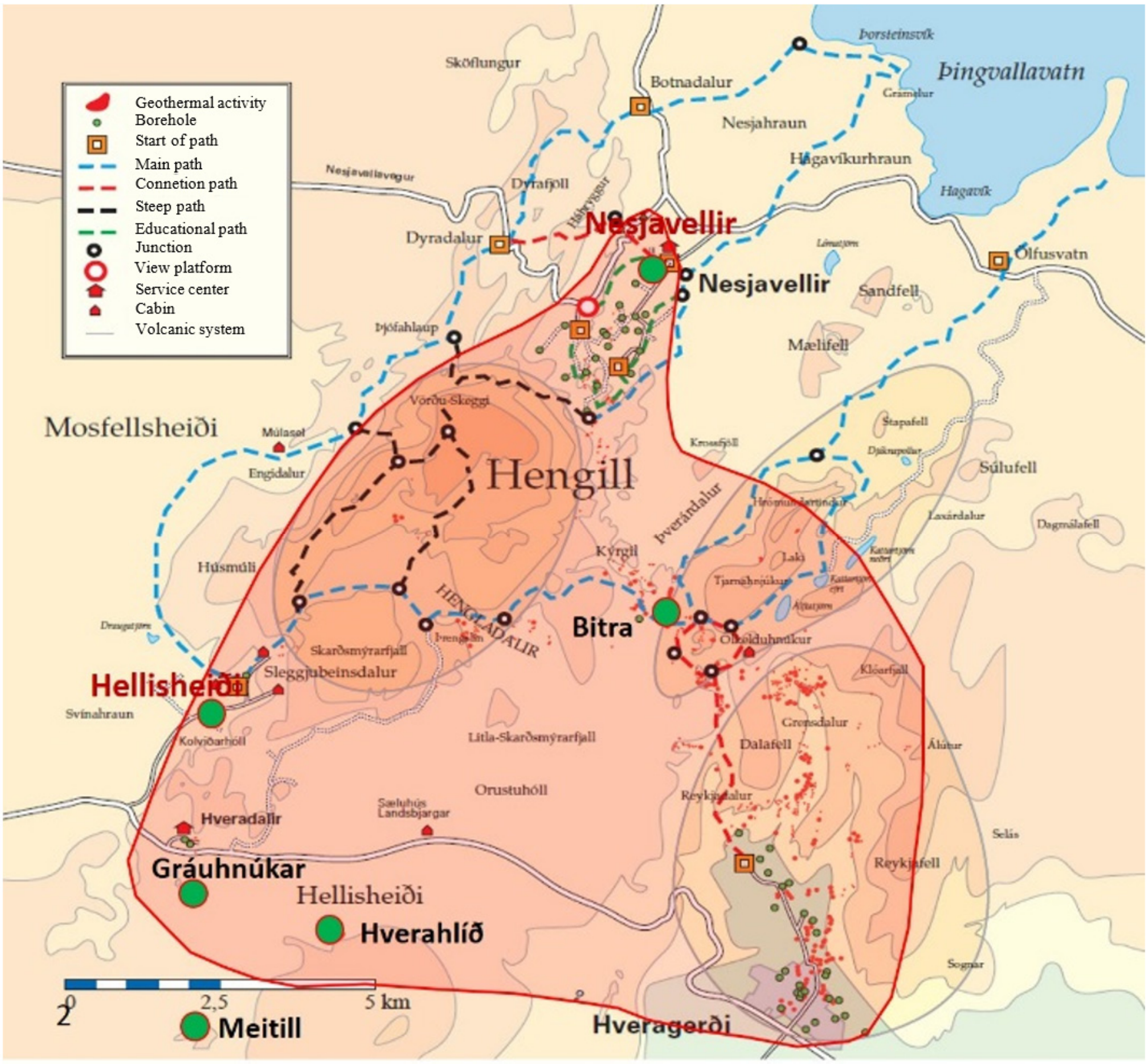

FIGURE 2: The Hengill geothermal area and some of its subfields
(modified from Gunnlaugsson, 2012)

The present well field in Hellisheidi covers some 12 km². The first exploration well was drilled in 1985 at Kolvidarhóll (KhG-1) on the western boundary of the Hellisheidi field. A total of 49 exploration and production wells have been drilled in the Hellisheidi field, the last one was drilled in 2016. The depths of these wells are in the range 1400 m to 3300 m. A total of 35 productions wells in this field are connected to the power plant. A total of 17 reinjection wells have been drilled for the Hellisheidi power plant at two locations, Gráuhnúkar and Húsmúli. The depths of these wells are 1000 m to 3000 m. The majority of both the production and reinjection wells, are deviated wells (Gunnlaugsson, 2012).

In the Hverahlíd field, a geothermal power plant was planned and it was described in an Environmental Impact Assessment report (Reykjavik Energy, 2005). Six exploration and production wells have been drilled at Hverahlíd. Four of the six wells in this field have now been connected to the Hellisheidi power plant.

Data from flow tests of two wells were made available for this study. These wells are HE-58 in Hellisheidi, which is a deviated well and HE-21 in Hverahlíd, which is a vertical well. The main features of these wells are shown in Table 1.

TABLE 1: Wells used in this study

Well no.	Field	Location Latitude	Location Longitude	Drilling date	Depth m	Length m
HE-21	Hverahlíd	385369,47	391637,00	Feb. 2006	2159	2159
HE-58	Hellisheidi	383860,83	394397,07	Nov. 2015	2237	2531

Some features that describe the environment surrounding the field are:

- The main characteristics of the **weather** are that the air temperature is on average 2.6°C lower than in Reykjavík. Humidity is higher and the wind speed on Hellisheidi is generally 70% higher than in the capital area. Rainfall is three times that of Reykjavík.
- The main characteristic of the **groundwater system** in the area investigated is that it is divided from southwest to northeast by a range of the mountains Hengill, Stóra-Reykjafell, Stóri-Meitill and Litli-Meitill. On the eastern side, water flow is to the east from Hellisheidi. The hydrology is a little more complex on the western side, with a characteristic area of 15 km^2 west of Hengill where the level of the groundwater table is at around 172 m above sea level. From there, groundwater flows in three directions: West to the Ellidaár catchment area, northeast to Lake Thingvallavatn and to the south where it reaches the sea at Selvogur. Apart from small streams in Sleggjubeinsdalur, from Draugatjörn and in Engidalur there is little surface water in the development area. The river Hengladalsá runs out of Innstidalur in the eastern part of the Hengill region.
- The **vegetation** is mostly moss, grass and small shrubs. Grassland is less widespread than the moss-covered areas. About a quarter of the area is lava covered with moss. A large part of the development on Skardsmýrarfjall has little or no vegetation. The **animal life** is rather scarce, possibly because of shortage of surface water in the area. Fifteen to seventeen breeding bird species have been recorded at Kolvidarhóll, some of which seem to be found at Kolvidarhóll and surroundings only. Raven, which is an endangered species, has bred at Hellisskard. Five to six breeding bird species were found on Skardsmýrarfjall, golden plover being the most common one.
- **Cultural remains** in the area are particularly linked to transportation and many old trails crossing the area.
- **Habitation and recreation.** There are no residential houses but some summer houses in the area. The Hengill area is popular for recreation and marked hiking trails and the publication of maps have increased its accessibility. Some old trails are also used for horseback riding (Reykjavik Energy, 2005).

3.2 Purpose and importance of the production tests

The main purpose of well production tests is to obtain relevant information about the reservoir, especially during new geothermal field exploration because it can give an idea of the main reservoir parameters such as temperature, permeability and storativity, and also other important factors such as type of reservoir (porous or fractured), skin factor and location of the reservoir boundaries (Axelsson, 2013), that can be used to construct a conceptual model of the new field, or even make an update of an existing conceptual model, in which the main production and recharge zones can be included.

3.3 Types of production tests

When a well has been drilled it is necessary to measure fluid flow, determine its energy content and analyse its characteristics. High enthalpy wells are expected to have a warmup period of 2-4 months after drilling is completed. The well is opened up and allowed to flow to the atmosphere. High-temperature geothermal wells are usually discharged into a silencer which also acts as a steam-water separator at atmospheric pressure.

There are many methods used to estimate flow from wells during production testing but two methods are most commonly used in Iceland for two-phase flow measurements: the lip pressure method and the chemical tracer method. The production tests be can classified as:

3.3.1 The pressure diffusion equation

The basic equation of well testing theory is the pressure diffusion equation. It is used to calculate the pressure (P) in the reservoir at a certain distance (r) from a production well producing at a given rate (q) as a function of time (t). The most commonly used solution to the pressure diffusion equation is the so-called Theis solution or the line source solution (Earlougher, 1977).

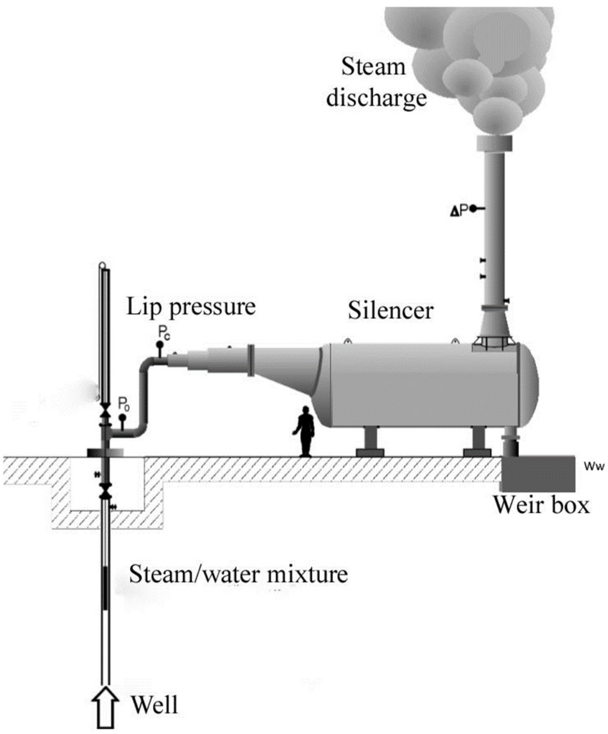

FIGURE 3: Schematic representation of the Lip Pressure method (Steingrímsson, 2016)

3.3.2 Lip pressure method

The lip pressure method is based on an empirical formula developed by Russel James (James, 1962). To use this method, a steam-water mixture is discharged through an appropriately sized pipe into a silencer or some other simple device to separate the steam and water phases at atmospheric pressure. This is the most common method used for two-phase mixtures (Steingrímsson, 2016).

Assuming that we have a fairly large amount of steam/water mixture flowing at sonic velocity through an open-ended pipe to the atmosphere, the absolute pressure at the external end of the pipe is then proportional to the mass flowrate and enthalpy (Figure 3). The flow in geothermal wells is assumed to be isenthalpic (adiabatic). Water flow from the silencer is commonly measured by the weir-box method (Grant et al., 1982).

The formula that Russel James deduced is (Equation 1):

$$\frac{\mathrm{Wt}Ht^{1.102}}{APlip^{0.96}} = 1680 \tag{1}$$

where:

P_{lip}= lip pressure at the end of the pipe (MPa)
W_t = total mass flow rate (kg/s)
A= cross-section area of the lip (cm^2)
H_t= Total fluid enthalpy (kg/kJ)

The lip pressure is measured at the extreme end of the discharge pipe using a liquid-filled gauge to dampen out pressure fluctuations. Water flow from the silencer is measured using a V sharp-edged weir box near the silencer outlet, shown in Figure 3. When water flow W_w (kg/s) from the atmospheric silencer, measured in the weir-box, and the lip pressure are known, the total fluid enthalpy is given by Equation 2:

$$\frac{Ww}{\mathrm{APlip}} = Y = \frac{0.74(2675 - \mathrm{Ht})}{\mathrm{H}t^{1.102}} \tag{2}$$

This equation can also be solved for H_t between 400 and 2800 kJ/kg as a function of Y with an accuracy of 1.5% (Grant et al., 1982).

The water flow W_w is related to the total mass flow as shown by equation (3), where X is the steam mass fraction ratio.

$$\mathrm{Wt} = \frac{Ww}{1 - \mathrm{X}} \tag{3}$$

3.3.3 Chemical tracer (tracer flow test)

In this method two different tracers are used, one for the liquid phase and one for the steam phase. The principle of this method involves measuring the dilution when a solution containing a chemical indicator is injected into the well discharge. The solution is injected at a known constant rate at an upstream location. Analysis of a downstream sample will then make it possible to determine the well discharge by the formula (Equation 4):

$$Q = \mathrm{q}\frac{\mathrm{C1} - \mathrm{C2}}{\mathrm{C2} - \mathrm{C0}} \tag{4}$$

where q is the injection rate of the chemical solution and C0, C1 and C2 are respectively the concentrations of the chemical indicator in the well fluid, the solution injected and the downstream sample. For the steam phase, the same principle as for liquid water is applied. Instead of injecting solution into the flow stream, a non-condensable gas (SF_6 diluted in N_2) is more commonly used (See Figure 4). The tracers used by Reykjavik Energy are sulphur hexafluoride (SF_6) for the steam and fluoride (KF) for the liquid (Elmi 2008).

3.3.4 Injection tests

Injection testing is in principle a simple variant of discharge flow testing, with the flow reversed. Water is injected into a well and the flow rate recorded along with changes in down-hole pressure or depth to water level. A quasi-stable flow versus pressure curve can be obtained, and transient behaviour measured as changes in flow rate.

Injection is a simple inverse of production, if the fluid injected is of the same enthalpy (quality or temperature) as that produced. Generally, the fluid injected is water that is cooler than the reservoir fluid, then it has different viscosity and compressibility from the reservoir fluid (Grant et al., 1982). The non-isothermal injectivity index obtained from these tests depends on the mobility ratio of the cold region to the hot reservoir and the extent of the cold spot.

During injection tests, the injectivity index is often used as a rough estimate of the connectivity of the well to the surrounding reservoir. Here it is given in the units [(L/s)/bar] and it is defined as the change in injection flow rate divided by the change in stabilized reservoir pressure (Grant et al., 1982).

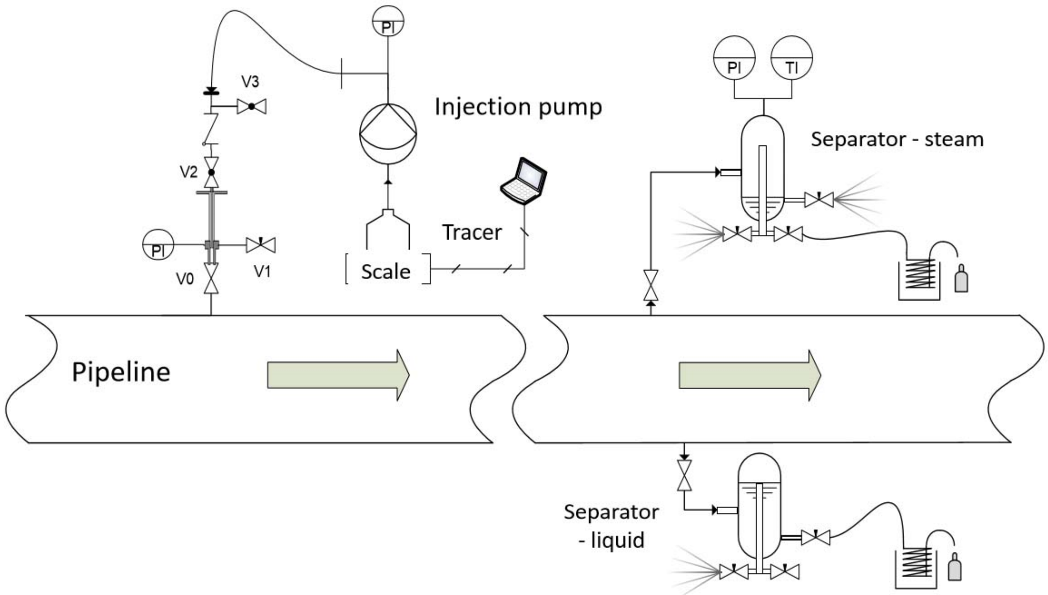

FIGURE 4: Schematic representation of chemical tracer methodology (Steingrímsson, 2016)

4. GEOTHERMAL WELL STIMULATION

4.1 Purpose and importance of the well stimulations

Stimulation techniques have the potential to increase formation permeability and remove the damage to the formation which causes a low flow-rate in the well. Low productivity, due to lack of communication with the naturally occurring main conduits for fluid flow, can be improved by cleaning and by thermal and/or hydraulic fracturing of wells, usually applied at the end of drilling. Sometimes it is necessary to treat damage due to mud invasion into open fractures, blocked pores or minor flow channels (Flores et al., 2005).

The design of any stimulation should start with a thorough assessment of the characteristics of the specific system. The type of stimulation is appropriate and the chemical composition of the produced fluid must be determined**.** Damage formation, resistance to mechanical and thermal stresses of rock, background temperature, and ore mineralogy are analysed (Galindo, 2015).

4.2 Types of stimulations

Geothermal wells can be stimulated in two main ways: hydraulics or acid, which are subdivided according to specifications of each method. The different types of stimulations are shown in Figure 5.

4.2.1 Hydraulics

A geothermal well can be stimulated by creating fractures either by pumping at fluid pressures greater than the fracture pressure or by injecting cold water, which upon contact with the hot rock will have the effect of a thermal shock and rock strength creating conductive channels (Galindo, 2015).

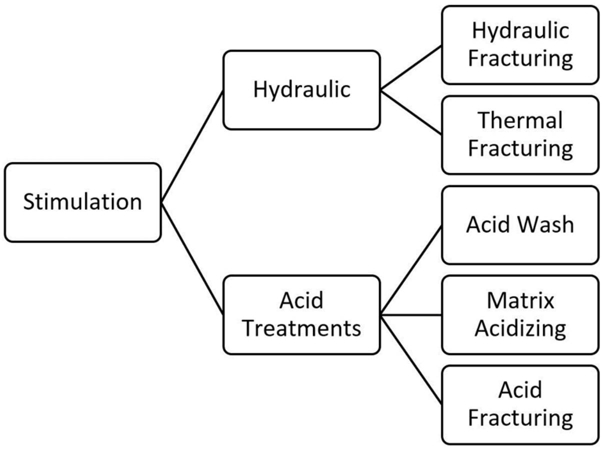

FIGURE 5 : Types of stimulation (Galindo 2015)

Hydraulic Fracturing: is performed by pumping specially engineered fluids at sufficiently high pressure for a fracture to be opened. Connection of many, pre-existing fractures and flow pathways within the reservoir rock with a larger fracture may be achieved. The final stage of the treatment is the injection of a proppant[1] (usually sand) slurry. This proppant maintains the fracture flow capacity created after relaxation of the hydraulic pressure (Flores et al., 2005).

Thermal fracturing: takes place when a fluid (e.g. produced water, seawater, aquifer water or surface water), considerably colder than the hot receiving formation, is injected. Injection of the cooler water leads to thermal contraction of the reservoir rock in the region near the injection well, reducing the stresses. The reservoir can be fractured at a lower pressure than the original in-situ stress would indicate, if there is a large temperature difference between the injected water and the formation (Galindo, 2015).

4.2.2 Acid treatment

Acids have the ability to dissolve formation minerals and foreign material, such as drilling mud, which may be introduced into the formation during well drilling, as well as after precipitated minerals have formed during production. This is the reason for utilizing acids to stimulate geothermal wells, to increase flow production or injection capacity (Galindo, 2015).

Acid cleaning: is employed to remove scale from production lines, discharge lines and the face of the producing formation, and is the oldest stimulation technique still used today. Each geothermal system is subject to different scaling problems, due to the chemical characteristics of the geothermal fluid and pressure and average temperature of the well, and also to the petro-physical properties of the producing formation such as permeability and porosity (Galindo, 2015).

Matrix acidizing: involves injecting acid into the formation of the well at a pressure below the pressure at which a fracture can be opened. On the other hand, acid fracturing requires that acid is injected into the formation at a high enough pressure to fracture the formation or open existing fractures. Acid treatment for sandstones differs significantly from treatment intended for carbonate rocks. Carbonate rocks rapidly dissolve in hydrochloric acid and the reaction products are water soluble. Unlike acidification reactions in carbonate rocks, chemical reactions in siliceous rocks are extremely complex. The sandstones are comprised of quartz grains, different types of clays, feldspar, chert, micas and various carbonate minerals. HCl is not effective in dissolving most components of siliceous rocks. Hydrofluoric acid (HF) combined with hydrochloric acid (HCl), formic acid or acetic acid is commonly used in sandstone acid treatment, and the acid formulation used in any specific case depends on the

[1] A material that prevents the fracture from closing after completion, ending pumping and ensuring a newly created conductive channel.

mineralogy of the formation. Commonly employed solutions are 10% HCl, a mixture of 12% HCl and HF 3%, for dissolving silicates and silica (Galindo, 2015).

Acid fracturing: involves injecting acid into naturally fractured or previously fractured rock. The injection should be carried out at a greater pressure than the formation pressure. It is widely used to stimulate carbonate rocks or formations that are more than 85% acid soluble. This involves first injecting a viscous fluid at a pressure exceeding the fracture pressure of the formation. The following injection increases the length and width of the fracture, and injecting acid sets off a reaction along the fracture to create a channel extending deep into the formation. The key to success is the penetration of acid along the fracture. However, the volume of acid used in fracturing treatment is much larger than that used in the matrix acidification treatment. The effective fracture length depends on the type of acid used, and the reaction rate of acid fluid lost in the formation (Galindo, 2015).

5. DESCRIPTION OF ACTIVITIES DURING PRODUCTION TEST AND STIMULATIONS

Different sub-activities are carried out during production tests (lip pressure and tracers flow test) and stimulations (matrix acidifications), e.g. activities that need to be considered for environmental analysis. The DASI method (dissociation of aspects/ synthesis of impacts) has been used for the identification of environmental (Arévalo and Padilla, 2008) activities and sub-activities identified and shown in Table 2.

TABLE 2*:* Typical actions or sub-activities realized during productions test and stimulations

Activities	Typical actions/sub-activities
1. Production test (Lip Pressure)	1.1Transportation and conditioning of equipment 1.2 Measurement equipment installation 1.3 Measurements of steam flow 1.4 Measurements of water flow
2. Production test (TFT)	2.1Transportation and conditioning of equipment 2.2 Injection of tracers 2.3 Collection of sample
3. Production test with stimulation (Matrix Acidifications)	3.1 Transportation and conditioning of equipment 3.2 Preparation and mixing of chemicals 3.3 Injection of treatment fluids 3.4 Rest or warm up 3.5 Measurements of steam flow 3.6 Measurements of water flow

5.1 Activities during production tests (lip Pressure)

Once a well is stimulated its fluid is directed into the muffler, located on the side of the main platform. Separation to a two-phase fluid is effected by sending steam to the atmosphere and water to the weir box and after this, water is drained to the pipeline and finally injected into a reinjection well.

5.1.1 Transportation of equipment and materials

This stage involves the transportation of equipment that will be used for discharge of steam and water, and the equipment with which the measurements will be made. For example, portable mufflers, weir-box, pipe, pressure gauges, etc.

5.1.2 Measurement equipment installation

At this stage one proceeds to the placement of equipment such as a portable muffler, weir box and piping system to channel water to the reinjection well. In this case it must be ensured that flanges and valves are tightened, the pipeline is anchored and that the water piping system is properly installed.

5.1.3 Measurements of steam flow (discharge steam to atmosphere)

Once the equipment is properly installed, the total flow of water and vapour from the well is passed through a pipe, which discharges it. The steam is discharged to the atmosphere vertically through a muffler for approximately one month (depending on the technical and environmental characteristics of the site where this discharge test takes place) until the pressure is stable. The variables that are monitored are:

- Wellhead pressure
- Lip pressure
- Gas concentrations

5.1.4 Measurements of water flow (injection of waste water)

The muffler is connected to a weir box where flow measurements are made, then the water is conducted through a pipe system to the well where it will be reinjected. The variables that are monitored during this activity are:

- Water flow in weir box
- Temperature of water

5.2 Production test (TFT)

5.2.1 Transportation and conditioning of equipment and materials

This stage involves the transfer of equipment to be used to carry out the tracer flow test. For the transportation it is only necessary to pick up the equipment for the injection of tracers, sampling separators and complementary equipment.

5.2.2 Injection of tracers (SF_6 and KF)

Once the specialized equipment for the tracer flow test has been installed, the tracers are injected, the KF,1% concentration and injective velocity is 200 cm^3/min, is used to evaluate the liquid phase, and for the gas phase 1% SF_6 with velocity of flow 20 g/min is used.

5.2.3 Collection of samples (steam and water)

The sampling point is located about 40 meters downstream of the injection point after a bend or valve to provide sufficient mixing. Samples are collected to determine the concentrations of the tracers. Collection of samples starts when the injection has reached equilibrium, usually 10-15 minutes after injection started. Samples are collected from downstream sampling points using sampling separators operating at line pressure (Figure 6). Separated steam and water are passed through condensing coils and collected into screw-cap containers (Lovelock, 2001).

5.3 Activities during stimulation (matrix acidifications)

This part describes one type of stimulation. The procedure for matrix acidification is as described in the following sections.

5.3.1. Transportation of equipment, materials and chemicals

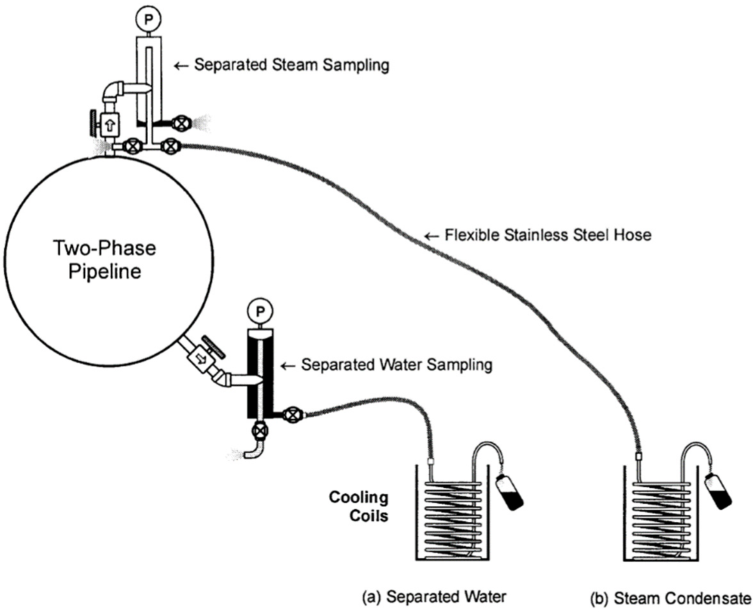

FIGURE 6: Tracer sampling equipment (Lovelock, 2001)

For chemical stimulation piping systems, valves, hoses and tanks are required; and are handled on the platform as follows:

To make the transfer from the tanks it is necessary to use a crane and a truck. When it has reached the work platform, the tanks are put on a layer of sand, the space between individual tanks is 40 cm and 3" valves are installed parallel to facilitate the discharge of the acid mixture into the manifold. Behind the mixing tanks it is necessary to put a set of scaffolds, which will be used for the personnel that carries out the mixing. The water supply system is installed too.

To transfer chemicals and produce agitation, an air supply from a compressor with air at 125 psi and 100 ft^3 / min flow rate is installed. The racking system is completed by installing pipes and hoses needed to direct the air to the air pump. Besides, the pump must be close enough to reach with a 1½" hose each of the barrels containing chemical additives and acids, that can be discharged with a hose to all tanks available for the stimulation of a given well. Likewise, the stirring system is complete when air can reach each of the tanks and every one of them can be shaken.

5.3.2 Preparation and mixing of chemicals

The addition totes and ammonium bifluoride bags are transported to the platform trucks, these are packed in specific locations on pallets to avoid ground contact. Similarly, hydrochloric acid is transported to transport tanks.

Before the start of mixing, the proper operation of the equipment, water supply line and mixing tanks is checked by a hydrostatic test. A mixture of primary acids (hydrochloric acid 15% more additives) and the main component (Sandstone acid 6%), is prepared according to formulations depending on the possible damage to the well. Then the manifold is ready to be installed or the flow diverted to the different tanks by means of flexible hoses and the pump.

5.3.3 Injection of treatment fluids

Injection of treatment fluids is the most important process in chemical stimulation and involves a sequential way of cooling, pre-flow injection, main injection of fluid (MUD Acid) and displacement.

Initially, gaskets, screw connections and the operation of each component of the injection circuit are checked. One of the outlets of the main pump manifold is fed with the acid mixture. When ready to pump, operation of the opening valve starts from the first tank and keeping valves on other tanks closed so that the mixture is downloaded from each of the tanks to the manifold and pumped into the well. The injection is a continuous process lasting from 20 to 23 hours, depending on the progress of the operation. Each of the activities included in the sequential injection process has a specific function, as described below:

- Pre-flow displaces formation water out of the rock matrix to create a potential environment for the reaction of the main mixture (HCl-HF) and is directed specifically to damage treatment without the risk of precipitate formation.
- The main fluid is used to restore the permeability of the damaged area. Permeability damage may occur from drilling, cementing, and/or a critical matrix formed by fluid invasion causing saturation changes or solid migration.
- The primary fluid has the capacity to dissolve all the minerals that are soluble in 15% HCl. Moreover, it will dissolve all siliceous material such as bentonite, clays and other minerals. Chlorides of calcium, magnesium, sodium and potassium brines react with HF to form insoluble precipitates.
- The displacement flow objectives are to move the main acid (mud acid) into the formation to displace the reaction products out of the critical rock matrix, maintaining the pH of spent acid as low as possible, because some of the acid reaction products may form insoluble precipitates as the pH is increased. Therefore, it is always advisable keep the pH of the reaction products low.

5.3.4 Rest or warm up

HCl with ammonium bifluoride reacts completely with sludge, cuts and minerals. When thermal degradation is applied: the additives are completely degraded by the effect of temperature; which reaches about 200°C. Producing wells are opened from 1 to 2 months after injection in order for the fluids to degrade with temperature.

5.3.5 Measurements of steam flow (Discharge steam to atmosphere)

When the measured temperature is higher than 200°C, it is necessary to take measurements during the discharge test usually with the lip pressure methodology.

The variables that are monitored are:

- Wellhead pressure
- Lip pressure
- Gas concentrations

5.3.6 Measurements of water flow (injection of waste water)

When the measured temperature is higher than 200°C during a steam flow measurement, it is necessary to make measurements during the discharge test usually with the lip pressure methodology. The following variables are monitored:

- Water flow in weir box
- Temperature of water
- pH

6. POSSIBLE ENVIRONMENTAL IMPACTS OR EFFECTS DURING PRODUCTION TESTS AND STIMULATION

This section provides an assessment of potential direct environmental effects of a production test (lip pressure and TFT) and stimulation with matrix acidification. Direct environmental effects include potential impacts to air quality, water quality, induced seismicity, and other impacts.

6.1 Specific interaction matrix and identification of possible impacts

This section consists of linking the interaction of each project activity (described in chapter 5) to environmental factors, so that, a relationship between the two is established This allows positive or negative potential environmental impacts of an activity to be identified, generating a specific interaction matrix for each of the activities analysed (Tables 3-5):

For lip pressure there are 1 positive impacts and 9 negative impacts (Table 3); for TFT 9 negative impacts and 1 positive impact (Table 4).; and for stimulation there are 11 negative and 1 positive impacts (Table 5). More detail about matrix interaction is shown in Appendix I. These impacts were evaluated using the Rapid Impact Assessment Method (RIAM).

TABLE 3: Identification of possible impacts for lip pressure

Environmental factors	**Results**			**Possible potential impacts**
	+	**0**	**-**	
Geology and site stability risk	0	3	1	Microseismicity
Soil quality	0	3	1	Soil pollution
Water quality	0	3	1	Water pollution
Noise	0	2	2	Noise
Air quality. Chemical (odours and gases)	0	3	1	Air pollution
Vegetation cover	0	3	1	Effects on flora
Local traffic	0	3	1	Traffic accidents
Tourism	0	3	1	Effects on tourism
Effective visibility	0	3	1	Change in landscape
Employment	1	3	0	Employment creation

TABLE 4: Identification of possible impacts for tracer flow test

Environmental factors	**Results**			**Possible potential impacts**
	+	**0**	**-**	
Geology and site stability risk	0	2	1	Microseismicity
Soil quality	0	1	2	Soil pollution
Water quality	0	1	2	Water pollution
Noise	0	1	2	Noise
Air quality Chemical (odours and gases)	0	2	1	Air pollution
Vegetation cover	0	2	1	Effects on flora
Local traffic	0	2	1	Traffic accidents
Tourism	0	2	1	Effects on tourism
Effective visibility	0	2	1	Change in landscape
Employment	1	2	0	Employment creation

TABLE 5: Identification of possible impacts for matrix acidizing

Environmental factors	**Results**			**Possible potential impacts**
	+	**0**	**-**	
Geology and site stability risk	0	5	1	Microseismicity
Soil quality	0	2	4	Soil pollution
Water amount	0	4	2	Water supply
Water quality	0	1	5	Water pollution
Noise	0	2	4	Noise
Air quality Chemical (odours and gases)	0	3	3	Atmospheric pollution
Vegetation cover	0	3	3	Effects on flora
Wild life	0	5	1	Disturbance of wildlife
Local traffic	0	5	1	Traffic accidents
Tourism	0	5	1	Affectation tourist
Effective visibility	0	5	1	Change landscape
Employment	4	0	2	Employment generation

6.2 Description of possible impacts

6.2.1 Air pollution (chemicals)

During well tests (lip pressure and TFT) some gases such as H_2S, CO_2 and CH_4 contained in the steam are emitted to the atmosphere. The steam composition from well HE-58 during a lip pressure method test of approximately 35 days duration with an average flow 10.81 kg/s, a total steam discharge of 31,840 tons, is shown in Table 6. The behaviour of these in the atmosphere depends on several factors such as the meteorological conditions at the site where discharge is made.

TABLE 6: Amount of gases discharged during production test of well HE-58

Name of gas	**Average concentration (ppm)**	**Average emission (g/s)**	**Accumulated quantity discharged (ton)**
Carbon dioxide (CO_2)	2944.8	31.1	93.8
Hydrogen sulphide (H_2S)	822.6	8.7	26.2
Nitrogen (N_2)	83.7	0.884	2.7
Hydrogen (H_2)	24.8	0.262	0.789
Methane (CH_4)	3.4	0.036	0.108
Oxygen (O_2)	2.1	0.022	0.067
Argon (Ar)	0.5	0.005	0.016

If a TFT discharge test is applied it is necessary to know the amount of SF_6 (greenhouse gas and its global warming potential is 23900 with respect to CO_2 according to UNFCCC (1995)) discharge to the atmosphere. A flow of 0.005 l/s was injected for 60 min 0.1 l/min at 5% total amount discharge to the atmosphere therefore 0.3 l per TFT measurement. If four TFT measurements are made during a flow test the total SF_6 discharged is about 1.2 l or 943.2 g (equivalent to 22.5 ton CO_2). If a well has been stimulated through the matrix acidizing procedure it is necessary to take into account the possible sub-products resulting from the operational use of HCl, HF, additives.

According to an environmental study, the estimated annual emissions for Hellisheidi power plant are 57,000 tons of CO_2, 11,000 tons of H_2S and 48 tons of CH_4. Compared to these values, the emissions from the discharge test for one month are 0.19% CO_2, 2.9 % H_2S and 2.7 % CH_4 of the total annual emissions from the Hellisheidi power plant.

One effect that is necessary to be considered is that of the weather conditions such as wind speed, direction and amount of precipitation, because it modifies the dispersion of chemicals in the air with the corresponding effect of increase or decrease in the concentration that is received by the receptor.

6.2.2 Water pollution

Water pollution generated can be any spillage during reinjection of wastewater resulting from test discharge. The most important potentially polluting chemicals in the liquid fraction are hydrogen sulphide (H_2S), arsenic (As), boron (B), mercury (Hg) and other heavy metals such as lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn) and manganese (Mn). Lithium (Li), ammonia (NH_3), and aluminium (Al) are also found (Kristmannsdóttir and Ármannsson, 2003). In Table 7 the concentration of some substances in the geothermal water in the Hengill area and a calculated amount from a 35 day flow test of well HE-58 is shown. The arsenic concentration is above the limits in the Icelandic regulation and WHO regulations for drinking water, and the concentration of potassium is above that stipulated in the Icelandic regulation for drinking water only. The concentrations of other substances are below the limits. During the test at well HE-58 the amount of water discharged was 22,692.72 m^3 (start date 11/16/2015 12:50 end 12/21/2015 10:00) and the maximum flow around 21.5 l/s compared with a total of 1,100 l/s (Reykjavik Energy, 2005) estimated for the Hellisheidi power plant or 1.95% of the total amount of water injected.

TABLE 7: Water chemical concentration in the Hengill area (Reykjavik Energy, 2015) with a calculated amount from a 35 day flow test of HE-58

Substance	Average concentration (mg/L)	Accumulated Quantity (kg)
Sodium (Na)	160	3630.8352
Potasium (K)	26.8	608.1649
Fluoride (F^-)	0.98	22.2389
Boron (B)	0.917	20.8092
Arsenic (As)	0.074	1.6793
Lead (Pb)	0.00369	0.0837
Copper (Cu)	0.00134	0.0304
Barium (Ba)	0.00066	0.0150
Nickel (Ni)	0.00022	0.0050
Cadmium (Cd)	0.0001	0.0023
Chromium (Cr)	0.00006	0.0014
Mercury (Hg)	0.00001	0.0002

During flow tests the impacts of water discharge on water quality of surface and groundwater in the shallow aquifers during production and normal injection were investigated. The fluid from the power plant is, on the other hand, injected into the geothermal reservoir, which is not connected to the groundwater system. However, the local water quality could deteriorate if system failures occur. Accidental spills of liquid geothermal surface drainage could take place if released due to escapes during drilling. Leaking pipes or wellheads, and overflowing sinks can be problems, but the biggest concern is the protection of public drinking water supplies (Noorollahi, 2005). Injection and mixing may cause some leakage of substances used in the process (HCl and ammonium bifluoride).

During flow tests, occasional TFT measurements are commonly performed, usually at different wellhead pressures. Each TFT measurement takes approximately 60 minutes and 30 g/m of KF are used. The total discharge is therefore 1800 g per TFT measurement. If four TFT measurements are carried out during a flow test the total KF discharged is about 7.2 kg.

6.2.3 Soil pollution

Contamination of the ground could be due to spills to faults in the injection system when downloading, and water injection tests (LP and TFT) are carried out during production. In an acid stimulation, tanks where acids or spillage use substances for the formulation are stored, could leak.

6.2.4 Noise

The noise during production tests (LP and TFT) is from monitoring wells connected to the plant system. Noise exposure is small because the duration of the tests is short and the noise generated by the equipment is muffled. However, if wells are discharged for the first time the noise generated can exceed 120 dB if they are not silenced, but if the system is silenced the noise generated can be about 90 dB (Kristmannsdóttir and Ármannsson 2003). These noise levels are generated in the vicinity of the operations. Therefore, it is important that the workers use hearing protection. During stimulation, maximum noise is experienced at the time of injection of fluids and can reach 90 dB, so that hearing protection is required.

6.2.5 Occupational risks

During well discharge tests (TFT and LP) personnel is exposed to certain risks such as burns, inhalation of gases (H_2S), falls and exposure to high noise levels. During acid stimulation, staff may be exposed to harmful substances (HCl, ammonium bifluoride and additives) due to injection and mixing

6.2.6 Traffic accidents

During the test stage of production, transport of pipes, valves and measuring equipment is needed. In the case of Hellisheidi the equipment is transported by a road in good conditions.

In the case of acid stimulations, the impact may be more significant to traffic due to pumping and injection equipment that has to be moved by cranes and trucks. Tanks and substances used in the process of mixing (HCl, ammonium bifluoride and additives) are also transported and therefore special care should be taken, as appropriate permissions for handling and use are needed. The proximity to villages, schools, power lines, routes used by the population etc. should also be taken into account because of possible damages.

6.2.7 Microseismicity

Separated water (geothermal water) and condensate need to be reinjected to protect surface and ground water, and for a good utilization of the geothermal reservoir (Reykjavik Energy, 2015). During 2011 microseismicity was observed in the Hellisheidi area, about 40 earthquakes over 2.5 ML and 8 between ML 3 and 4, (Thorsteinsson, 2016). That year the total amount of disposal water injected was around 1.8 million tons per month as a result of separated water via overflow and the disposal at Gráuhnúkar, Húsmúli areas. Wells HE-13 and HE-40 receive effluent from the Hellisheidi Power Plant.

The work procedure for a large scale reinjection and a temporary shutdown, or when significant changes are made in the reinjection, was revised. In the procedure the pumping increases in stages with lag times in between. The result of this is very little seismic activity during changes of flow in the reinjection wells. In September 2016 a large seismic event took place at the Húsmúli reinjection site. This was not connected to any changes in the reinjection procedure and has to be studied further.

The average flow from HE-58 was 11.6 l/s (Appendix 2) or 30,000 tons of water per month, less than 1% of the total annual amount of water injected during all field operations, so it is not expected to significantly affect the environment.

6.2.8 Effects on flora

During well tests, steam and spray can have an adverse effect on the local vegetation with trees and grass being scalded (Noorollahi, 2005). In the case of Hellisheidi the environment is not very sensitive to such effects since e.g. there is not a lot of vegetation in the vicinity of well HE-58. But analysing chemical stimulation depends on the sensitivity of the medium. To find out whether there can be a significant impact on the vegetation in some areas it is important to take into account whether these areas are near woods or other vegetated areas as there may be deposition of chemical substances on the vegetation.

6.2.9 Disturbance to wildlife

From the analysis of environmental parameters in wells HE-58 and HE-21 these are not considered to present a significant impact on the nature of the area. Analysis of matrix acidizing suggests that wildlife can especially be affected by noise, odours and transport of materials, and equipment.

6.2.10 Effects on tourism

Such impacts are especially harmful in geothermal areas that are much visited by tourists. These may be effected by unloading activities, especially by the use of paths. This impact has been listed as negative but in many tourists' opinion geothermal operations constitute a tourist attraction.

6.2.11 Water consumption

This impact has been considered by evaluation because of the sensitivity of the environment to water availability in the area of indirect influence and the amount of water that the project requires. In this case, acid stimulation is being considered and this impact will be evaluated depending on the sensitivity of the environment to water availability in the area, because a specific area for acidification is not under discussion, but this impact will be considered generally. The production test does not require much water, but for the stimulation it is necessary to use a significant amount of water. For example, it is necessary to use approximately 1000 m^3 for matrix acidizing. This could impact consumption, depending on the characteristics of the aquifer and the time of year when the work is carried out, potentially reducing the availability of groundwater

6.2.12 Changes in landscape

When the steam plume is discharged to the atmosphere, a visual effect is created. Occasionally wells being tested are near vehicular access routes and may impair visibility or distract drivers on these roads.

6.3 Prioritization of impacts

In Section 6.1 the impacts of discharge tests (LP and TFT), and discharge test with stimulation (matrix acidizing) are identified. These impacts were subsequently grouped and described in Section 6.2. In this section, the impacts are prioritized by the RIAM method.

The RIAM method is based on the definition of important evaluation criteria and existing environmental considerations in the area where the project will be developed. This method provides a holistic research approach, classified as the environment for evaluation of four environmental components: physico-chemical, biological-ecological, socio-cultural and economic-operational (Arévalo, 2003).

The classification criteria are divided into two groups, A and B, these in turn are subdivided and classified as shown in Table 8.

TABLE 8: Classification criteria

Criterium	Value	Importance of condition
A1	4 3 2 1 0	Important to national/international interests Important to regional/national interests Important to areas immediately outside the local condition Important only to the local condition No importance
Criterium	**Value**	**Magnitude of change/effect**
A2	3 2 1 0 -1 -2 -3	Major positive benefit Significant improvement in status quo Improvement in status quo No change/status quo Negative change to status quo Significant negative dis-benefit or change Major disadvantage or change
Criterium	**Value**	**Permanence**
B1	1 2 3	No change/not applicable Temporary Permanent
Criterium	**Value**	**Reversibility**
B2	1 2 3	No change/not applicable Reversible Irreversible
Criterium	**Value**	**Cumulative**
B3	1 2 3	No change/not applicable Non-cumulative/single Cumulative/synergistic

Once the impact criteria have been qualified, the environmental scores are calculated (Equation 5).

$$\text{Score ES} = (A_1 X A_2)\ X\ (B_1+B_2+B_3) \tag{5}$$

In Table 9, the impact or effect is categorized according to the corresponding range.

TABLE 9: Significance level impacts

Environmental score (ES)	Range	Description
+72 at +108	+E	Major positive impacts
+36 at +71	+D	Significant positive impacts
+19 at +35	+C	Moderate positive impacts
+10 at +18	+B	Positive impacts
+1 to +9	+A	Lightly positive impacts
0	N	“status quo” or not applicable
-1 to 9	-A	Lightly negative impacts
-10 at -18	-B	Negative impacts
-19 at -35	-C	Moderate negative impacts
-36 at -71	-D	Significant negative impacts
-72 at +108	-E	Major negative impacts

The items in the following matrices have been assessed and quantified using the RIAM method. In Table 10, the impacts from the discharge test using lip pressure and evaluated for HE-58 in Hellisheidi are shown. For this activity 2 moderate negative impacts, 3 negative impacts, 4 lightly negative impacts and 1 positive impact are recorded. This activity was evaluated for a duration of approximately 35 days.

TABLE 10: Prioritization of impacts from discharge test using lip pressure

Environmental Impacts	RIAM					Score ES	Range RV
	A1	A2	B1	B2	B3		
Air pollution (Chemical)	2	-2	2	2	2	-24	**-C**
Noise	2	-2	2	2	2	-24	**-C**
Traffic accidents	2	-1	3	2	2	-14	**-B**
Water pollution	2	-1	2	2	2	-12	**-B**
Effects on flora	2	-1	2	2	2	-12	**-B**
Microseismicity	2	-1	2	2	1	-10	**-A**
Change landscape	2	-1	2	1	1	-8	**-A**
Effects on tourism	2	-1	2	1	1	-8	**-A**
Soil pollution	1	-1	2	2	2	-6	**-A**
Employment creation	3	1	2	1	1	12	**+B**

The impacts from the discharge test using tracer flow test, evaluated for HE-21 in the Hellisheidi are shown in Table 11. For this activity 2 moderate negative impacts, 3 negative impacts, 4 lightly negative impacts and 1 positive impacts are recorded. This activity was recorded for one day and well (HE-21) was connected to the power plant, but the evaluation method for this activity assumes a duration of approximately 35 days and the well is considered not to be connected to the power plant.

TABLE 11: Prioritization if impacts from discharge test using TFT

Environmental Impacts	RIAM					Score ES	Range RV
	A1	A2	B1	B2	B3		
Air pollution (Chemical)	2	-2	2	2	2	-24	**-C**
Noise	2	-2	2	2	2	-24	**-C**
Traffic accidents	2	-1	3	2	2	-14	**-B**
Water pollution	2	-1	2	2	2	-12	**-B**
Effects on flora	2	-1	2	2	2	-12	**-B**
Microseismicity	2	-1	2	2	1	-10	**-B**
Changes in landscape	2	-1	2	1	1	-8	**-A**
Effects on tourism	2	-1	2	1	1	-8	**-A**
Soil pollution	1	-1	2	2	2	-6	**-A**
Employment creation	3	1	2	1	1	12	**+B**

The impacts from the discharge test when the well is stimulated (matix acidification) are shown in Table 12. The duration is assumed to be 2 weeks, and the location of the well that is evaluated is at a normal

TABLE 12: Prioritization of impacts discharge test with stimulation (matrix acidification)

Environmental Impacts	RIAM					Score ES	Range RV
	A1	A2	B1	B2	B3		
Air pollution (Chemical)	2	-2	2	2	2	-24	**-C**
Noise	2	-2	2	2	2	-24	**-C**
Water supply	2	-1	3	2	2	-14	**-B**
Water pollution	2	-1	3	2	2	-14	**-B**
Effects on flora	1	-2	3	2	2	-14	**-B**
Traffic accidents	1	-2	3	2	2	-14	**-B**
Soil pollution	1	-2	2	2	2	-12	**-B**
Microseismicity	2	-1	2	2	1	-10	**-B**
Changes in landscape	2	-1	2	1	1	-8	**-A**
Effects on tourism	2	-1	2	1	1	-8	**-A**
Employment creation	3	1	2	1	1	12	**+B**

location in the field. Two moderate negative impacts, 6 negative impacts, 2 lightly negative impacts and 1 positive impacts were obtained.

7. ENVIRONMENTAL AND OCCUPATIONAL SAFETY REGULATIONS

The most relevant regulations to establish a control level for environmental aspects include consideration of air and water quality.

7.1 Air quality

7.1.1 Environmental regulations

Hydrogen sulphide (H_2S) is the gas most people relate to geothermal fields and the utilization of geothermal energy. The levels of H_2S in the atmosphere in geothermal areas are commonly in the range from 0-0.5 ppm. Humans detect smell at very low concentrations (Gunnlaugsson et al., 2010).

In 2010, the Government of Iceland set a health limit in Iceland at 50 μg/m^3 for a running 24-hour average. This regulation requires the geothermal industry in Iceland to lower H_2S emissions (Gunnarsson, et al., 2013).

The environmental regulations that can serve as a reference are the air concentration guidelines by the World Health Organisation (WHO) as well as an Icelandic regulation from 2010 on the atmospheric concentration of H_2S. Stricter rules than the WHO guidelines took effect in 2014 (Table 13).

Noise. Guidelines for community noise of the World Health Organization, (WHO, 1999); stipulate that the values have been set at 50 or 55 dBA, representing daytime levels below which the adult population will be protected from becoming moderately or seriously annoyed.

TABLE 13: Environmental guidelines for H_2S air concentration and emissions (Franco, 2010)

Guidelines/regulation	Averaging period	Level (μg/m^3)	Notes
WHO Air quality guidelines, 2nd Edition	30 min 24 hour	7 150	To avoid odour annoyance This guideline was obtained by dividing the threshold for eye irritation of 15,000 μg/m^3 by factor 100
2010 Icelandic regulation on atmospheric H_2S concentration	3 hours 24 hours 1 year	150 50 * 5	*Allowed instances of surpassing limit decreased from 5 to 3 times per year in 2014

7.1.2 Occupational safety regulations

Occupational safety guidelines and limits include the American Conference of Governmental Industrial Hygienists (ACGIH), the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH). These authorities consider different exposure limits, as described below in Table 14. They consider different times of exposure and the activity that is developed.

TABLE 14: Occupational safety guidelines and limits (OSHA, 2012a)

Sustance	Limits values	Agency
Hydrogen sulphide (H_2S)	1 ppm, 1.4 mg/m^{3}TLV-TWA (8-hour) 5 ppm, 7.0 mg/m^3 TLV-STEL (15 min)	ACGIH (2010)
	10 ppm , 15 mg/m^3 REL-C (10 min)	NIOSH (2005)
	20 ppm PEL-C	OSHA (2012b)
Carbon dioxide (CO_2)	5,000 ppm (9,000 mg/m^3) TLV-TWA 30,000 ppm (54,000 mg/m^3) TLV-STEL	ACGIH (2001)
	5,000 ppm (9,000 mg/m^3) TWA 30,000 ppm (54,000 mg/m^3) REL-STEL	NIOSH (1978a)
	5,000 ppm (9,000 mg/m^3) PEL-TWA	OSHA (2012c)
Hydrogen chloride (HCl)	2 ppm (3 mg/m^3) A4 TLV-C	ACGIH (2003)
	5 ppm (7 mg/m^3) PEL-C	NIOSH (1978b)
	5ppm (7 mg/m^3) C	OSHA (2012d)
Hydrogen fluoride (HF)	0.5 ppm TWA-TLV 2 ppm TLV-C	ACGIH (2005a)
	3 ppm (2.5 mg/m^3) TWA-REL 6 ppm (5 mg/m3) (15 minutes) REL-C	NIOSH (1978c)
	3 ppm (2 mg/m^3) TWA-PEL	OSHA (2012e)
Sulphur hexafluoride (SF_6)	1000 ppmTWA-PEL	ACGIH (2005b)
	1000 ppm TWA-REL	NIOSH (1978d)
	1000 ppm PEL	OSHA (2012f)

PEL: Permissible Exposure Limits, are regulatory limits on the amount or concentrations of a substance in the air, and they are enforceable.
REL-C: Recommended Exposure Levels-Ceiling: the concentration that should not be exceeded during any part of the working exposure.
STEL: Short Term Exposure Limit: the concentration to which it is believed that workers can be exposed to continuously for a short period of time without suffering from irritation, chronic or irreversible tissue damage, or narcosis.
TVL: Threshold Limit Values are defined as an exposure limit to which it is believed nearly all workers can be exposed day after day for a working lifetime without ill effect,
TWA: Time Weighted Average, the time weighted average concentration for a conventional 8-hour workday and a 40-hour workweek, to which it is believed that nearly all workers, may be repeatedly exposed, day after day, without adverse effect.

Noise. Under OSHA standards, workers are not permitted to be exposed to an 8-hour TWA equal to or greater than 90 dBA. OSHA uses a 5-dBA exchange rate, meaning the noise level doubles with each additional 5 dBA. In Table 15 it is shown for how long time workers are permitted to be exposed to specific noise levels (OSHA, 2016).

TABLE 15: Extended work shifts and action level reduction

Permissible duration (hours per day)	Sound level (dBA, slow response)
16	85
8	90
4	95
2	100
1 ½	102
1	105
½	110
¼ or less	115

7.2 Water quality

For the water quality the guidelines for drinking water quality from WHO (2011) shown in Table 16 have been used. The components listed are expected to be present in geothermal fluids, knowing that this will be related to the reservoir composition, so that the reference will need to be consulted for different components.

7.2.1 Environmental regulations

TABLE 16: Chemical composition of geothermal water in Hellisheidi and guidelines for drinking water quality, 4th edition. WHO (2011)

Substance	Average concentration (mg/L)	Limits WHO	Iceland regulation 1995
Sodium (Na)	160	50	200
Potasium (K)	26.8	N.E	12
Fluoride (F^-)	0.98	1.5	1.5
Boron (B)	0.917	2.4	1000
Arsenic (As)	0.074	0.01 (AT)	0.01
Lead (Pb)	0.00369	0.01 (A, T)	0.01
Copper (Cu)	0.00134	2	2
Barium (Ba)	0.00066	0.7	0.7
Nickel (Ni)	0.00022	0.07	0.02
Cadmium (Cd)	0.0001	0.003	0.005
Chromium(Cr)	0.00006	0.05 (P)	0.05
Mercury (Hg)	0.00001	0.006	0.001

NB: A, provisional guideline value as calculated guideline value is below the achievable quantification.
T, provisional guideline value because the calculated guideline value is below the possible level, which can be quantified.
N.E, occurs in drinking-water at concentrations well below those of health concern

8. ENVIRONMENTAL AND OCCUPATIONAL SECURITY CONSIDERATIONS

The most important possible environmental impacts according to the prioritization of impacts are shown in Section 6.4 using lip pressure and TFT methodology for the discharge test and stimulation with matrix acidification. The possible impacts and some considerations grouped according to their environmental effect are selected and shown in
17.

A protocol with guidelines to be followed should be prepared in the development of activities, whose general features take into account the possible impacts set forth below:

8.1 Considerations for atmosphere pollution and noise

8.1.1 Use of a muffler

A silencer to be used during discharge or production tests should be installed. The equipment also separates liquid and vapour. The liquid phase is directed to a landfill where temperature and flow measurements are performed during production tests and the vapour phase ascends through the silencer where it produces a controlled discharge into the atmosphere. This separator allows isenthalpic expansion and reduces the fluid pressure, which attenuates the noise levels at the source and thus reduces the impact on the environment.

TABLE 17: Environmental and occupational security for impacts

Environmental impacts or effects	Environmental and occupational security considerations
Atmospheric pollution	1. Designing and planning a monitoring and control system 2. Mitigation of H_2S emissions 3. Use of personal protective equipment (PPE)
Noise	1. Designing and planning a monitoring system 2. Use of a muffler 3. Use of PPE
Water and soil pollution	1. Check of equipment and leakage control 2. Containment barriers
Effects on flora	1. Designing and planning a monitoring and control system 2. Compensation for effects
Water supply	1.Compensation for water consumption can be a social approach or reforestation
Microseismicity	1. Designing and planning a monitoring and control system for injection
Traffic accidents	1. Warning signs and special routes

8.1.2 Mitigating H_2S emissions

Injection using 50% NaOH will be on a stoichiometric scale that allows for the absorption of 80% of the H_2S in the vapour discharged to the atmosphere. The injection system will be known as a "scrubber" and consists of the following components: a diaphragm pump, a 1 m^3 tank for storing NaOH and an injection nozzle connected to the expansion nozzle muffler.

This system can be applied during a discharge test (LP and TFT) and with the well stimulated.

8.1.3 Designing and planning a monitoring system

For designing and planning a monitoring system the next steps are the following:

1. The components to be monitored are shown in Table 18, where the relation of different components to the planned activity is shown, the matrix acidification is the activity with most chemical components used. It is important to define locations measurement of the components shown in Table 18. These sites can be classified as emission sources or receivers.

TABLE 18: Identification of components for monitoring

Components monitored	LP	TFT	Matrix acidification
Hydrogen sulphide (H_2S)	X	X	X
Carbon dioxide (CO_2)	X	X	X
Noise	X	X	X
Hydrogen chloride (HCl)			X
Hydrogen fluoride (HF)			X

2. Characterization of the receptor environment and other possible sources of emission. For this the knowledge of certain variables such as other possible natural emission sources (fumaroles, power station), topographic conditions (elevation place activity, elevation where there is a possible receptor such as communities), weather (wind speed, direction and precipitations) and other characteristics such as the state of vegetation etc. is necessary.

3. Baseline monitoring: The concentrations of different gases present in the area before the activity is developed have to be known, so that an environmental baseline can be established. The components to be monitored have to be those in Table 18. Monitoring takes place at the point of baseline establishment.
4. Process for monitoring - discharge test: Once the discharge of the well has started it will be necessary to monitor the concentrations of each component. The components monitored will be the same and from the same location that were determined for the base line for the method used depending of the activity, commonly H_2S and noise.
5. Injection and mixing monitoring (for stimulation only): For the injection and mixing, it is necessary to monitor for occupational security. In this case, the control level the health of workers should be accounted for, and the most important components to monitor are: noise, HCl, and HF.

For monitoring process the following is required to have in mind:

1. Equipment for monitoring: The equipment below is used in LaGeo El Salvador for monitoring during discharge test: for noise soundProud DL I/3, for CO_2 AIQ Surveyor II and for short time H_2S monitoring Jerome 631 and Jerome j605, for long time monitoring ODA log low range an H_2S logger. For more detail see Appendix III.
2. Control levels: A system of control levels needs to be established and these may differ according to the H_2S concentration needed to activate the alarm system. In the ACGIH it is 1 ppm, but this level may be increased.

8.1.4 Use of personal protective equipment (PPE)

For exposure to gas the workers need use a mask and to HCl a mask and protective clothing. Protection against noise is also necessary.

8.2 Considerations for water and soil pollution

8.2.1 Check of equipment and leakage control

When LP or TFT is operating it is necessary to check if the storage tanks are properly prepared to receive all geothermal water that later will be reinjected. This includes a check that there is no structural damage that can produce a leakage. The reinjection system has to be checked to verify that there is no risk of water contamination. Storage tanks for temporary storage shall be constantly checked during any test to prevent that the level goes above 90% of tank capacity. If this level is reached the test has to be stopped.

Prior to well opening it is necessary to check whether there is any leakage in storage tanks and all the components of the piping system that discharge all the chemicals that will be injected for the stimulation. The storage tanks have to be located above a uniform surface to prevent any damage to them.

8.2.2 Designing and planning a monitoring and control system

If there is any suspicion of aquifer contamination with reinjection water during or after well testing, analysis for the suspected contaminating components, principally components identified in Table 16 is suggested, followed by actions to be taken in case of contamination.

Negative impacts to surface water may be avoided by introducing strict discharge criteria and appropriate means to bring water quality and temperature to acceptable standards.

For matrix stimulation it is necessary to manage the concentration of HCl, and other chemicals used especially with regard to storage and transportation, using protective barriers to contain possible spills.

8.3 Considerations for effects on flora

Prior to any activity, the surrounding vegetation has to be identified to establish a baseline, and after that it will be necessary to monitor to find out if there has been any change in vegetation that could be caused by well testing. If the results of the monitoring show that vegetation has been affected by the test it will be necessary to implement a compensation plan for the effects in line with the national regulations.

8.4 Considerations for water supply

After the test it will be necessary to quantify how much water has been used during the test, and if it has been a significant quantity that can affect the surroundings. This will need to be compensated for through reforestation or rain collection and infiltration.

8.5 Considerations of microseismicity

Considering that seismicity can be induced by reinjection, this has to be monitored during a test and if seismic activity starts on a scale between 2 and 3 (Richter scale) it will be necessary to set an alarm. If the quakes observed are between 3 and 4 the reinjection has to be reduced to a level of seismicity previously observed. If the seismicity is greater 4 the test has to be stopped immediately.

8.6 Considerations for traffic accidents, prevention signs and special routes

To prevent any accident on the platform, the “weir-box”, the muffler area or the route, it will be necessary to place the correct signs that inform occupants, visitors or neighbours about the risks or equipment in use.

9. CONCLUSIONS

The most important impacts identified for the three activities (LP, TFT and Matrix Acidification) were air and noise pollution. Monitoring is especially important for air quality because it is essential to keep such activities under control and not exceed either environmental or occupational limits.

According to the environmental evaluation, a well discharge that has been stimulated requires special attention to the chemicals that are injected. Because the products of the stimulation are unknown, unlike those from unstimulated wells, several components have to be monitored. Characterization of the emissions are recommended due to their possible effects on the environment but depending on the sensitivity of the environment, where they are emitted, they may present a different degree of importance or magnitude from an environmental point of view, for example considering activities that take place near inhabited areas. It is recommended to strengthen the relationship with the communities through various actions in order to build trust, commitment and collaboration from the communities when such activities are performed.

Simulation using a dispersion model for all wells and for each chemical species identified for a discharge test using software such as AERMOD or CALLPUFF is recommended because it can help in places where no information is available.

Impacts that initially were believed to be significant such as water consumption and pollution and seismicity were found to be insignificant because the quantity of water injected during well testing is less than 1% of the quantity of water injected by the power plant. Nonetheless, the effects of reinjection on seismicity and groundwater quality should be monitored to be able to prevent any impact.

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APPENDIX I: Matrix interactions

1	Positive environmental impacts
-6	Negative environmental impacts

ENVIRONMENTAL COMPONENTS		ENVIRONMENTAL FACTORS	ACTIVITIES: Production test (Lip Pressure) 1.1Transportation of equipment and conditioning	1.2.Installation Equipment Measurements	1.3.Measurements of steam flow (Discharge steam to at	1.4.Measurements of water flow (Injection waste water)	TOTAL: Frequency of positive impacts by factors	Frequency of negative impacts by actions	Indifferent frequency impacts factors
PHISYCAL-CHEMICAL	LAND- GEOLOGY	Land use	0	0	0	0	0	0	4
		Organic soil	0	0	0	0	0	0	4
		Drains	0	0	0	0	0	0	4
		Soil permeability	0	0	0	0	0	0	4
		Geology and site stability risk	0	0	0	-8	0	1	3
		Subsidence and disturbance	0	0	0	0	0	0	4
		soil quality	0	0	0	-9	0	1	3
	WATER	Water amount	0	0	0	0	0	0	4
		Water quiality	0	0	0	-10	0	1	3
	AIR	Air quality Physica (Noise)	-1	0	-3	0	0	2	2
		Air quiality Chemical (odors and gases)	0	0	-4	0	0	1	3
BIOLOGICAL-ECOLOGICAL	FLORA	Vegetal cover	0	0	0	-11	0	1	3
	FAUNA	Wild life	0	0	0	0	0	0	4
		Habitats	0	0	0	0	0	0	4
SOCIAL - CULTURAL	POPULATION	Local trafic	-2	0	0	0	0	1	3
		Quality life	0	0	0	0	0	0	4
		Tourist	0	0	-5	0	0	1	3
	LANSCAPE	Effective visibility	0	0	-6	0	0	1	3
ECONOMIC - OPERATIONAL	ECONOMY	Local economy	0	0	0	0	0	0	4
		National economy	0	0	0	0	0	0	4
		Employment	0	0	7	0	1	0	3
		Taxes	0	0	0	0	0	0	0
TOTAL	Frequency of positive impacts by actions		1	1	1	1	1		
	Frequency of negative impacts by actions		2	1	3	4		10	
	Indifferent frequency impacts actions		18	19	17	16			73

FIGURE 1: Matrix interactions for lip pressure

1	Positive environmental impacts
-6	Negative environmental impacts

ENVIRONMENTAL COMPONENTS		ENVIRONMENTAL FACTORS	ACTIVITIES: Production test (TFT) 2.1Transportation of equipment and conditioning	2.2 Injection tracers (SF6 and KF)	2.3 Sampling (steam and water)	TOTAL: Frequency of positive impacts by factors	Frequency of negative impacts by actions	Indifferent frequency impacts factors
PHISYCAL-CHEMICAL	LAND- GEOLOGY	Land use	0	0	0	0	0	3
		Organic soil	0	0	0	0	0	3
		Drains	0	0	0	0	0	3
		Soil permeability	0	0	0	0	0	3
		Geology and site stability risk	0	0	-6	0	1	2
		Subsidence and disturbance	0	0	0	0	0	3
		soil quality	0	-3	-7	0	2	1
	WATER	Water amount	0	0	0	0	0	3
		Water quiality	0	-4	-8	0	2	1
	AIR	Air quality Physica (Noise)	-1	0	-9	0	2	1
		Air quiality Chemical (odors and gases)	0	0	-10	0	1	2
BIOLOGICAL-ECOLOGICAL	FLORA	Vegetal cover	0	0	-11	0	1	2
	FAUNA	Wild life	0	0	0	0	0	3
		Habitats	0	0	0	0	0	3
SOCIAL - CULTURAL	POPULATION	Local trafic	-2	0	0	0	1	2
		Quality life	0	0	0	0	0	3
		Tourist	0	0	-12	0	1	2
	LANSCAPE	Effective visibility	0	0	-13	0	1	2
ECONOMIC - OPERATIONAL	ECONOMY	Local economy	0	0	0	0	0	3
		National economy	0	0	0	0	0	3
		Employment	0	5	14	1	0	0
		Taxes	0	0	0	0	0	3
TOTAL	Frequency of positive impacts by actions		1	1	1	1		
	Frequency of negative impacts by actions		2	4	5		12	
	Indifferent frequency impacts actions		18	16	15			51

FIGURE 2: Matrix interactions for tracer flow test

1	Positive environmental impacts
-6	Negative environmental impacts

ENVIRONMENTAL COMPONENTS		ENVIRONMENTAL FACTORS	ACTIVITIES: Stimulations (Matrix Acidifications)						TOTAL		
			3.1.Transportation and conditioning of equipment	3.2 Preparation and Mixing Chemicals	3.3 Injection of treatment fluids	3.4.Rest or warm up	3.5. Measurements of steam flow (Discharge steam to atmosphere	3.6 Measurements of water flow (Injection waste water)	Frequency of positive impacts by factors	Frequency of negative impacts by actions	Indifferent frequency impacts factors
PHISYCAL-CHEMICAL	LAND- GEOLOGY	Land use	0	0	0	0	0	0	0	0	6
		Organic soil	0	0	0	0	0	0	0	0	6
		Drains	0	0	0	0	0	0	0	0	6
		Soil permeability	0	0	0	0	0	0	0	0	6
		Geology and site stability risk	0	0	0	0	0	-28	0	1	5
		Subsidence and disturbance	0	0	0	0	0	0	0	0	6
		soil quality	0	-3	-10	-16	0	-29	0	4	2
	WATER	Water amount	0	-4	0	0	0	-30	0	2	4
		Water quiality	0	-5	-11	-17	-18	-31	0	5	1
	AIR	Air quality Physica (Noise)	-1	-6	-12	0	-19	0	0	4	2
		Air quiality Chemical (odors and gases)	0	-7	-13	0	-20	0	0	3	3
BIOLOGICAL-ECOLOGICAL	FLORA	Vegetal cover	0	-8	-14	0	-21	0	0	3	3
	FAUNA	Wild life	0	0	0	0	-22	0	0	1	5
		Habitats	0	0	0	0	0	0	0	0	6
SOCIAL - CULTURAL	POPULATION	Local trafic	0	0	0	0	-23	0	0	1	5
		Quality life	0	0	0	0	0	0	0	0	6
		Tourist	0	0	0	0	-24	0	0	1	5
	LANSCAPE	Effective visibility	0	0	0	0	-25	0	0	1	5
ECONOMIC - OPERATIONAL	ECONOMY	Local economy	0	0	0	0	0	0	0	0	6
		National economy	0	0	0	0	0	0	0	0	6
		Employment	2	9	15	0	26	0	4	0	2
		Taxes	0	0	0	0	0	0	0	0	6
TOTAL	Frequency of positive impacts by actions		1	1	1	1	1	1	4		
	Frequency of negative impacts by actions		1	6	5	2	5	3		22	
	Indifferent frequency impacts actions		19	14	15	18	15	17			102

FIGURE 3: Matrix interactions for matrix acidizing

APPENDIX II: Water flow in discharge test (Lip pressure)

Date / Time	Water flow
16.11.2015 12:50	21.5
16.11.2015 13:20	21.5
16.11.2015 14:47	21.5
16.11.2015 16:22	21.5
17.11.2015 12:00	17.5
18.11.2015 12:30	16.3
19.11.2015 11:00	18.8
20.11.2015 16:00	16.3
23.11.2015 11:00	11.0
23.11.2015 14:40	11.0
23.11.2015 15:25	8.4
23.11.2015 15:00	11.0
24.11.2015 11:00	11.0
24.11.2015 13:00	11.0
24.11.2015 13:00	11.0
24.11.2015 15:00	11.0
25.11.2015 08:00	10.1
25.11.2015 09:00	11.0
25.11.2015 15:00	10.1
25.11.2015 15:25	10.1
30.11.2015 10:24	5.6
2.12.2015 11:00	4.4
2.12.2015 11:00	4.4
3.12.2015 14:04	3.9
4.12.2015 10:50	5.6
7.12.2015 11:45	5.0
11.12.2015 13:30	4.4
18.12.2015 09:40	3.4
21.12.2015 10:00	2.5

APPENDIX III: Equipment use for monitoring in discharge test

Component to monitoring	**Technical description**	**Figure**
Noise	Equipment for noise monitoring Brand: Quest Technologies Model: SoundPro DL 1/3 Range: 12.5 Hz to 20,000 Hz Permissible sound level: 55 dB(A)	
CO_2	Equipment for CO_2 monitoring Brand: GrayWolf Model: IQA Surveyor II Range: 0 to 5,000 ppm Permissible exposure limit: 5,000 ppm	
H_2S Short term monitoring	Equipment for H_2S monitoring- Short term monitoring Brand: Arizona Instrument LLC Model: Jerome 631 Range: 0.003 to 50 ppm Resolution: 0.001 ppm Brand: Arizona Instrument Model: Jerome j605 Range: 0.003 to 10 ppm Resolution:0.00002 ppm	
H2S Long term monitoring	Equipment for H2S monitoring- Long term monitoring Brand: App Tek International Model: OdaLog Low Range H_2S Logger Range: 0.003 to 10 ppm Memory Capacity: 30,000 data points Permissible exposure limit: 0.102 ppm in 24 hours