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Some Aspects Related to Chemicals Systems Used in the Exploitation at the Dr. Alfredo Mainieri Protti Geothermal Field (formerly Miravalles Geothermal Field), Costa Rica

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ABSTRACT

The chemical systems used for the exploitation of producing wells in the Dr. Alfredo Mainieri Protti Geothermal Field (formerly Miravalles Geothermal Field) change over time, according to variations in geothermal fluids. New formulations of inhibitors of calcium carbonates, variations in doses according to productive conditions, changes in the chemism of fluids, costs, are some elements discussed in different sections. The neutralization systems have also changed according to the evolutionary conditions of the acid wells. Power generation at the Dr. Alfredo Mainieri Protti geothermal field currently depends on the utilization of systems for inhibition of calcium carbonate scale, as well as, acid-neutralization systems, in the field´s production wells. Some aspects are discussed under the appropriate sections.

1. INTRODUCTION

Exploitation of geothermal energy began in Costa Rica in 1994 with the installation of a power plant of 55 MWe in the Miravalles zone (Figure 1). By 2003, the installed capacity increased to about 163 MWe with the integration of new units, and it has conserved so until nowadays. Furthermore, a new geothermal field was developed in Las Pailas zone, in 2011(Figure 1). The production of this field starts with 35 MWe installed in a binary plant (42 MWe gross). By the moment, there are two geothermal fields in exploitation phase, Dr. Alfredo Mainieri Protti and Pailas I. Pailas II development will start the commercial exploitation phase in 2019, with a contribution of 55 MW. Some prospective areas are planned to be researched soon according to the plan for Costa Rica´s geothermal expansion (Table 1).

Table 1. Geothermoelectric capacity installable in Costa Rica (in MWe) (Cataldi and Mainieri, 1995)

Area	***Capacity that can be fed by the reserves (MWe)***			***Priority***
	Single Flash	**Dual Flash**	**Average**	
Miravalles	164	213	189	I
Rincón de la Vieja (Las Pailas)	137	177	157	
Irazú - Turrialba	101	130	116	II
Tenorio	97	123	110	
Platanar	97	122	110	
Poás	90	116	103	
Barva	85	109	97	
Fortuna	61	77	69	III
Orosi - Cacao	33	41	37	
Seven other areas*	---	---	---	IV
Total	865	1108	987	

*: Caño Negro, Liberia, S. Jorge, Tilarán, Puerto Viejo, San José and Tigra

In Dr. Alfredo Mainieri Protti, the current capacity installed is around of 165 MWe (Table 2), thus remaining for an extended period of time. The geothermal utilization in the country is only for electrical energy production (Mainieri, 2005). Although there are some swimming pools that use natural geothermal water.

During Dr. Alfredo Mainieri Protti field drilling, it was discovered (delimited by) that some of the wells belonged to an acid aquifer. The *Acid sodium-chloride-sulphate aquifer* (Na-Cl-SO4) is located in the northeast sector of Dr. Alfredo Mainieri Protti (Rodriguez, 2006). The fluids from this aquifer have a high content of sodium-chloride sulphate, and pH values are between 2.4 and 3.2. These acid wells had high productivity (7 MW in average); however, it did not seem possible to exploit those wells for energy production due to corrosion problems in the pipelines, casing and other superficial stations. Then, it was necessary to develop a neutralization system which makes it possible to take advance of the resource, and also to recover the initial investment (drilling).

Table 2. Installed capacity, net power and gross power in Dr. Alfredo Mainieri Protti (Miravalles) Geothermal Field

Unit	*Power according to plate (MWe)*	*Net Power (MWe)*	*Gross Power (MWe)*	*Type*	*Start-up date*	*Final date*	*Belongs to*
Unit 1 (Dr.Alfredo Mainieri Protti 1)	55.1	55	60	SF	March, 1994		ICE
WHU-1	5.0	5	5	BP	January, 1995	July, 2006	ICE
					December 2006		
WHU-2	5.0	5	5	BP	September, 1996	August, 1998	CFE
WHU-3	5.0	5	5	BP	February, 1997	January, 1999	CFE
Unit 2 (Dr.Alfredo Mainieri Protti 2)	55.1	55	60	SF	August, 1998		ICE
Unit 3 (Dr.Alfredo Mainieri Protti 3)	29.5	26	29	SF	February, 2000	February, 2015	GG
					March, 2015		ICE
Unit 5 (Dr.Alfredo Mainieri Protti 5)	21.0	15	19	ORC	November, 2003		ICE
Total	160.7	156	173				

SF = Single flash; BP = Backpressure; GG = Geoenergía de Guanacaste Ltda., in a BOT system (Build-operate-transfer); ORC = Organic Rankine Cycle. It is a binary plant; ICE = Instituto Costarricense de Electricidad; CFE = Comisión Federal de Electricidad (México); WHU = Wellhead Unit. The WHU-1 changed the location during 2006 to other zone

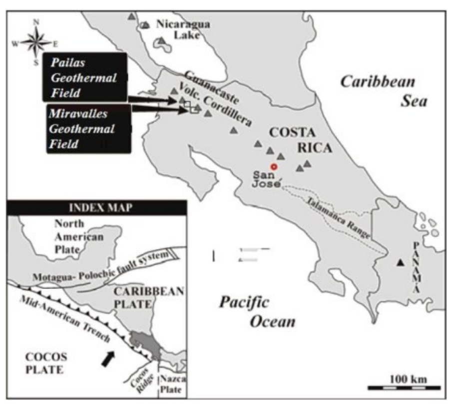

Figure 1: Location map showing Costa Rica and two Geothermal Fields, Dr. Alfredo Mainieri Protti and Pailas.

Several changes have been done since the application of the neutralization system: the alloys in the capillary tube, the reduction of the NaOH concentration and changes in operative system are some examples.

In all processes, it is necessary to monitor and control the main variables, so the sampling system plays a fundamental paper in the record and control of these variables. The commercial exploitation of the neutral and acid wells (its geothermal application) could not be possible without an adequate sampling system which is responsible to define if the neutralization process is carried out correctly or not. Then the measures must be reliable in all moment.

This paper presents a compilation and update of information from other presented papers, related to the topic (Moya and Nietzen, 2010 - 2012, Nietzen, 2007 and others).

2. CHEMICALS SYSTEMS

There are two main chemical systems in Dr. Alfredo Mainieri Protti field and each one treats to avoid any trouble relative to incrustation (by calcium carbonate) or corrosion (low pH for acid wells). Since 1994, it was necessary to implement a calcium carbonate inhibition system on neutral wells. Nowadays, there are 21 systems installed at production wells.

Moreover, there were four wells related with the aquifer acid, of which only two wells are presently in operation. In order to prevent the corrosion of casings and surface structures, it was needed to implement the neutralization systems on these wells. The systems were implemented since 2000, starting in the well PGM-19.

The inhibition system and the neutralization system operate 24-7 (24 hours a day, 7 days a week).

2.1 Calcium Carbonate Inhibition Systems for Neutral Wells

The neutral fluids from production wells have a tendency to form CaCO3 precipitation at Dr. Alfredo Mainieri Protti Geothermal Field, according to the following reaction mechanism:

$$Ca^{2+} + 2HCO_3^{-} \Leftrightarrow CaCO_3 \downarrow + CO_2 + H_2O \quad (1)$$

where Ca^{2+}, HCO_3^-, $CaCO_3$, CO_2 and H_2O are calcium ion, bicarbonate ion, calcium carbonate (calcite), carbon dioxide and water, respectively.

The geothermal fluid (from neutral aquifer) is saturated of salts. When the well begins producing, the vapor phase is increased in flashing point of downhole, and the mass is decreased in liquid phase. This causes the excess undissolved salt is scaled in the inner walls.

Then it is necessary a carbonate inhibition system for commercial exploitation of the neutral aquifer. The diagram of calcium carbonate inhibition system in neutral geothermal wells is shown in Figure 2.

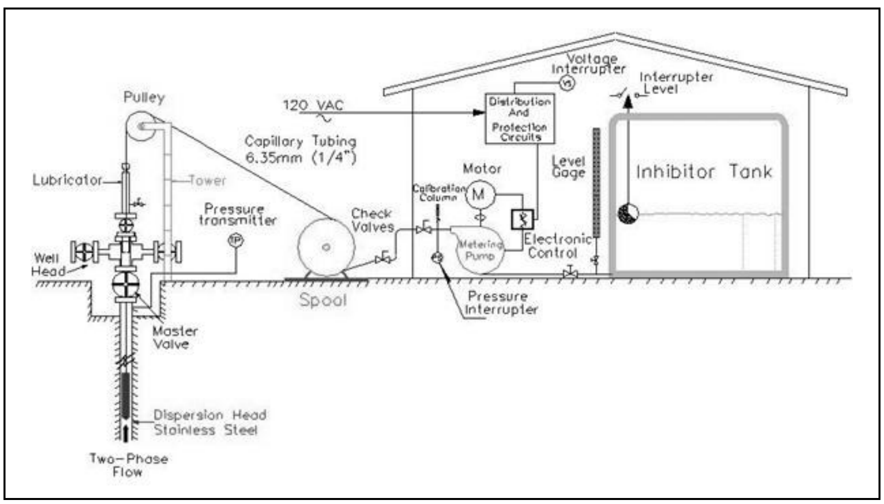

Figure 2: The calcium carbonate inhibition system (neutral geothermal well).

The diluted inhibitor is stored in the tank located at each well. There is a sensor that it is activated when the level is low and the inhibitor is injected into production well by action of the system pump, through to capillary tubing to the boiling point of the well (between 1000 to 1400 meters, depending on the well). The capillary tubing is connected to the injected head and the weigh bar which helps system stability. The capillary length is between 1100 to 1500 meters and the material is alloy 316L, but it is also used incoloy 825 alloy in some cases.

Some parameters of control are:

Operating parameters

- Consumption time, T100 (seconds): time that takes a column of 100 ml of inhibitor to be injected into the well. This parameter is indicative of the flow inhibitor.
- Pumping pressure (bar m): the pumping pressure is important to detect a possible problem in the capillary tubing (example: partial or total obstruction, broken tubing, others).
- Tank levels (m): it indicates the level of inhibitor in the tank.
- Wellhead pressure (bar m): it is operation pressure of the well.
- General conditions (energy, pumping, capillary tubing, water, others).

Chemical parameters

- Calcium: calcium content to calculate the ratio Ca/Cl. It indicates the effectiveness of the inhibition process.
- Chlorides: chloride content to calculate the ratio Ca/Cl. It indicates the effectiveness of the inhibition process.
- Bicarbonates: it is used to adjust the inhibition dose.

The above parameters are monitored periodically. If any of the parameter is out of control, it is taken corrective actions in order to adjust the system to normal conditions.

There are some other processes related to inhibition of calcium carbonate, such as:

- Receipt of the inhibitor (pure product). The product is received at the Dilution Plant. It is analyzed, quantified and stored in several tanks of 50000 kg each.
- Diluted inhibitor ready to be distributed. The pure product and water are mixed for dilution to different concentrations. This is done at the dilution Plant. The product is diluted to different concentrations, depending on the pumping system and on the recommended dose.
- Distribution of the diluted product. The diluted product is distributed to the various storage tanks located at the neutral producing wells (Figure 2) and quantifies the mass delivered. A cistern is used to distribute the inhibitor.

Corrective maintenance is done every time it is required. Preventive maintenance as well as electrical and mechanical maintenance follows yearly maintenance programs which have been improved continuously.

The quantity of injected inhibitor changes over time. Figure 3 shows an example of the bicarbonates evolution in well PGM-12, during the period 1999 - 2014. Initially, the well needed a dose of 0.50 ppm of inhibitor, but nowadays it needs a dose of 1.50 ppm. In some other wells the behavior has been just the opposite, and therefore, the inhibitor consumption might increase or decrease with time.

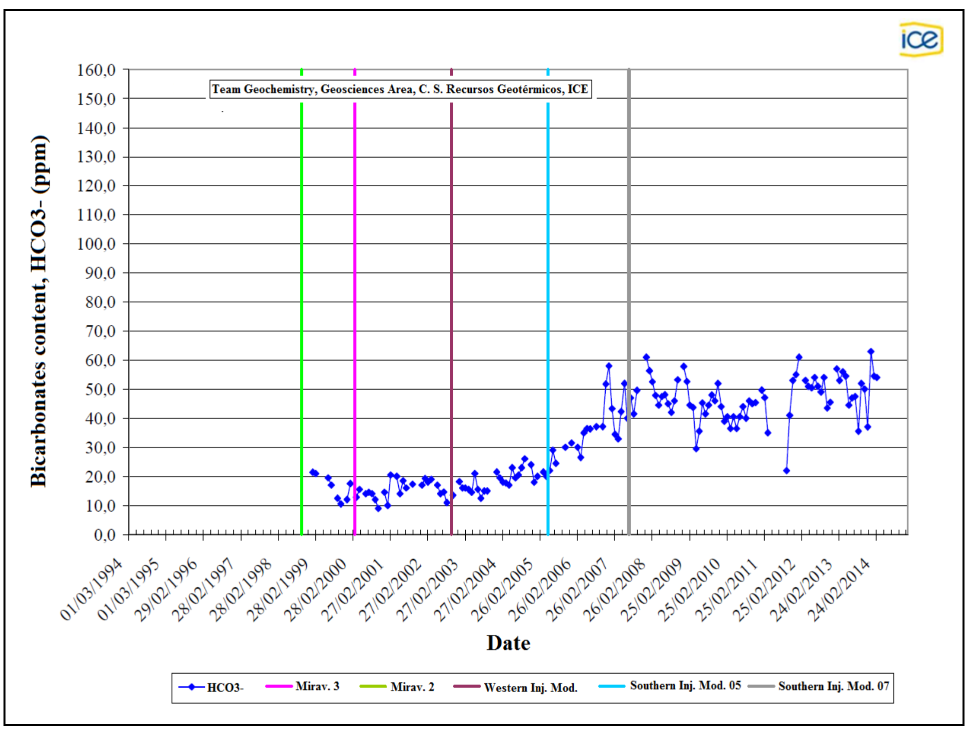

Figure 3: Bicarbonates evolution in well PGM-12 (Torres, 2014).

Different types of inhibitors have been tested since 2000 with success. Some of them have been Nalco 1340 HP Plus, Geosperse 8410CN+, BWA DP 3537 and BELGARD EV2035. However, one of them presented serious problems with the formation of bacteria during the storage stage, which led to a series of additional costs and inconveniences. Pilot tests (bacterial formation) should be performed on potential inhibitors. These tests could last at least 2 months, in the same storage environments.

2.2 Neutralization Systems for Acid Wells

There is an acid sodium-chloride-sulphate aquifer (Na-Cl-SO4) at the Dr. Alfredo Mainieri Protti geothermal field. Therefore, the fluids have a sodium-chloride sulphate composition and they are located in the northeast sector of the field. The pH ranges between 2.3 and 3.2 and then it is necessary to carry on chemical treatment to avoid corrosion inside the well and surface equipment.

There are four acid wells situated in this zone: PGM-02 (integrated since March 2006), PGM-06 (has not been integrated), PGM-07 (integrated since October 2001) and PGM-19 (integrated from February 2000 to March 2011, and then in June 2014). It was required the implementation of neutralization systems to neutralize the acidity. However, the degree of acidity in the well diminished over time. Nowadays there are 2 neutralization systems in continuous operation.

The fluids from these wells are highly corrosive unless treated previously. The materials and equipment in contact with the fluids (pipes, casing, capillary tube, separators, others) must be protected. The aim of neutralization system is to protect the production casing as well as all surface equipment from the corrosion. It injects a neutralizing fluid (like caustic soda, NaOH) inside the well through the capillary tube (1000 m depth, approximately). Three pumps are used and the neutralizer is stored in tanks. The Figure 4 shows the overall diagram about the neutralization system applied in the most of the wells.

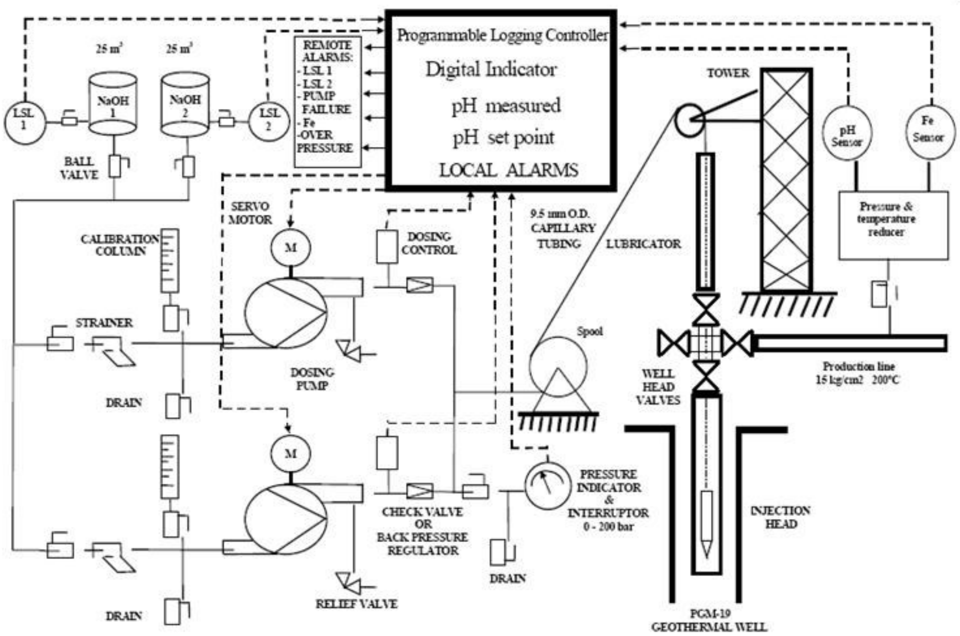

Figure 4: Neutralization system well PGM-19.

The acid fluid from the wells is neutralized with NaOH solution to 40 wt %. This concentration is diluted with water that is being simultaneously pumped into the NaOH solution (dilution on line). There are two NaOH storage tanks located in a building close each well. The time of the store depend of the NaOH consume (this is between 15 and 30 days). The material can be carbon steel or polyetilene (high density).

Two pumps inject the NaOH in the well; one of them is the backup pump, they work in an alternating way to maintain the internal components in operation. These pumps are specially designed for chemicals such as NaOH and high pressure (more than 100 bar); the flow is between 10 and 50 l/h (depending of the well). There is another pump for water. This pump keeps the concentration of NaOH around 30 % (w/w), and the temperature of the fluid increases (solution heat), reducing the viscosity, and helping to the work of the pumps. All the pumps are positive displacement (diaphragm).

The capillary tubing is coiled in a drum (spool). During the operations of lowering down or lifting up the tool, the spool is set on a truck and the depth (capillary in the well) is controlled. The capillary is made of a special steel stainless (alloy 825), with a diameter about 9.5 mm (3/8 "). Its total longitude is approximately 1300 m, but its position in the well depends on the zone to be protected, of the boiling zone and the well completion (if there is liner, general state of casing, etc.).

The capillary tubing needs to stay stable in the well. For this reason, the capillary is connected to a neutralization head by means of a subjection system. This head is connected with a bar of weight, made of a special stainless steel tube (alloy 825), filling of lead.

The control variables are:

- pH (between 5.5 and 6.0)
- Iron (ppm Fe)
- Pressures and Levels
- Flows
- Others

All recorded variables or parameters are incorporated in an integral record, which helps to keep control on the parameters related to the neutralization system for acid wells. The parameters are taken continuously by operators in each well (24 hours a day). The analysis of each parameter or group of them, generate sufficient information to the operator (at site) to take corrective actions on the neutralization system if necessary, keeping the parameters within their normal range.

There are some other items that need to be considered to keep the neutralization system running properly (Nietzen, 2007):

- Supply of NaOH: The NaOH is brought to the Dr. Alfredo Mainieri Protti geothermal field by cisterns. A cistern with 20 000 kg carries the NaOH to the well each 15 or 30 days, depending on the consumption of each particular well. The safety measurements for personnel and environment are responsibility of the supplier during the transport. At the well, the safety measurements are ICE`s responsibility.
- Winch: Its function is to lift or lower down the capillary tubing into the well. It is a truck with a hydraulic winch and a hydraulic arm to lift and lower the spool with the capillary tubing. The system has high torque; therefore, care should be taken when the system is ascending the capillary tubing, to avoid applying a bigger force than the rupture force of the capillary tubing. This equipment is used in the calcium carbonate inhibition system too.

3. COSTS OF SYSTEMS

The purpose of chemical treatment systems is the commercial exploitation of geothermal wells. Without an appropriate chemical system, neutral and acid wells will be damaged or lost productivity over time. This would result in high operating costs and substantial losses (time - generation). The following sections justify the investments of the systems used in Dr. Alfredo Mainieri Protti Geothermal Field.

3.1 Calcium Carbonate Inhibition Systems

The inhibition increases the lifetime of the well, increasing periods of production, without needing the intervention of mechanical cleaning. The inhibition system may be divided into three modules, depending on process:

- Systems in the field (Figure 1: Inhibition booth systems, internal and external surface)
- Dilution Plant Systems
- Auxiliary Machinery and Equipment

Each module consists of special equipment used for the transfer of the inhibitor from the Dilution Plant to the boiling zone of the well. A summary of cost per module is shown in Table 3. Equally, it displays an initial investment of $1 810 552 for the inhibition system in a field with 5 producing wells, with an annual load (including depreciation and operation and maintenance costs) of $.243.227.

Table 3. Inhibition system costs on an annual basis (summary of modules).

Description Cost	*Total costs ($)*	*Annual Depreciation ($ / year)*	*Operation and Maintenance Costs ($ / year)*	*Total annual cost ($ / year)*
System in the Field (cost per well - producer)	93 058	15 617	6 191	21 808
System in the Field (5 wells)	465 292	78 084	30 957	109 041
Plant Systems	664 187	99 273	3 628	102 901
Auxiliary Machinery and Equipment	892 753	49 406	10 316	59 721
Inhibition System	**2 022 232**	**226 762**	**44 901**	**271 664**

A well without inhibition, can last for three months on average, and over time, productivity will decline until the pressure does not allow the integration. To reactivate it again, the well must be intervened with a drilling machine. It creates additional costs, such as equipment, personnel and time to no generation, which on average is fifteen days. Table 4 shows some important data.

Table 4. Important parameters in determining additional costs associated with the missing inhibition system.

Parameter	*Value*	*Unit*
Wells		
Average generation per well	7	MW
Average selling power 2014	0.181	$/kWh
Total wells integrated system	5	
Interventions		
Average cost mechanical intervention	180 201	$
Average costs of operation and maintenance before and after intervention	13 285	$
Average time intervention	15	days
Process without inhibition system		
Estimated time of well production without inhibiting	350	days
Decay rate of the well	0.0280	MW/day

Table 5 shows the distribution of production and intervention time, as well as the energy lost by the perceived shortfall of inhibition system for a well, based on one year.

Table 5. Energy not perceived by missing inhibition system. Annual basis per well.

Parameter	*Production*	*Intervention and Recovery*	*Totals*
Days	350	15	365
Energy delivered without inhibition system (kW·h)	48 507 550	0	48 507 550
Energy delivered with inhibition system (kW·h)	58 800 000	2 520 000	61 320 000
Difference between Energies (Total energy not delivered due to missing inhibition system) (kW·h)	10 292 450	2 520 000	12 812 450

It displays the energy loss during periods of operation of the well (last row, Production column) due to the gradual fouling. Additionally, there is an annual, where the well is not producing as a whole. Aggregating all energies, yields a total of 12 812 450 kW • h per year per well, the system fails to generate. The quantity increases when considering the 5 neutral wells model, for a total of 64 062 250 kW • h.

An overview is shown in Table 6, which details the two scenarios, with and without inhibition system. The magnitude of the costs incurred through lack of inhibition and the costs of the system (distributed annually) is significantly different. With the annual cost of the system for inhibition of 5 wells ($271 664), saving $ 12 558 862.

Table 6. Associated costs with interventions and no generation periods, versus the value of the inhibition system, on annual basis per well.

Costs and expenses	***Cost ($)***
Annual costs per well, without inhibition system	
Cost interventions	193 485
Costs of not generating	2 318 287
Total expenses	2 511 772
Total costs for 5 producing wells	12 558 862
Inhibition system costs on an annual basis (Table 3)	271 664
Percentage relationship cost / expense (with inhibition system / without inhibition system)	**2 %**

3.2 Neutralization Systems

The aim of neutralization system is to protect all surface equipment from the corrosion. However, the pH must be lower than 6 to avoid the silica formation into the well. Since it was changed the control of pH to a range (between 5.5 and 6.0, on March 2004), intervention with mechanical drilling equipment for cleaning has been eliminated until now. The graph of the Figure 5 shows the produced steam mass the acid wells over time.

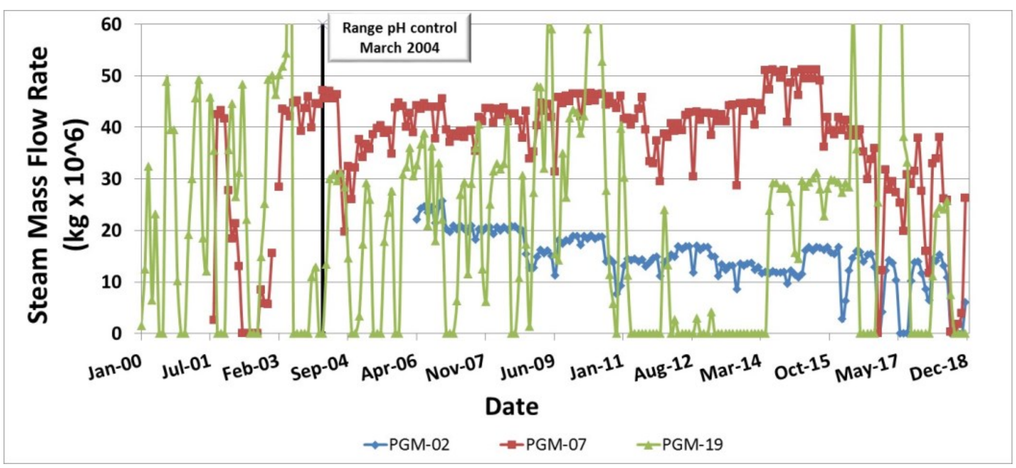

Figure 5: Steam production of acid wells.

The PGM-19 was the first acid wells on line, however, its production is not constant (various interventions, evolution, etc). The second one was the PGM-07 with a production more constant, and de last ones were the PGM-02 and PGM-06. The PGM-06 is not on line, it is a well of reserve.

The silica scaling was cleaned with mechanical drilling equipment before the change (vertical black line on Figure 5). The Table 7 shows the mechanical interventions in acid wells.

After March 2004, there are not mechanical interventions in acid wells. The saving costs per well (per year) are similar to the related to lack of inhibition system, $ 2 511 772 (costs without inhibition system in Table 6, row 4)

The general costs of the neutralization system can be separated in two: fixed cost and variable cost. The Table 8 shows some cost relative with the neutralization system.

Table 7. Mechanical interventions in acid wells.

Well PGM	*Number of cleaning*	*Initial Date*	*Final Date*	*Duration (days)*
02	1	03/11/2003	07/12/2003	38
06	1	05/10/2003	09/10/2003	13
07	1	19/01/1998	28/02/1998	44
07	2	05/06/2002	08/06/2002	8
07	3	28/06/2002	30/06/2002	7
19	1	28/06/2000	04/07/2000	11
19	2	24/06/2001	04/07/2001	15
19	3	11/07/2002	22/07/2002	16
19	4	10/07/2003	21/09/2003	76

Table 8. Costs descriptions of the Neutralizations System.

Type Cost	*Description*
Fixed costs	Neutralization system (controllers, lines, equipment in general such as valves, pipes, fittings, tanks)
	Infrastructure (civil works, towers, etc.)
	Design, supervision and implementation
	Lands
	Well Drilling
Variable costs	Operating Costs
	Chemicals for neutralization (NaOH)
	Chemical analysis of water (kid `s)
	Chemicals for monitoring equipment
	Staff in product testing
	Monitoring System
	Technical – Professional support
	Sampling and chemical analysis
	Maintenance
	Electrical energy consumed by the neutralization
	Water, Phone
	Tubing
	Intervention of the well with other equipment (drill)

Some approximate data costs are shown in Table 9. There is an estimated income by sell energy in the same Table (base: 1 acid well).

Table 9. Estimated costs and income of the acid wells (base by well).

Parameter	*Value*	*Unit*
Fixed costs	4 688 159	$/year
other fixed costs (pipe racking, separator, valves)	841 637	$/year
Variable costs (per year)	317 992	$/year
Total costs (annual basis) *	686 645	$/year
Income from energy sales	11 094 678	$/year

* Depreciation total fixed costs in 15 years

The supported resource that gives the acid well in sales of energy is high compared with the costs in one year. The initial costs could recover in a year.

To keep the acid wells on line with the contribution of approximately 11 MW (to Dr. Alfredo Mainieri Protti Field and to the national interconnected system), it is essential to control the neutralization system in the site carried out by trained personnel. Nowadays, there are three wells on line, PGM-02, PGM-07 and PGM-19. However, sometimes these wells do not show acidic characteristics in the initial stages of production (evolution of the zone). PGM-06 has been withdrawn.

4. FINAL REMARKS

The chemical systems (inhibition of Calcium Carbonate and Neutralization) are excellent options for keep the production of geothermal wells in fields where some conditions (calcite deposition or acidic areas) are presented.

The economic balance shows the efficiency of calcium carbonate inhibition versus the option of mechanical intervention. The main advantage could be the productivity of the well where it does not lose production time and no need to withdraw for cleanout. Other advantage is the increase in lifetime of the well: minimizing the possible damage to internal parts for mechanical intervention, adverse effects when closed, are cooled and re-open, the possibility of total loss of the well. The mechanical intervention cost is reduced at time due that the number of interventions is reduced.

Furthermore, the economic analysis is different for the neutralization system, although in both cases the aim is to keep the well producing most of the time. The accelerated corrosion in acid wells avoids its production. The neutralization is the only option to keep them in production. The costs associated to control are higher than the inhibition of calcite (controls, operators, chemical fluxes, tubings and their changes, etc.). However, they keep the acid wells on line with a great income. It is essential to control the neutralization system in the site carried out by trained personnel.

5. CONCLUSIONS

The implementation of a calcium carbonate inhibition system is high investment, but is the option that represents a better return, compared with the costs and expenses from an intervention with heavy machinery. The cost-benefit analysis will show the profitability is important that the inhibition system in a geothermal field with fluids that deposit calcium carbonate.

In the last time, the neutralization system of the acid wells kept the pH value around 7. However, there were problems of scaling in the casing with this value of pH. The production of the well decreased in the time and a mechanical intervention was inevitable (costs of the intervention, the reduction of production and time without production). Then it was necessary to change the value of pH for minimize the silica scaling. This value is between 5.5 and 6.0. For values lower than 5.5 corrosion problems will be significant (damage in casing, pipes and superficial stations, with associate costs, and possible loss of the well). Contrary case, for values higher than 6.0 the scaling problems will be significant (loss in production, cost of mechanical intervention and cost to keep the well out of the production).

The behavior of wells varies over time, both the neutral nature as the acidic nature. For example, neutral wells changed their geochemistry, so it is necessary to vary the dose of inhibition (usually increases). In acid wells, the degree of acidity is changing, with a tendency to decrease. In the acid well PGM-07 the dose of neutralizer is minimal, and the final tests of the well PGM-19, the fluids have been neutral. These phenomena can be associated with decays in the acidic area, and an invasion of neutral aquifers. Therefore, chemical systems must be adjusted in order to maintain controlled processes.

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