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Reservoir Management at the Miravalles Geothermal Field, Costa Rica

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ABSTRACT

The Miravalles Geothermal Field has been continuously exploited since 1994. The total installed capacity has reached 163 MW, accounting for about 8% of Costa Rica's total electrical production and it has become the foundation of the electrical supply in the country. The reservoir has evolved since the start of its massive production, and different actions and strategies have been implemented for sustaining the steam supply to the power plants and for reservoir management. These include monitoring of reservoir characteristics, accounting of mass production rates, numerical modeling, production and reinjection pipeline network design, designing and implementing the silica scaling inhibition and acidic fluids neutralization systems, maintenance and replacement wells programs, work-over and drilling and casing perforation.

1. INTRODUCTION

The Miravalles Geothermal Field is one of three geothermal reservoirs under exploration and exploitation in Costa Rica (Figure 1). Deep drilling started in 1978, when a high-temperature reservoir was discovered. Subsequent drilling stages completed the steam necessary to feed three flash plants commissioned in 1994, 1998 and 2000, and one binary plant in 2004, totaling an installed capacity of 163 MW. Three 5 MWe wellhead units have also produced for different periods, and one of them is still in use.

The reservoir is a 800-1000 m thick high-temperature liquid-dominated type, located at about 700 m depth with reservoir temperatures naturally declining to the south and west. The main reservoir fluids have a sodium-chloride composition with TDS of 5300 ppm, a pH of 5.7 and a silica content of 430 ppm. The fluids present a tendency for carbonate scaling in the wells, which is prevented by using an inhibition system and injecting a chemical into the wellbores. The main aquifer is characterized by a 230-255 ºC lateral flow. A shallow steam dominated aquifer is located in the northeastern part of the field, and it is formed by the evaporation of fluid from the main aquifer that moves along fractures (Vallejos, 1996). Another important sector shows an acid aquifer, and so far five wells have been drilled that present these kinds of fluids. Two of these wells have been systematically exploited and neutralized. There are plans to test and further put online the rest of the acid wells.

2. PRODUCTION HISTORY

The Miravalles reservoir has been exploited intensively since March 1994, when the first unit was commisioned. Since then, two more units have been added and three small wellhead units have operated as is shown in Table 1. All these units are flash-type, and a fifth binary-type unit (Unit 5) was commissioned by early 2004. All the actual operative units are owned by ICE.

Table 1: Generation at the Miravalles Field.

Unit	Operator	Power Output	Operation Time	
			Start	End
Unit 1	ICE	55	03/1994	---
Wellhead 1	ICE	5	11/1994	---
Wellhead 2	CFE	5	09/1996	08/1998
Wellhead 3	CFE	5	04/1997	01/1999
Unit 2	ICE	55	08/1998	---
Unit 3	Geo	29	03/2000	---
Unit 5	ICE	19	12/2003	

ICE means Instituto Costarricense de Electricidad
Geo means Geoenergía de Guanacaste. Geoenergia operates Unit 3 under a BOT contract.

The installed capacity of Miravalles accounts for about 8% of the country´s total installed capacity; however, it represents more than 15% of the country´s total generation (ICE, 2004(1)). Since the geothermal plants produce constantly throughout the year round, they are used as the basis for the country´s electrical generation, because of the variation in the hydro electrical plants production due to the seasonal variations of the weather (Figure 2).

The importance of geothermal energy in Costa Rica is increasing. In 2002, geothermal represented the 8% of Costa Rica's total electrical production and accounted for 13% of the country´s total generation (CEAC, 2002). A year later, the installed capacity reached an 8.4% and the generation was 15.1% (ICE, 2004(1)). During the first quarter of 2004, geothermal was the 8.4% of the total installed capacity of the country, and it generated the 17.8% of the total supplied by the National Electrical Grid (ICE, 2004(2)), or SEN (in Spanish). SEN includes all the electrical generation companies of Costa Rica (public and privates), and the total installed capacity of the country reaches 1946 MW (Table 2).

The mass extraction and injection rates in Miravalles are shown in Figure 3. Injection rates account for 85% of the total mass extracted from the field.

The injection strategy has changed along the production history. These changes have been made mainly for operational reasons, but since the reservoir is affected by injection returns this factor has been added as the decision making procedure. Injection into the different sectors at the Miravalles Field is shown in Table 3 as a percentage of the total injected mass into the field (Vallejos, 2003).

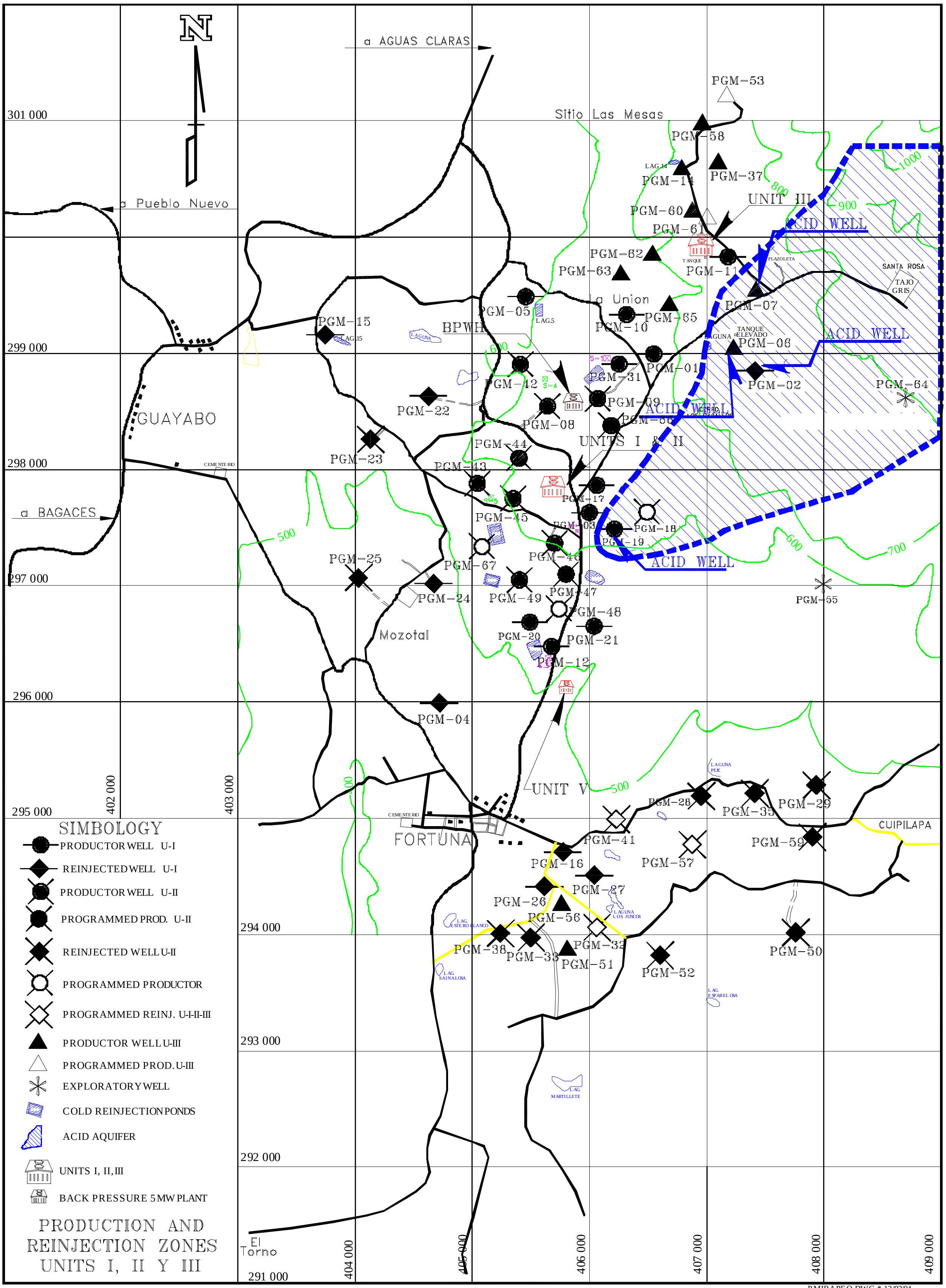
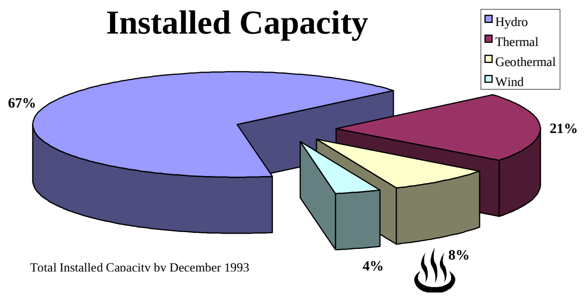


Figure 1: The Miravalles Geothermal Field.

The injection of waste brine has been made in “hot” conditions, that is around 165 °C, and a small proportion in “cold” conditions (less than 60 °C). These conditions changed when the Unit 5 came online, since this unit is a binary plant and it will recover some of the heat of the waste brine, lowering its temperature to 136 °C. A big part of the total waste brine will pass through Unit 5 and then be injected into the southern injection zone. The western injection zone will continue receiving brine at around 165 °C.



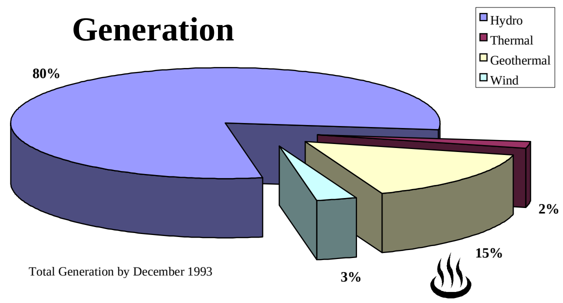


Figure 2: Costa Rica Installed Capacity and Generation.

3. RESERVOIR MONITORING

As part of the field management, a monitoring program was set up with the initial productive tests before the first power plant commissioning. This allowed having reference parameters for assessing the changes that would be produced due to the reservoir exploitation. The monitoring program includes well output testing, chemical sampling and downhole surveys (flowing temperature and pressure profiles) in all the productive wells every six to twelve months. A control on the calcium, chloride and bicarbonates content are also performed in the production wells, as part of the calcium carbonate inhibition program. Sometimes, the temperature and pressure static profiles, godevils and caliper surveys are taken. A three units downhole pressure data gathering system monitored the reservoir since June 1994 (Vallejos et al, 1995). The system was later replaced and improved by mid 1998 with five new units. The reservoir pressure is also measured by taking hydraulic levels in all the idle wells (Castro, 1999).

Several tracer tests have been conducted in the field, for tracing the waste brine injection returns and preventing possible problems due to the cooling of the reservoir. Some of these tracer tests were done in 1995 (Yock et al, 1995) and 2000 (González, 2001).

Table 2: Costa Rica Installed Electrical Capacity and Generation.

Type	Installed KW (2003-04)	Generated KWh (2003)	Generated KWh (2004)
Hydro	1295634	6021868	1449549
Thermal	419569	168794	27363
Geothermal	162710	1144245	341013
Wind	68550	229986	100510
Total	1946463	7564893	1918435

4. NUMERICAL MODELLING

Different numerical models of the Miravalles reservoir have been developed over the years, for forecasting the future behavior of the field according to the data collected.

In 1991 the Lawrence Berkeley Laboratory and ICE developed a preliminary natural-state and exploitation numerical models of Miravalles, based on the present conceptual model (Haukwa et al, 1992). The TOUGH2 code (Pruess, 1990) was used for the 62-block model.

ELC Electroconsult and ICE developed another numerical model in 1995, based in one used for the first feasibility studies done in 1985 and 1988 (made by using the GEMMA code). Natural state and exploitation models were created, based on the information gathered by ICE during the exploration and the first eight months of massive reservoir exploitation. TOUGH2 was also used for this 146-block model (ICE/ELC, 1995).

In 1998 GeothermEx, Inc. developed a 1953-block numerical model (made using the TOUGH2 code), based on all the information previously obtained by ICE and including the data from three years of continuous field exploitation. The model comprises and area of 12 km long N-S and 9 km long E-W, extending from +100 to –1500 m m.s.l. (1600 m total thickness) and divided into six layers of non-uniform thickness. The numerical model history matching and forecasting runs under different production and injection schemes were accomplished in that study (Pham et al, 2000).

GeothermEx, Inc. carried out a complete update of this last numerical model in early 2001. The grid blocks were refined and increased to 5110, and a double porosity and two-waters options were used (recently added to the TOUGH2 code version 2). This code was used for matching the chloride returns observed in the fluids. Also, the model took into account the new information gathered from July 1997 to March 2001 (production and new wells drilled). The update contemplated the rematching of the initial state and production historical data and new forecast scenarios for the field exploitation. (GeothermEx, Inc., 2002).

This current model has been used for evaluating different possible exploitation scenarios which have been proposed, i.e. increasing the generation capacity of Unit 5, injecting waste brine into the north zone of the field, moving the wellhead unit to PGM-29, etc.

Table 3: Injection Into the Miravalles Field Zones.

Start	End	South	PGM22	PGM24	PGM04
1994	1998	30%	30%	30%	10%
1998	2000	65%	13%	13%	9%
2000	2002	73%	9%	9%	9%
2002	2003	63%	11%	17%	9%

South means injection in wells PGM-16, 26, 27, 28, 51 and 56.

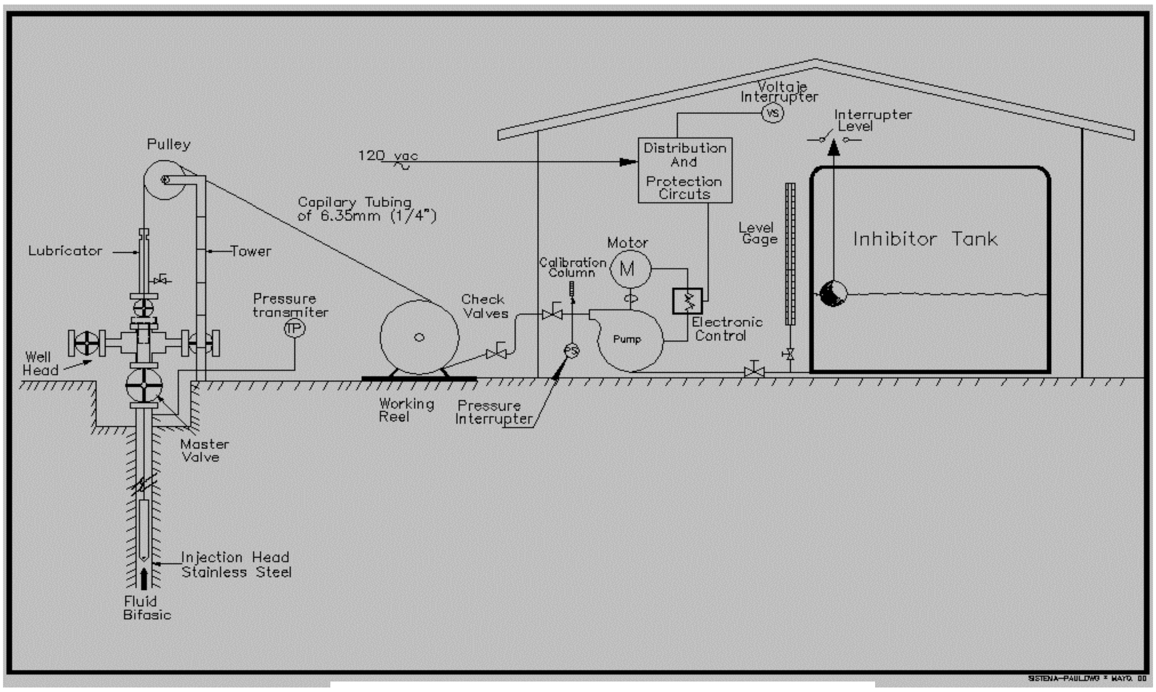


Figure 4: Calcite Scaling Inhibition System Scheme.

5. SILICA SCALING

The Miravalles reservoir fluids have a tendency of carbonate scaling in the wells, which ranges from strong to severe depending on the area and kind of aquifer present (at least three different aquifers have been defined in Miravalles). This scaling is severe enough to obstruct a well in terms of days or weeks (Sanchez et al, 2005). Due to this, the production wells at the Miravalles Field require deep chemical treatment to avoid the problems of $CaCO_3$ scaling and maintain permanent fluid production, thus saving money in lost production and costs due to cleaning of wells by using drill rigs. The system used for the scaling inhibition is shown in Figure 4, and it has been used since the start of exploitation at Miravalles.

During the exploitation of the field the chemical inhibition treatment applied to the production fluids has shown to be totally reliable in eleven years of continuous production. The control of the inhibition system efficiency is carried out individually for each well. The deposition evolution trends are monitored through the variations of the deposition level in time by using a triangular plot (Figure 5), in order to adapt the inhibitor dosage.

6. ACIDIC FLUIDS NEUTRALIZATION

The Miravalles Geothermal Field reservoir fluids typically have a neutral composition, but five of the wells drilled produce acid fluids. These wells were drilled in the northeastern sector of the field, where a sodium-chloride acidic aquifer with pH values between 2.3 and 3.2 is present. This corrosive character would cause irreparable damages to the well casings and surface equipment, which would force discarding them after a few weeks of production (Sanchez et al, 2005).

The condition of these fluids has required studies to determine the feasibility of neutralizing the acid fluids and using the wells in a safe manner (Sanchez et al, 2000). These studies started in 1994, and the experience gained due to continuous experimentation has allowed maintaining two wells (PGM-19 and PGM-07) in continuous production for long periods of time (Moya and Sánchez, 2002). Today, these wells are an important part of the production system, because some wells exploiting the main aquifer have declined their production, and the acid wells have been used to fulfill the steam requirements for maintaining production to the actual levels.

The commercial exploitation period at wells PGM-07 and PGM-19 has shown that the neutralization systems at depth are working properly. They have achieved their goals, which are to raise the pH at depth and to protect the well casings and surface installations, allowing favorable operating conditions with iron values that show a low level of corrosion.

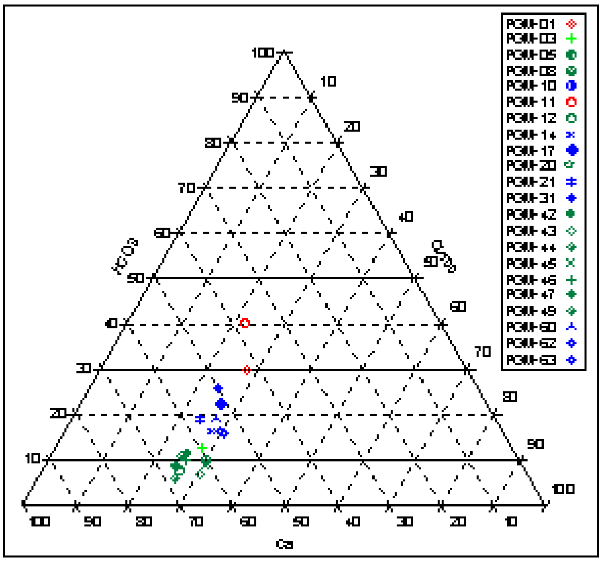


Figure 5: Calcite Scaling Control Plot.

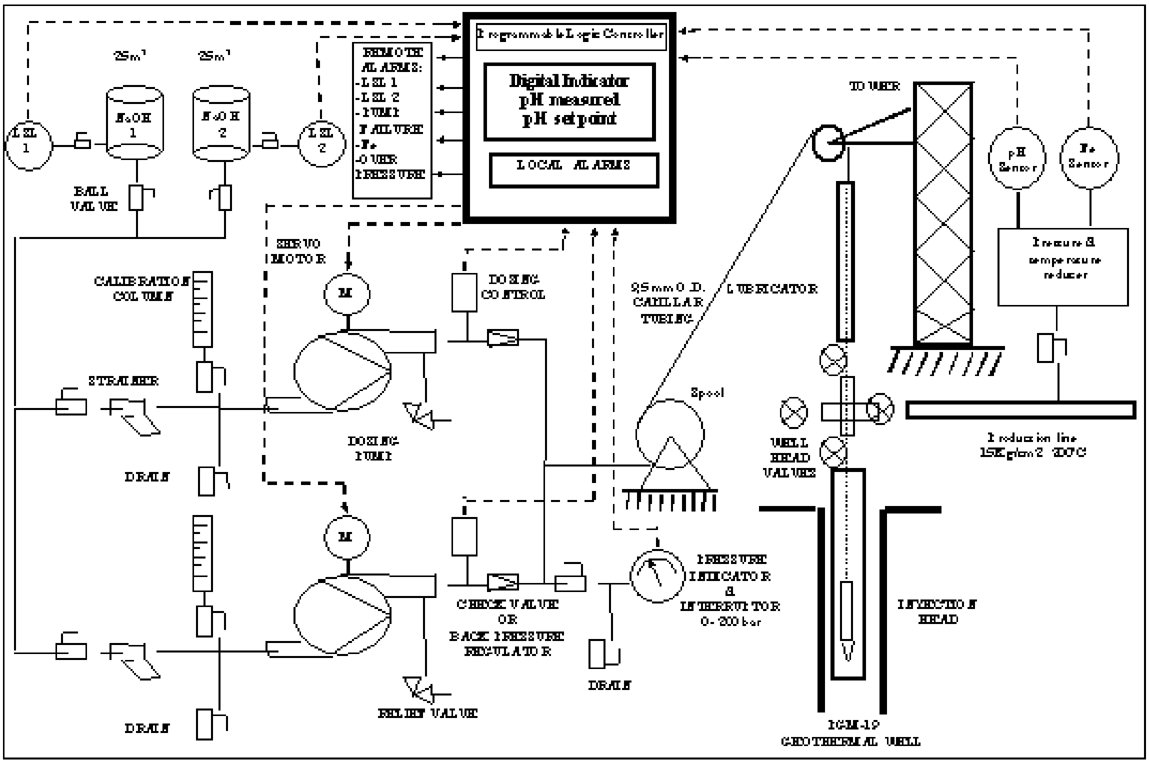


Figure 6: Neutralization System Scheme.

The neutralization process consists of adding a solution of sodium hydroxide to the geothermal fluid. This neutralizes the H^+ acid groups, thus raising the pH. The injection of the sodium hydroxide must be continuous and it has to be accomplished to an adequate depth within the well, to protect the casings and all the surface equipment against corrosion. The system designed for injecting the sodium hydroxide is shown in Figure 6.

However, there is a side effect in the anhydrite neutralization process. With a pH above 3.5 and temperatures over 215 °C, the acid fluid is supersaturated with respect to anhydrite (calcium sulfate, CaSO4). Therefore, with the current chemistry of these wells, the formation of anhydrite is unavoidable during the neutralization process (Sánchez et al, 2000). Currently, ICE has carried out some studies focused on controlling the pH for retarding or avoiding the anhydrite formation into the wells. Also, a couple of chemical companies are developing a thermally stable chemical inhibition product which can be injected through the NaOH dilution system and achieve a constant chemical dosage that will inhibit the formation of CaSO4 and the amorphous silica complex at depth and at the surface.

The economic and technical studies carried out have shown that the acid wells can be integrated into commercial production through a neutralization process of their fluids and that this is economically feasible. These studies have also shown that the investment in these two wells has or has almost been paid for in a short period of time (Moya and Sánchez, 2002).

7. PIPELINE NETWORKING

The wells at Miravalles are located in a wide area of 8x4 Km (Figure 1). This extension represents kilometers of pipelines carrying the fluids (steam, brine and biphasic fluid) from production wells to separation stations, power plants and injection wells. The steam has to feed three power houses (located in different parts of the field) moving four turbines, and a part of the brine has to be moved through a binary cycle before it is sent to the injector wells.

The capacity of the turbines for handling the CO_2 content is different for each one of them (e.g. Unit 1 can handle a maximum of 0.66%; Unit 2, 8.88%). This condition represents a serious problem, since the CO_2 content in the non-condensable gases has some variations in the different zones of the Miravalles reservoir and the quantity arriving to the different plants is not the same for each one of them. Also, the CO_2 content in the mass extracted is also influenced by the degassed injection fluids return, influencing locally the different injection and production zones of the reservoir. This has lead to carefully monitored and controlled the non-condensable gas content arriving to the turbines for not surpassing the handling limit of each turbine.

For all of these reasons, the pipeline networking design is of particular importance in the field management. It has to be capable of transporting all of the fluids to their correct destinations, and also to have enough flexibility for responding to different production and injection schemes (changes in production strategies and CO_2 content due to the field evolution).

The pipeline network was modified throughout the evolution of the field, first responding to the increase in production (with the commissioning of Unit 2 and 3), then on due to the CO_2 content of the non-condensable gases, and finally as a result of the changes made due to the commissioning of a power plant with a new technology

(Unit 5 as a binary plant). A simple scheme of the pipeline network, wells, power plants and other facilities is shown in Figure 7.

8. DRILLING, MAINTENANCE AND REPLACEMENT WELLS

Drilling at Miravalles is highly successful, since only 3 out of 53 wells drilled so far have been lost. Among the rest, 29 wells are productors, 17 wells are injectors and 2 of them are used for continuous monitoring of the reservoir pressure drop. Four of the production wells remain as spare wells.

The evolution of the Miravalles field and the continuous effort of ICE in assuring an adequate mass production for electrical generation has forced the drilling of some wells for maintenance and to look for new productive zones, since new drilling into the central zones of the field will not increase the actual production of Miravalles.

One of these wells is PGM-55, located to the eastern part of the field (Figure 1). Future drilling in this zone is not intended to increase but to give support to the current production of Miravalles, which has reached its maximum (163 MW).

9. ACIDING AND WORK-OVER OF WELLS

Different actions have been undertaken for recovering the lost of production in some wells in Miravalles. These actions have included deepening of wells and acidizing. Some of these activities are discussed in the next paragraphs.

Well PGM-46 started production in March 1994 with an initial steam output equivalent to 11.7 MWe, but its production rate began to slowly decrease and by June 2001 it was down to 4.3 MWe. Due to this, the possibility of deepening the well was considered. Before making a decision, geological, geochemical and reservoir engineering information from nearby wells was studied to infer what would be encountered below 1,200 m depth (depth of PGM-46 prior its deepening).

Between July and September 2001 the well was recompleted to intercept a deeper, permeable fracture (Figure 8). The operation was successful, and at present the well produces enough steam to generate 10 MWe (Moya and González, 2003).

Well PGM-03 was one of the first wells drilled in Miravalles. It was finished in March 1980, and after a production test of 168 days in 1981 the well became completely obstructed by $CaCO_3$ scaling. A mechanical cleaning of the well was done in 1984, but this action damaged the production liner. Due to this, the well completion had to be modified as shown in Figure 9 (González et al, 1997).

The main change done in the well completion was the final accessible depth of the well, which changes from the original 1029 m depth to the actual 692 m depth. The only feed zone of this well is located between 700-800 m depth, so the actual completion of the well does not allow to reach the feed zone.

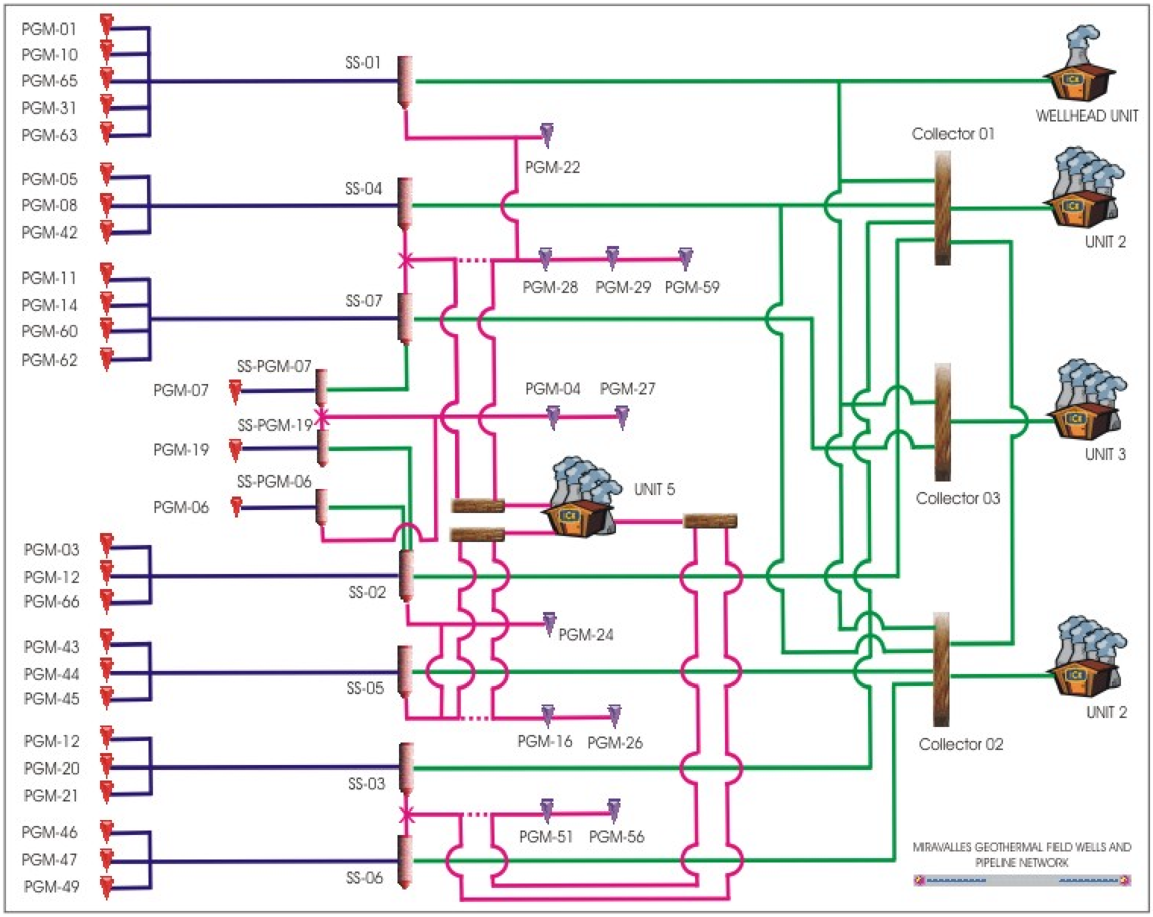


Figure 7: Pipeline Network at Miravalles.

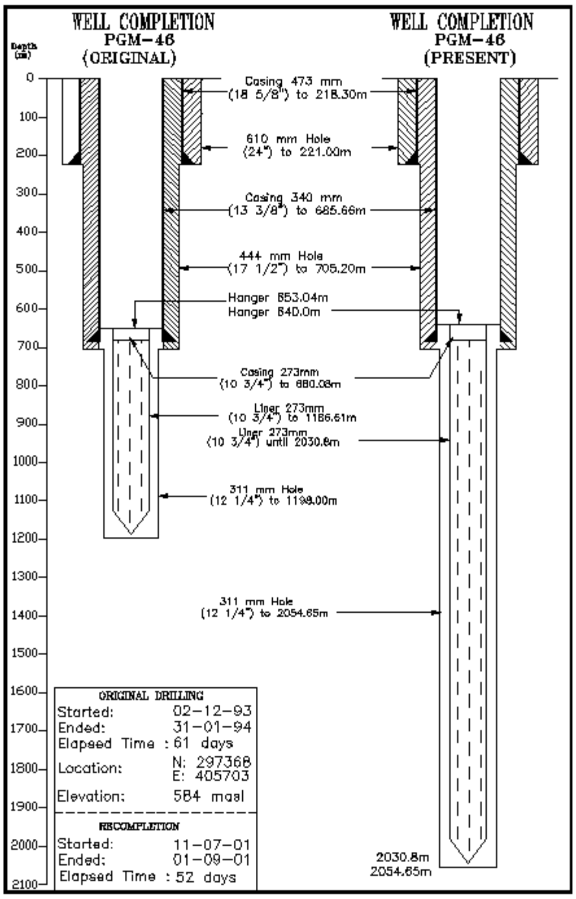


Figure 8: Well PGM-03 Before and After Deepening.

When the commercial production started in Miravalles in 1994, a silica inhibition system was implemented in all the wells, including well PGM-03. However, three years later this well started to decline in production. In October 1993 the well produced an equivalent of 7.9 MWe, but by March 1997 it was only producing 4.8 MWe. After some studies, it was found that the inhibition dispersion head could not reach a depth bellow the flashing point, doing the inhibition process ineffective (due to the well completion). Some actions were taken (modifying the dispersion head design, to restrict the production thus moving the flashing point depth), but it was finally decided to chemically clean the well. In April and May 1997 an HCl solution was injected into the well. After the injection, a production test showed that the well recovered its production by about 93%, reaching an equivalent of 7.2 MWe. However, this increase in production was not reflected in steam sent to the power plant, due to the previous problem presented (flashing point depth). Under these circumstances, well PGM-03 has to be produced at MPD thus reducing the production (González et al, 1997).

Due to the previously exposed, this well has to be periodically treated to recover some of the mass production lost.

10. SUMMARY

The Miravalles Geothermal Field has completed eleven years of successful exploitation, that has lead to an increase in its installed capacity from 55 to 163 MWe.

The installed capacity of Miravalles accounts for more than 8% of the country's total installed capacity, and produces more than 15% of the country's total generation. For this reason Miravalles is used as the basis for the country's electricity generation over the hydro electrical plants, due to the seasonal variations of the latter.

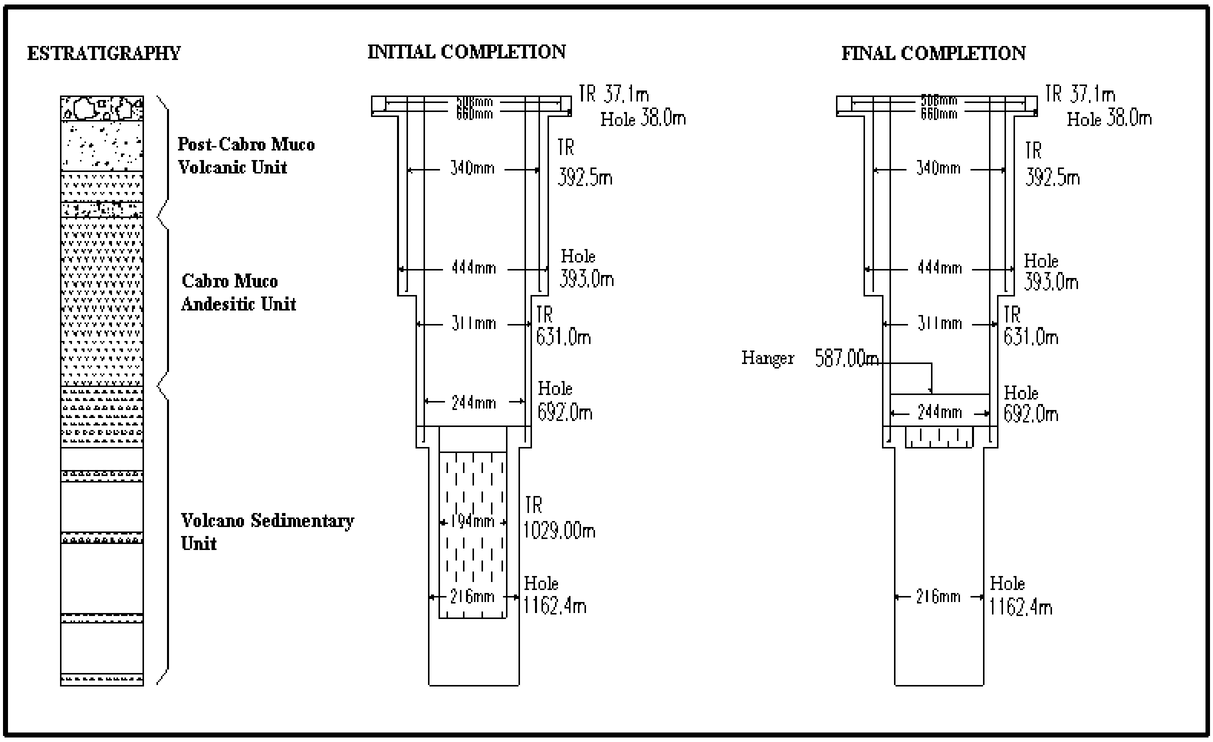


Figure 9: Well PGM-03 After and Before Intervention.

For maintaining a continuous operation of the field, different actions and strategies have been implemented by ICE. These actions have been focused on sustaining the steam supply to the power plants and also on reservoir management, and include monitoring of reservoir characteristics, accounting of mass production and injection rates, numerical modeling, production and reinjection pipeline network design, designing and implementing the calcium carbonate scaling inhibition and acidic fluids neutralization systems, maintenance and replacement well programs and work-over.

Numerical modeling studies have also been carried out for evaluating different possible exploitation scenarios, in order to improve the resource management and assure the long-term life of the geothermal field. Among these studies, it has been considered to shift some production to different productive zones, to inject brine for improving the pressure support, and so on.

So far, these actions have been very successful in increasing and sustaining the production of the field to the actual levels.

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