PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Fifty Years of Operation at the Ahuachapán Geothermal Field

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Keywords: Ahuachapán Geothermal Field, Operation, Field Case

ABSTRACT

The Ahuachapán Geothermal Field has reached 50 years of production. During the first decade, a pressure drawdown of approximately 15 bar led to the expansion of a steam cap and the lateral inflow of cool water from a shallow aquifer. In the 1990s, the borefield expanded to the southeast, stabilizing mass extraction by encountering highly permeable wells at deeper zones with varying water levels. Since reinjection began in Chipilapa in the early 2000s, on the northwest side of the field, pressure drawdown in the central area has decreased. As the conceptual model evolves, new wells drilled in the mid-2000s on the east side of the field have encountered temperatures of 275°C. However, the degree of connection with the existing wellfield is still under investigation. It is believed to represent a separate upflow, potentially serving as a prospect for future expansion. Numerical reservoir models predict that the current strategy will keep a stable power generation, though some cooling is anticipated.

1. INTRODUCTION

The Ahuachapán Geothermal Field (AGF) in El Salvador has been in continuous operation since 1975 playing an important role in the country's development. It is the third geothermal plant commissioned in Latin America, just behind Pathé (1959) and Cerro Prieto (1973) in Mexico (DiPippo, 2022). It is operated by LAGEO (2025) and it consists of a liquid-dominated reservoir with temperatures ranging from 210 to 250°C at the southern flank of the Salvadorean graben and northwest of the extinct andesitic stratovolcano Cerro Laguna Verde, a complex formed during the Quaternary time Pliocene tectonic block of Tacuba-Apaneca. The hydrothermal activity is associated with fault system trending E-W, NE-SW and NNW-SSE. The geological model considers three faults: La Planta, Buena Vista, and Agua Shuca as the conductors for the upflow into the geothermal system and the outflow part of the system occurs towards the NW in an area denominated El Salitre located approximately 7 km north of the geothermal field (Steingrimson, Bodvanson, & Escobar, 1989).

The initial exploration area is the production side of the field, developed between the late 1960s and mid-1990s. The geothermal reservoir is found at shallower depths, reaching temperatures of up to 235°C. Most of the main feed zones are located between 200 and 0 masl, within a layer of highly fractured andesites. The presence of boiling was observed in its natural state and has expanded over the years (see Figure 1). The reservoir exhibits high horizontal permeability and lateral recharge from flow originating in the southeast. The southwest area presents high temperatures (250 °C) at deeper levels (see Figure 2), corresponding to the bottom of the unit "Young Agglomerates", as defined by Aumento et al. (1982). Where highly hydrothermal pyroclastics and andesites are found. The hydraulic connection with the initial exploration area has been confirmed by monitoring pressure at the same elevations in two different wells, 1.8 km apart. A pressure disturbance was observed in one of the monitoring wells after a well test in the southwest, 12-hour later the pressure was observed at the initial exploration area monitoring well (Quijano, 2016). The physical connection has also been proven with a tracer test, by injecting 1.6-NDS at the well AH-18, the first arrival time was recorded as 12.8 days at well AH-23 located at the initial exploration area and 19.86 days for well AH-33B in the southwest area (Funes, 2023). The wells in the southeast area are all located at well pad AH-35. This area is pressurized by approximately 12 bar more compared to the rest of the production wells at same levels and has a slightly lower temperature compared to the southwest wells, at 245°C (see Figure 2). Trending northwest, well AH-35C is the second-best producer at the AGF, with a steam flow rate of 20 kg/s and a brine flow rate of 110 kg/s. Pressure monitoring has revealed that the pressure drawdown does not follow the trend observed in other areas, likely due to a semi-permeable structure between well pad AH-18 and AH-35.

The power plant consists of two single flash 30MW units and one double flash 35MW unit. The three of them with direct-contact type condenser, crossflow mechanically induced draft cooling towers (DiPippo, 1980). The NCG gas extraction system for the single flash units uses a steam ejector and a hybrid system with a liquid ring vacuum pump for the double flash unit. The gathering systems primarily use individual cyclonic separators at the well pads.

After fifty years of operation, the AGF has successfully overcome various challenges related to reservoir management through injection strategies and the expansion of production areas. Each challenge has come with its own unique circumstances to overcome. The aim of this paper is to present a brief history of the development of the AGF, highlight the main projects accomplished, share the lessons learned, and provide insights about future plans.

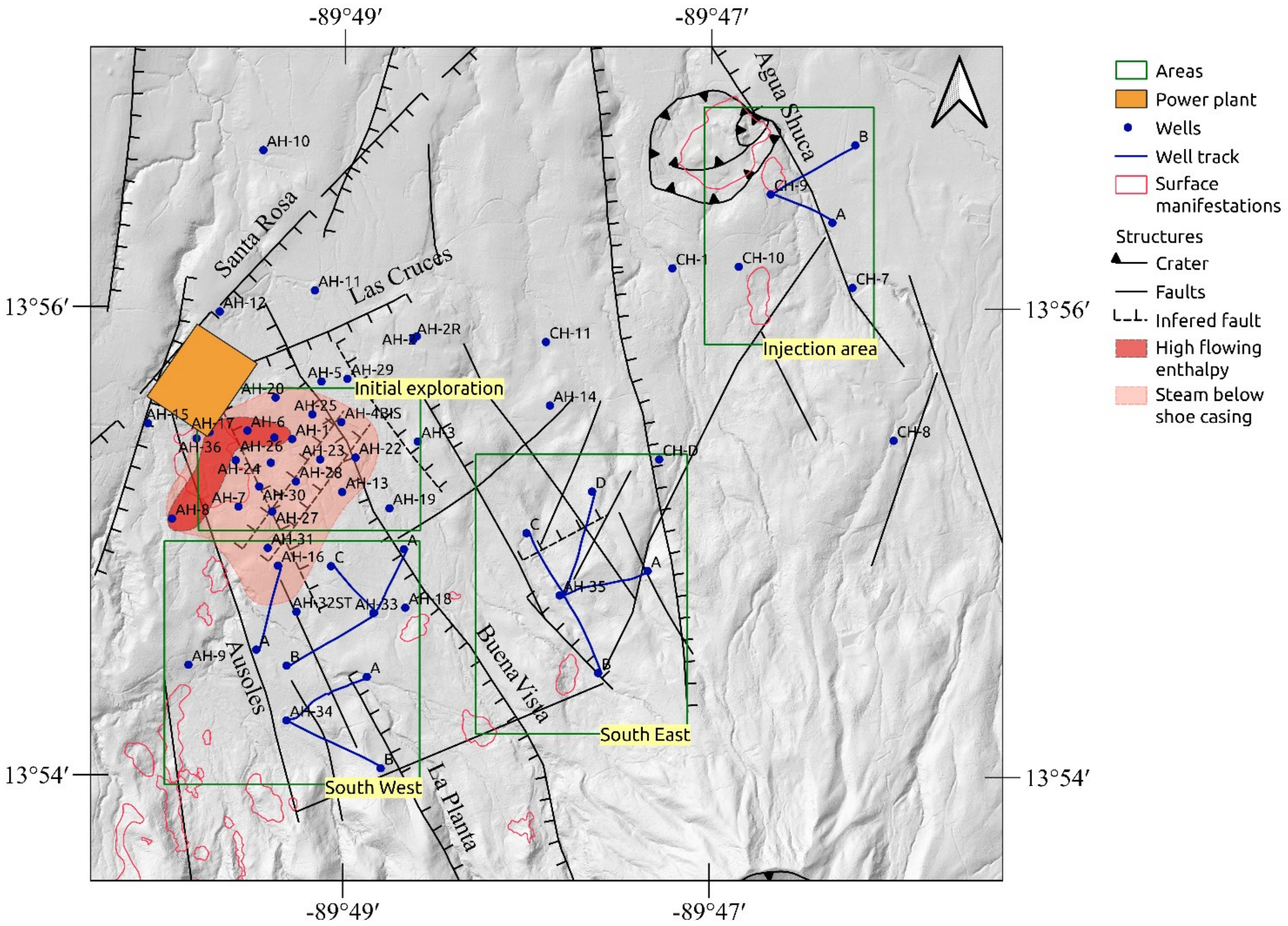


Figure 1: Ahuachapán Geothermal Field wells, structures, and surface manifestations.

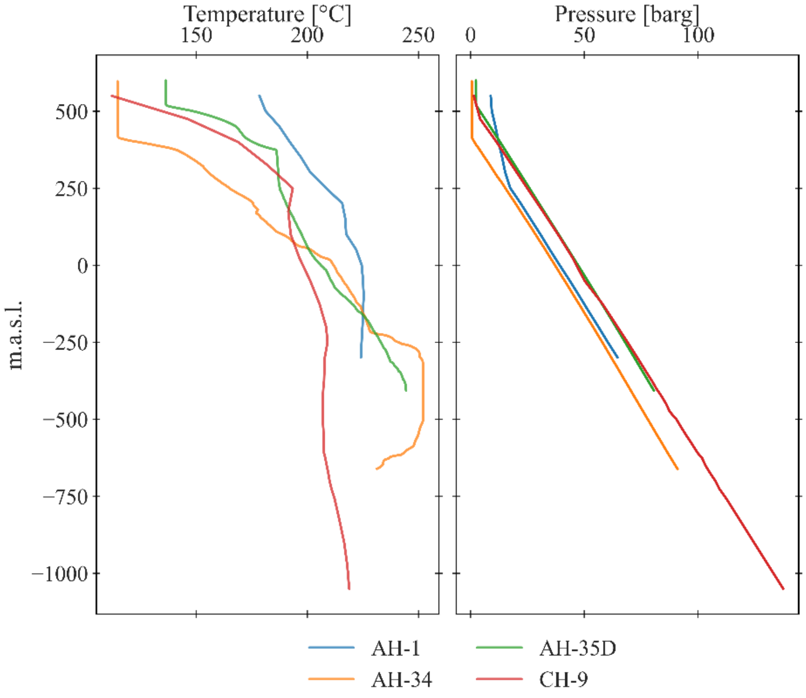


Figure 2: Temperature and pressure profile at different areas from the AFG.

2. FIELD DEVELOPMENT

2.1 Early exploration

During 1952, following a preliminary survey by the Smithsonian Institution of the surface manifestations in the Ahuachapán area, the Comisión Ejecutiva Hidroeléctrica del Río Lempa (CEL) initiated the evaluation of El Salvador's geothermal resources. Several exploration wells were drilled in the areas of Agua Shuca, El Sauce, San Carlos, El Playón, and El Salitre. At least four of these wells were able to discharge, confirming the resource and resulting in the creation of a hydrological map and several geophysical studies (Rodriguez & Cañas-Dinarte, 2005).

2.2 First drilling campaign and commissioning

By 1967, deep geothermal exploration began, funded by the United Nations Development Programme. The first wells were drilled by Loffman Brothers Inc. and Foramines S.A. By 1973, the construction of the powerhouse and other facilities had started, and in 1975, the first single-flash unit was commissioned by Mitsubishi. By 1976, the second single-flash unit was already operational. A third unit, this time a double-flash unit, was commissioned in November 1980, completing the total installed capacity of 95 MW. The power plant was officially inaugurated on November 6, 1980 (Rodriguez & Cañas-Dinarte, 2005).

2.3 Production decline

In 1981, approximately 41% of El Salvador's electricity demand was supplied by the Ahuachapán Power Plant (APP) (Janelle, 2004). Figure 3 highlights the period of the Civil War conflict (1980 and 1992) (Betancur, Planchart, & Buergenthal, 1993). During this time, guerrilla forces sabotaged transmission lines from hydroelectric power plants in the northern region of El Salvador, making the APP an extremely valuable resource for the country (Rodriguez & Cañas-Dinarte, 2005). Figure 3 shows that crude oil barrel prices peaked in 1981 while the population was rapidly increasing, emphasizing the critical need for geothermal power generation during that period. However, due to the limited area covered by the field at the time and the discharge of brine into the Pacific Ocean, wellhead pressure and steam deliverability began to decline (Hutter, 2000). By 1992, the geothermal field operated with 14 productive wells covering an area of only 1 km², resulting in a rapid decline in reservoir pressure. Consequently, electricity generation decreased, with a power load factor of only 45% (Parini, Cappetti, Laudiano, Bertani, & Monterrosa, 1995).

Figure 4 shows the steam flow rate from well AH-6. During the late 1970s and early 1980s, the experienced changes in fluid saturation, with flowing enthalpies increasing from 1,200 kJ/kg in 1976 to 2,400 kJ/kg by 1984. Currently, it exhibits values of 2,600 kJ/kg, revealing the expansion of the steam cap in wells near the power plant.

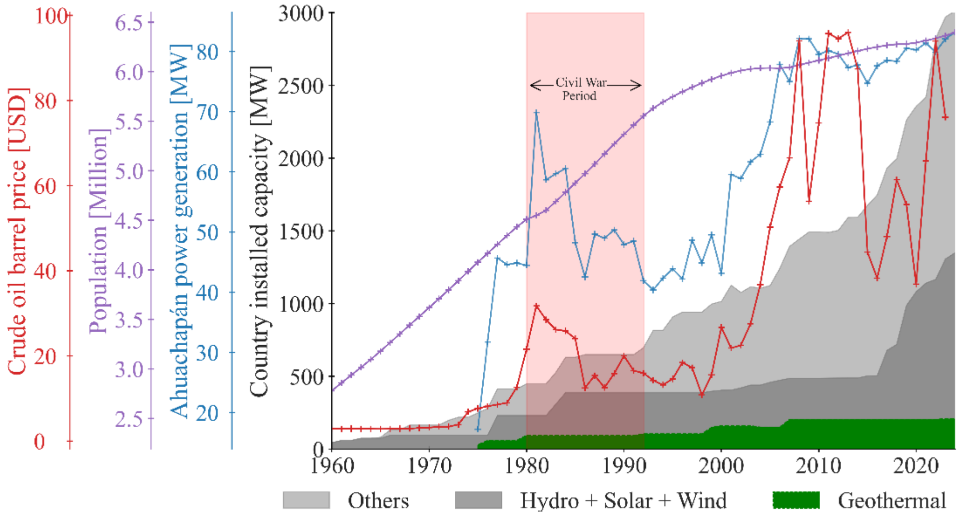


Figure 3: El Salvador's installed capacity addition through the years, yearly average of Ahuachapán Geothermal Power Generation, El Salvador's population and Yearly average of Crude oil barrel price. Population from United Nations (2024), Crude Oil barrel price from U.S. Energy Information Administration (2025) and Country Installed Capacity from SIGET, El Salvador's electricity and telecommunication sector regulator (2025).

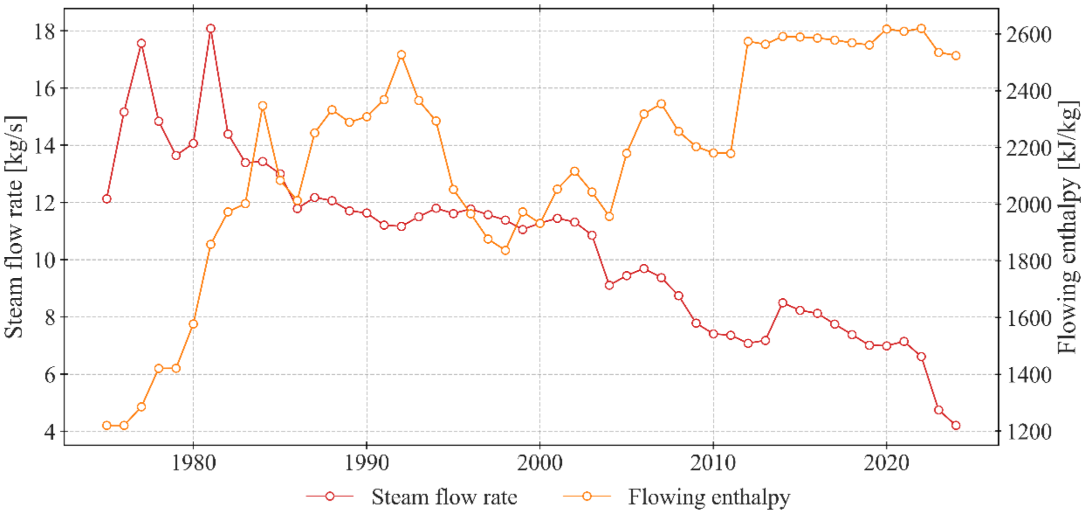


Figure 4: Steam from rate and flowing enthalpy from well AH-6.

2.4 Chipilapa development

Even though other geothermal prospects in the country, such as Berlin and Chinameca, had already been identified, the Civil War prompted the geothermal division of CEL, known as GEOCEL, to focus on a five-year deep exploration drilling campaign and other surveys in the Chipilapa area (Barrios, 1993). The study concluded that the Chipilapa area corresponds to the outflow of the AGF. Some wells, including CH-7bis, CH-9, and CH-D, encountered temperatures ranging from 180°C to 220°C and were capable of discharging. However, tests revealed low wellhead pressure in these wells, with CH-7 and CH-D showing high to moderate injectivity. Consequently, it was later decided to use the area for injecting separated fluid produced in Ahuachapán (Parini, Cappetti, Laudiano, Bertani, & Monterrosa, 1995).

2.5 Rehabilitation and Stabilization Project

In 1996, the Inter-American Development Bank (IADB) funded a $50 million (USD) project called the Ahuachapán Stabilization and Rehabilitation Project. The primary goal of the project was to modernize the power plant while ensuring its long-term sustainability. The project focused on four major objectives: drilling ten wells in the southern part of the production area, constructing a pipeline to inject brine into the existing wells in Chipilapa, building a gathering system for the new wells, and upgrading various electrical and mechanical equipment at the power plant (Rodriguez, 2000). By the end of the project, APP achieved a gross generation capacity of 85 MW and established brine injection in the Chipilapa area (Guidos & Burgos, 2012).

Figure 5 illustrates the rapid development of the southwest and southeast areas of the AGF, which significantly increased power generation by the early 2000s. This growth included the addition of new wells in Chipilapa, located approximately 4 km from the power plant. Since 2008, power generation has remained relatively stable with few new wells added. This stability has been achieved through a consistent well workover program (primarily in the reinjection area), biennial overhauls of power units, and the construction of a new gathering pipeline connecting two production wells originally drilled in 1997 at the AH-34 well pad.

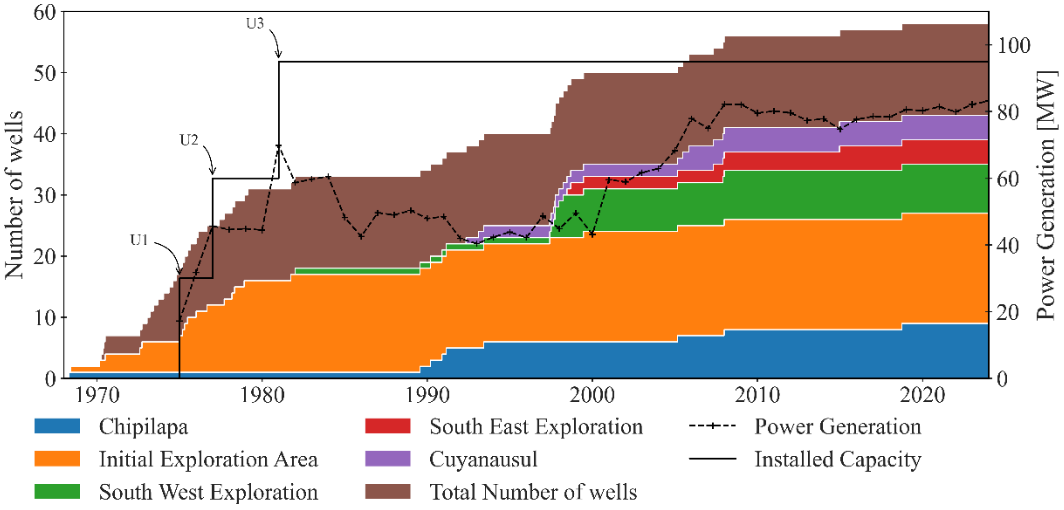


Figure 5: Number of well per developed area, installed capacity, and yearly power generation average.

2.6 Cuyanausul exploration

Cuyanausul is a geothermal prospect located east of the AGF (Figure 6). Recent studies suggest that the heat source and fluid origins might be shared with Ahuachapán and Chipilapa. During early 1990s two wells were drilled near the Cuyanausul fumarole, CH-A and CHA-1, multiple circulation losses were found at shallow depth, and 225°C at 200 masl. Nevertheless, the aquifer was cased off, deeper exploration found in minor permeable zones and temperature inversions (Barrios, 1993). In the early 2000s, as El Salvador's energy sector underwent reorganization, a strategic partner invested in the development of a third condensing unit in the Berlin Geothermal Field as well as the Cuyanausul project (Rodríguez & Herrera, 2005). Two wells, TO-1 and TO-1A, were drilled to a depth of 2,500 meters, with temperatures reaching as high as 278°C. The area is pressurized with about 13 bar more than the well located at the southeast of Ahuachapán and Chipilapa at the same levels. However, the productivity and injectivity of the wells did not meet expectations. Overall, the drilling campaign also identified a shallower aquifer with temperatures ranging from 150°C to 220°C, which could potentially be utilized for binary power generation.

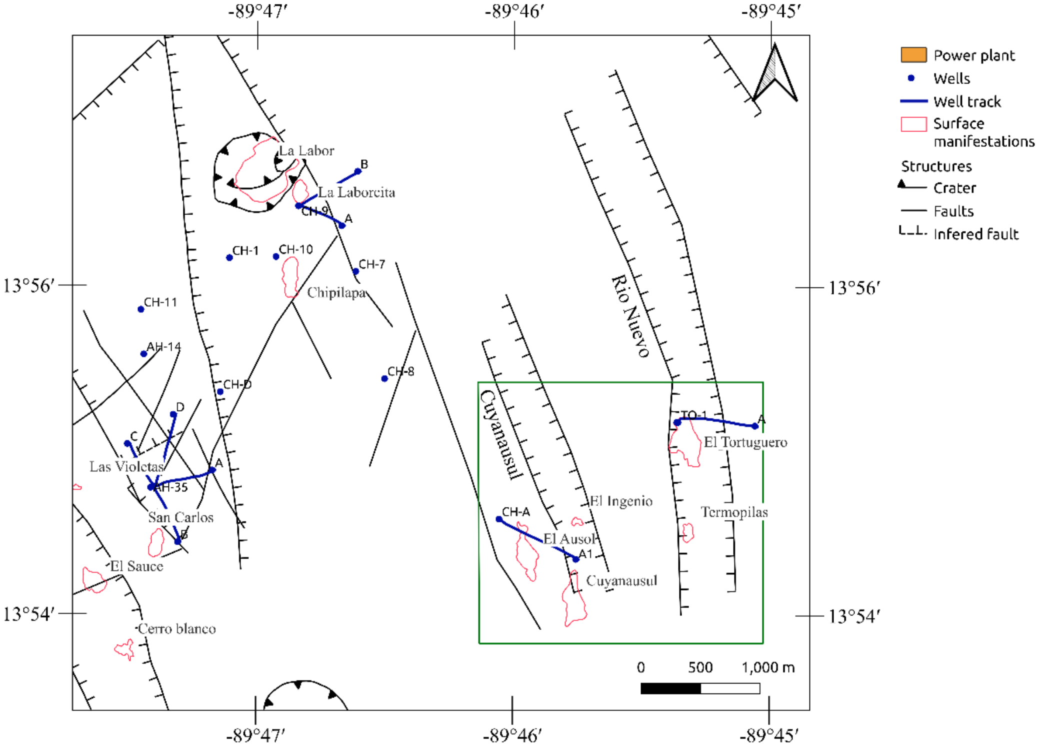


Figure 6: Cuyanausul exploration area

3. RESOURCE MANAGEMENT CHALLENGES, VARIOUS STEAM, AND WELL ISSUES.

3.1 Early reinjection

During the early days of generation (1975 - 1982), some wells near the power plant were used as injectors accounting for 25 – 30 % of the extracted fluids (Steingrimson, Bodvanson, & Escobar, 1989), including the wells AH-17 and AH-19, which after 21 and 9 months of injection respectively, have been delivering steam to the power plant ever since. However, the rest of the brine and steam condensate was disposed to Paz River between El Salvador and Guatemala (Jernelöv, Hultberg, & Rosenblum, 1976). Tracer test and chemical analysis performed at that time revealed injection water to be moving towards the production and thermal influence in the surrounding wells (Horne, 1982). In October 1982 a series of 75km long concrete channels and pipes connected the power plant and the Pacific Ocean where the water was disposed of until August 2004.

3.2 Total Reinjection Project

The project aimed to reinject water into the Chipilapa area to ensure reservoir sustainability. This was achieved by installing four centrifugal pumps, taking hot brine at 114°C from the expansion vessels that supply low-pressure steam to the double flash unit. Additionally, two pumps were installed to manage the blowdown discharge from the cooling towers, and two more were added to discharge fluid collected in an 8,000 m³ tank. This tank collects fluids from well tests, maintenance operations, and, most commonly, discharges from the expansion vessels (Umanzor, 2005). The system is connected to the Chipilapa wells by two 5km long and 24’’ Ø pipelines, the first one constructed in 1998 and the second in 2007 (Ábrego, 2010).

In Figure 7, the monitoring pressure at well AH-25 response due to mass injection is evident, as the pressure has remained stable under the current extraction regime. Several tracer tests have been conducted between the Chipilapa wells and the production field. However, after years of monitoring, no tracer has been detected, revealing a hydraulic connection between the two areas but no connectivity has been confirmed. This may be due to the natural discharge of AGF in the northern Chipilapa area in El Salitre spring or the presence of a barrier delineated by the Chipilapa Fault. Silica scaling is a constant issue to address due to the mixture of colder fluid coming from the emergency tank with about 600 kg/s of hot brine, the pipelines precipitate silica usually during the first couple of hundred meters, reaching up to 20 centimeters of deposition. The most common solution has been to rime the pipe with a mechanical tool during the power generation unit's overhaul. To further enhance management, a new, shallower well, AH-2R, has been drilled and connected to the system to handle the condensate and reduce the risk of silica scaling.

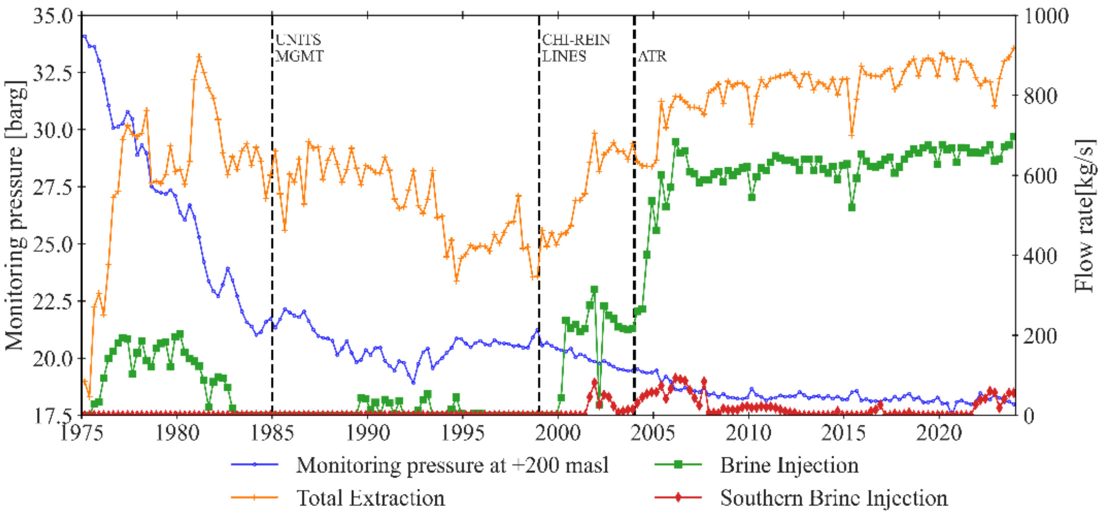


Figure 7: Yearly average monitoring pressure in well AH-25 at 200 masl. Total Extraction, low and high temperature brine injection yearly averages. Vertical lines: UNITS MGMT represents the time the load factor was reduced due to pressure decline, CHI-REIN LINES when injection started at the Chipilapa area and ATR when the pumping station started operating.

3.3 Drilling campaign 1997 – 1998

The drilling campaign in the southern area, at well pads AH-33, AH-34, and AH-35, was part of the Stabilization Project described in Section 2.5. This campaign resulted in the completion of seven wells: five producers, one used as an injector with a moderate brine injection rate of 35 kg/s at 160 °C, and one that failed to meet the required discharging wellhead pressure. The positive results of this campaign facilitated the drilling of additional wells in 2007 and 2015 in the southern areas. Figure 8 shows a steady cumulative production rate after 2001, when the connection from the well pads to the power plant was completed. Currently, the annual mass extraction is approximately 27.8 billion kg, while the injection rate stands at 21.1 billion kg. The reduction in depletion since reinjection began in 2004 is also notable, currently it accounts for 6.7 billion kg.

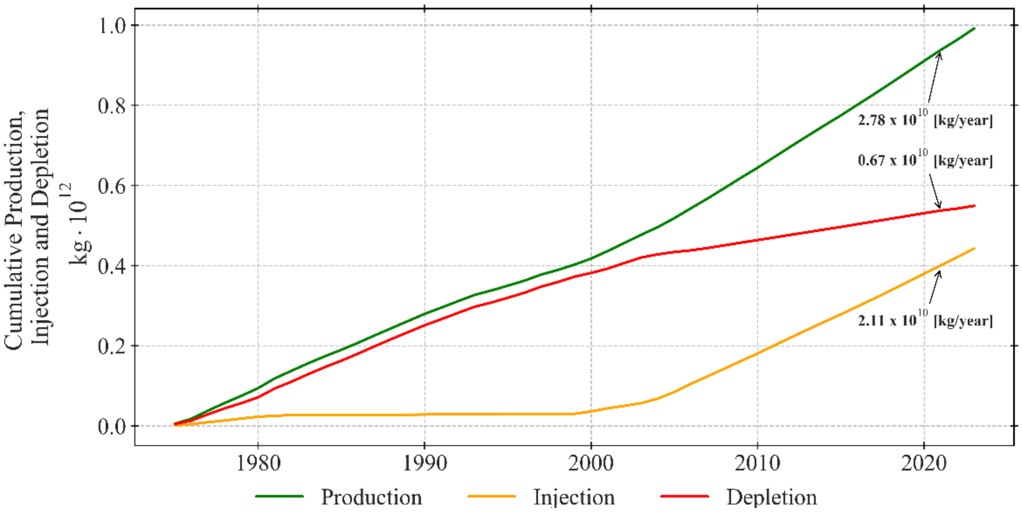


Figure 8: Cumulative production, injection and depletion for the AGF.

3.4 Calcite Inhibition

As production from the southern wells began, some wells exhibited a decrease in wellhead pressure below the gathering system pressure. Further analysis revealed that calcite deposition was blocking the wells, requiring well workovers and the installation of inhibition systems at each well pad. These systems inject the inhibitor below the well's flashing point through a capillary tubing and an inhibition chamber. The inhibitor must demonstrate thermal, microbial, and chemical stability to maintain its physical properties at high temperatures, prevent microorganism growth during storage, and avoid reactions with geothermal fluid components (Jacobo, Guerra, Cartagena, & Hernández, 2012). Currently, approximately 400 kg/s of geothermal fluid is treated with calcite inhibitors, extracting sufficient steam and brine to generate around 35 MW of power generation.

3.5 Well Workovers

Workovers performed at the AGF typically consist of: (a) mud acid injection from the wellhead, (b) mechanical cleanout using a drill rig and acid mud injection directly into the main feed zones through the drill pipe, and (c) the use of a flexible pipe (coil tubing) for mud acid injection. The latter was employed only during the first acid stimulation procedures. The primary objective of workovers is to enhance the well productivity or injectivity by removing calcite or silica deposits along the wellbore walls and at the main feed zones (skin damage). For new wells, the goal is to dissolve drilling mud and cuttings within the rock formation. The mud acid treatment is tailored to the specific characteristics of each well, including mineralogy, hydrothermal alteration, the number of permeable zones, and the extent of skin damage. As expected, incorporating a drill rig into the operation generally results in productivity improvements of up to 200%, compared to the 40% improvement typically achieved with wellhead acid injection alone (Barrios, Guerra, Jacobo, & Mayorga, 2012). Since geothermal and hydropower plants serve as baseload energy sources in El Salvador’s energy market, workovers are typically scheduled during or immediately after the wet season, when the reservoirs at hydropower plants have a surplus, or during power generation unit overhauls. The duration of workovers varies, ranging from a single event for the wellhead acid stimulation usually perform typically in one day to a few weeks when using a drill rig.

3.5.1. Silica scaling

Among the different production areas. There has been just one single case of silica scaling problem, it happened at the steam dominated well AH-17 in 1990, reducing its wellhead pressure and steam extraction. In 1992, a workover operation restored the well's integrity, the event is related with the influence of a lower liquid feed zone with a different fluid composition (Jacobo & Montalvo, 2013). In the other hand, the Chipilapa area has undertaken several chemical stimulations though the years as it is essential to reduce the pumping pressure at the pump station. Figure 9 shows the impact on discharge pressure produced by performing workovers on the injector wells.

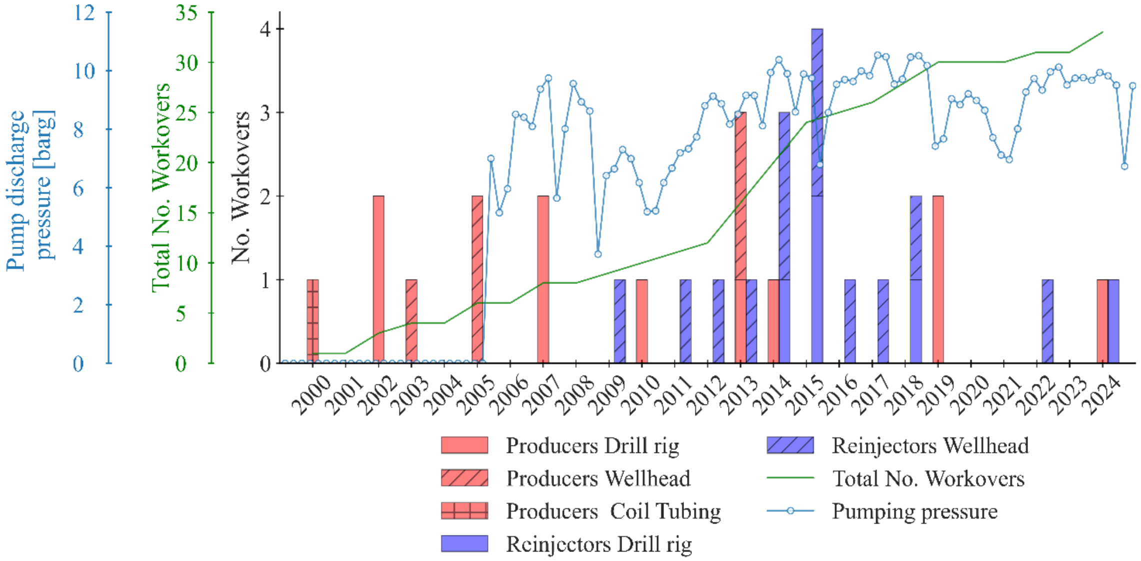


Figure 9: Workovers per year on producer and injector wells along with the average discharge pressure at the pumping station.

4. PHYSICAL CHANGES

4.1. Pressure response

Different areas of the AGF have experienced changes due to extraction and injection in various ways. The reference pressure in the initial exploration area has dropped by 17.2 bar at 200 masl in well AH-25. Prior reinjection in Chipilapa, there is a stabilization period around mid-1980s related with a higher storativity due to the development of two-phase condition at the reservoir **(Campos, 1985)**. Static PT logs from other wells indicate that the reference pressure is among the lowest values in the surrounding areas. This is represented in Figure 10 by the light brown colored area with solid lines at the edges. This phenomenon allowed the steam cap to expand at the northwest side of the field. Values at AH-25 are presumed to be the lowest due to the natural flow of deep fluids trending northeast toward the natural discharge at El Salitre. The pressure at the well AH-8 has not followed the changes from the nearby wells as it is located on the east side of Los Ausoles fault, which is believed to be at a different block and close to the west border of the geothermal reservoir. Well AH-14 is considered a consistent proof of pressure support from the injection area, as its pressure dropped during the first years of extraction and increased after the Chipilapa wells began operating as injectors. Other wells, such as those in the reinjection area, have experienced a general increase in pressure, whereas the southeast has shown minor changes throughout the year, likely because it is located at a larger undisturbed area near the upflow zone.

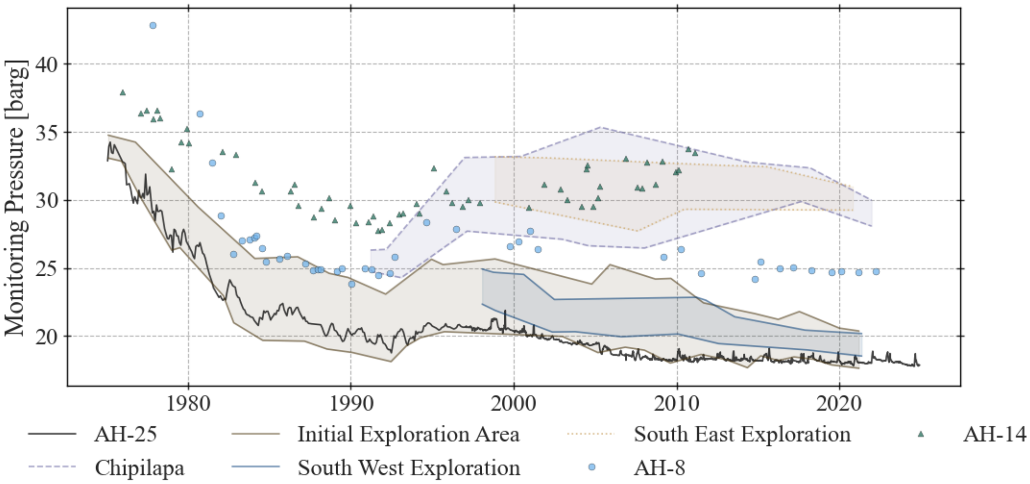


Figure 10: Monitoring pressure at well AH-25 and pressure range changes in other wells at different areas of AGF.

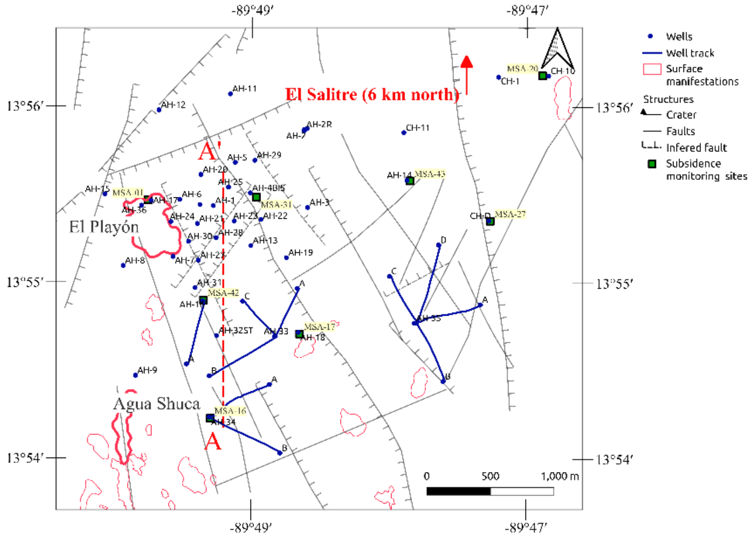
4.2. Temperature response

Figure 11b and 11c show temperature the cross-sections A-A’ prior mass extraction and current state respectively. During the natural state it is possible to observe the temperature deepening towards the south and the 210°C contour extension at the center of the initial exploration area. The current temperature distribution considers pseudo stabilized temperatures from wells at different times. However, the over all trend of decreasing temperature is noticeable. The cooling effects occur due to boiling and cold-water inflow from surrounding aquifers. The mixing with cold water has been documented by Jacobo & Montalvo (2013) at well AH-6 and AH-31 by comparing the flowing discharge enthalpy against NaKCa and Quartz geothermometers. Currently, the 210°C contour is found at greater depths, and it is primarily attributed to due to the brine injection at well AH-33A and AH-18 traveling towards north through the BuenaVista Fault.

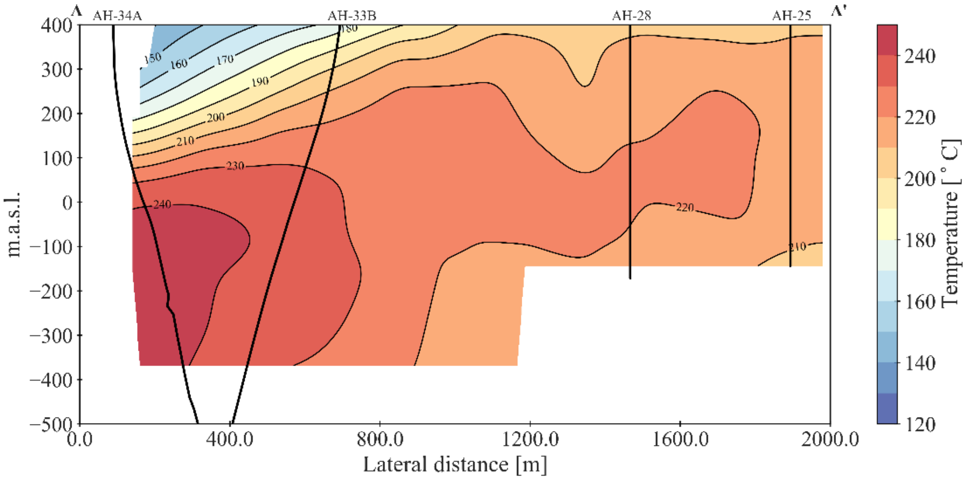
4.3. Changes in surface manifestations chemistry

As described before the main outflow from the geothermal system is at El Salitre (See Figure 11a). Located about 6km north from the injection area. Chloride content has changed over the year responding to the different production and injection strategies (See Figure 12). During the early days a decline is observed, as some of the natural flow was discharged at the production wells and disposed outside of the geothermal system. At the same time the measured temperature decline as less hot fluid was able to reach the outflow. However, the geothermal system footprint represented by Na-K Fourier geothermometer (Fournier, 1979) kept similar values through the years. The second stage started after the 600 kg/s low temperature injection into the Chipilapa wells. It is possible to observe the rapid increase in Chloride content after 2005 in Figure 12. Nevertheless, since the flow temperature has been reduced during the power generation process, the measured temperature keeps decreasing, in spite of that the Na-K geothermometer keeps a steady temperature as the fluid origine remains the same.

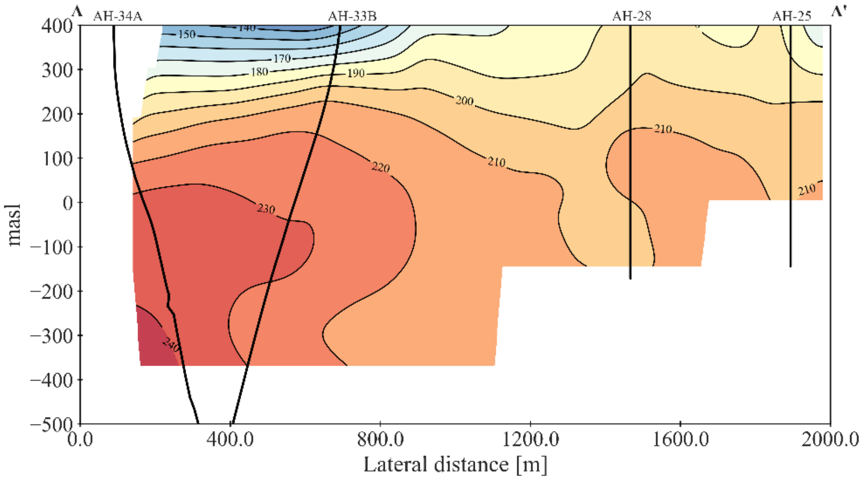
The Playon fumarole is located at the initial exploration area, around some wells with a long production history. Figure 13 shows a steady behavior for the D’Amore and Panichi (1980) gas geothermometer after a degassing stage during the early days of mass extraction. Agua Shuca fumarole located in the southeast (Figure 13) also presents a similar trend with higher temperatures. In addition, the well AH-27 near Playon fumarole presents a similar trend, showing a cooling effect of about 20°C over 27 years. In contrast, well AH-34B shows no cooling effects and similar temperature values at 0 masl.



(a) Plant view



(b) Temperature distribution at natural state



(c) Current temperature distribution

Figure 11: Plant view and vertical cross sections of temperature.

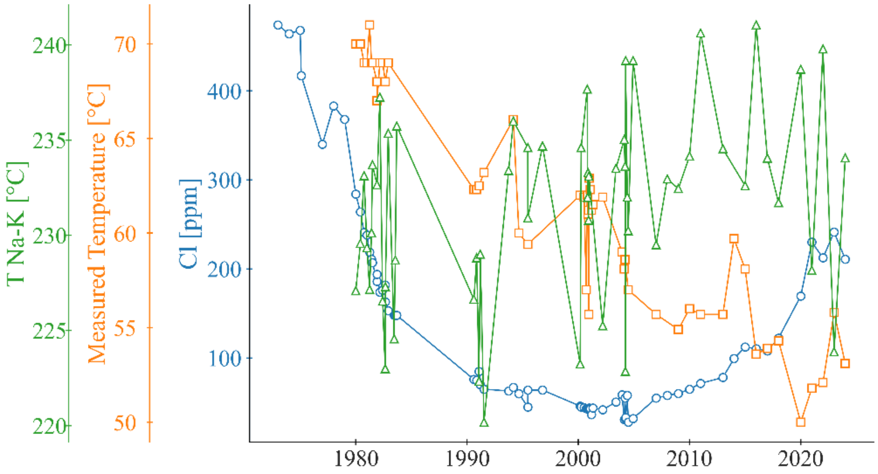


Figure 12: Chloride content, measured temperature and Na-K geothermometer at El Salitre hot spring.

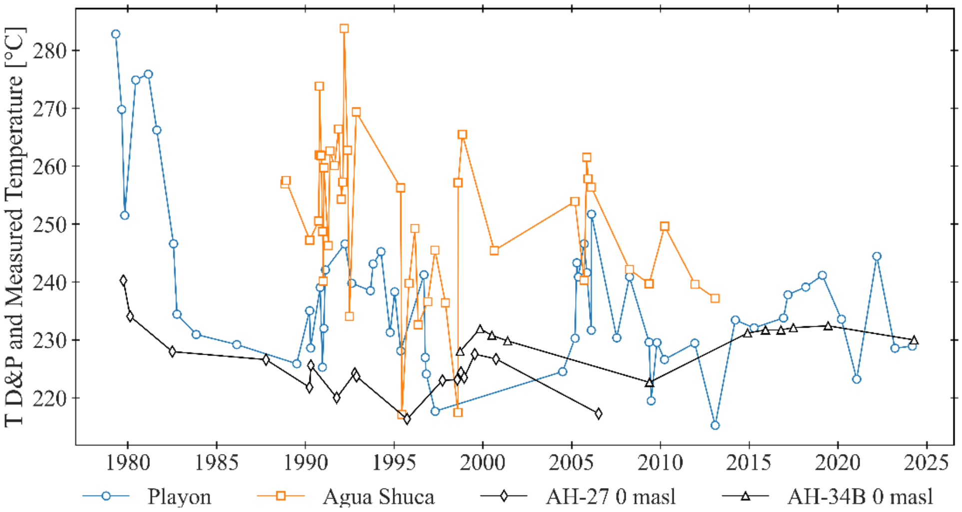


Figure 13: D'Amore and Panichi geothermometer for Agua Shuca and Playon fumaroles along with measured temperatures from surrounding wells as 0 masl.

4.4. Geophysical monitoring

Magnetotelluric and gravimetric surveys, seismicity activity and subsidence monitoring, performed by the operator staff (LAGEO), has contributed to the understanding of the geothermal system. The surveys and monitoring delineate the system extension and underground flow movement necessary for well targeting and reservoir sustainability. Figure 14 shows the cumulative change in elevation from some bench mark in the production area (See Figure 11a), overall the trend is downwards due to the withdrawal of mass, reaching changes up to 10 cm/year. Gravimetric surveys have demonstrated the flow of fluids east from the well AH-35 towards Chipilapa confirming the common origin of deep fluids (LAGEO, 2023).

Figure 14: Cumulative subsidence for bench marks over the years at the production areas.

5. FUTURE PLANS

In the near future, injection will play a vital role as it is the bottle neck for the generation process at this point in time. Managing the three types of disposal fluids: condensate, low pressure separated fluid and ambient temperature geothermal fluid in different gathering systems would not just increase the available medium pressure steam for the units as more brine would be able to carry but also to reduce the scaling problems encountered on the gathering system and injector wells. From the generation perspective two other opportunities arise: (a) as the southeast area has shown little response and higher temperatures compared to the other production areas, it is likely that an isolate development could be attractive as it would reduce the issues to overcome with long pipelines distance and avoid well interference. (b) Although the Cuyanausul area has shown low permeability, its high temperatures and the presence of shallower, more permeable aquifers remain attractive for power generation. Enhanced Geothermal Systems (EGS) and Advanced Geothermal Systems (AGS) can be applied to the deeper, low-permeability zones, while binary plants are well-suited for the shallower aquifers.

In spite of these proposals, the main goal is to reach a 100% load factor at the current facilities in a sustainable manner. Therefore, some scenarios of production by extending the production area to the southeast and enlarging the injection areas in Chipilapa have been proposed, including some make up wells (LAGEO, 2020). Including eight new producers and six injector wells. Figure 15 shows the results of a TOUGH2 model for the given scenarios. The pressure at 200 masl is estimated, it is expected that the monitoring pressure could reach values down to 15 bar in 2040 considering the new wells start producing in 2028. Another implication is the occurrence of boiling in the southeast area and cold water inflow from shallower aquifers in the initial production area. The current production strategy has been tested up to 2070, results show the pressure will remain above 15 bar at 200 masl while the two-phase zone enlarges.

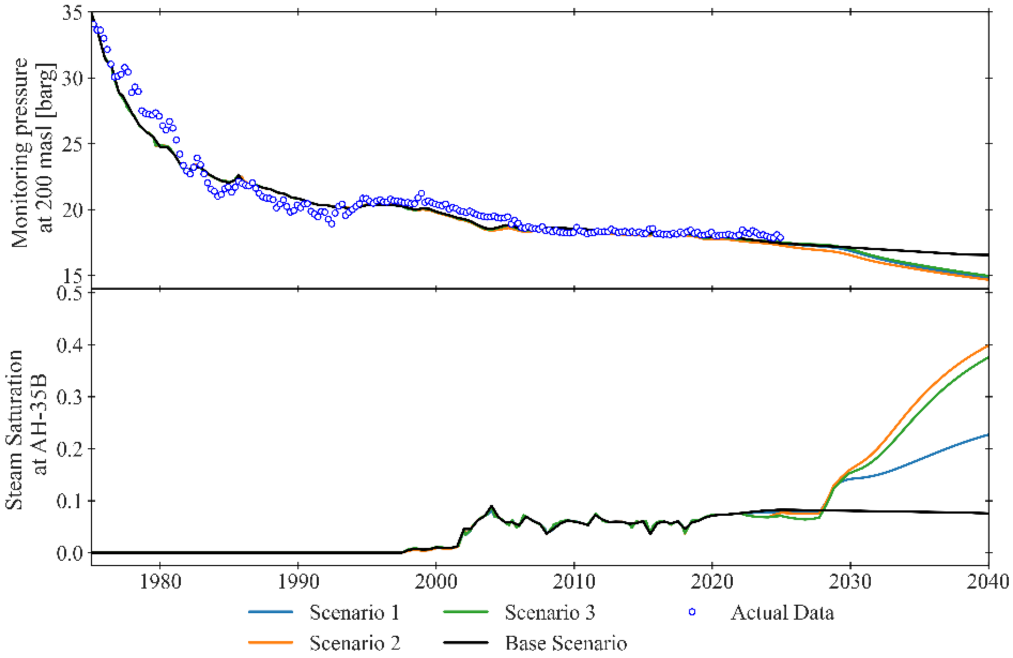


Figure 15: Estimated pressure response due to different production/injection strategies, and boiling development on the southwest.

CONCLUSIONS

Over fifty years of operation, the Ahuachapán Geothermal Field has overcome various resource challenges. The first critical issue was extending mass extraction to the south to prevent overexploitation in the central area of the field while increasing the power plant's capacity factor. The second challenge was ensuring effective reservoir management by injecting disposal water into the Chipilapa geothermal area.

Throughout years of exploitation, several findings have been observed through various geoscience surveys and monitoring programs: (a) pressure drawdown in the center of the field has expanded the two-phase zone while allowing inflow from shallow, colder aquifers in the east and north, leading to reservoir cooling; (b) the southeastern area is somewhat isolated from the rest of the production zones and exhibits similarities with wells from the Chipilapa and Cuyanausul areas, particularly in pressure gradient and fluid origin; (c) fluid flow in the Ahuachapán Geothermal Field primarily occurs through E-W, NE-SW and NNW-SSE trending structures that act as channels, with a natural discharge at El Salitre; and (d) injection in the Chipilapa geothermal area has provided pressure support to counteract the pressure drawdown in the production field.

Over the past fifteen years, constant field surveillance, a comprehensive power generation unit maintenance program, well workovers, operation of inhibition systems and few new wells have enabled sustained a fairly stable power generation while preserving the sustainability of the geothermal reservoir. A further expansion beyond the current installed capacity of the AGF is most likely related with southeast as it seems to have a larger extension with relatively high temperature and pressure. However, since carrying the geothermal fluid might not be economically feasible, suitable located new power plant should be able to use this energy.

ACKNOWLEDGEMENTS

The author would like to thank LAGEO S.A. de C.V. for allowing publication of this paper. Special thanks to Roberto Renderos for preparing chemistry data and reviewing this paper.

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