Geothermics 39 (2010) 370–381

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Sustainability analysis of the Ahuachapán geothermal field: management and modeling

Manuel Monterrosa*, Francisco E. Montalvo López

LaGeo S.A. de C.V., Reservoir Engineering, 15 Av. Sur, Colonia Utila, Santa Tecla, La Libertad, El Salvador

ARTICLE INFO

Article history:
Received 20 June 2009
Accepted 15 September 2010
Available online 30 October 2010

Keywords:
Geothermal
Reservoir monitoring
Modeling
Production
Reinjection
Chemistry

ABSTRACT

The Ahuachapán geothermal field (AGF) is located in north western El Salvador. To date, 53 wells (20 producers and 8 injectors) have been drilled in the Ahuachapán geothermal field and the adjacent Chipilapa area. Over the past 33 years, 550 Mtonnes have been extracted from the reservoir, and the reservoir pressure has declined by more than 15 bars. By 1985, the large pressure drawdown due to over-exploitation of the resource reduced the power generation capacity to only 45 MW_e. Several activities were carried out in the period 1997–2005 as part of "stabilization" and "optimization" projects to increase the electric energy generation to 85 MW_e, with a total mass extraction of 850 kg/s.

LaGeo is assessing the sustainability of geothermal reservoir utilization. Preliminary results indicate the planned power production and mass extraction (95 MW, 900 kg/s) cannot be sustained for more than 50 years using current power plant technology. To sustain the exploitation for at least 100 years, the following changes should be implemented: (1) improve the gathering system using large-diameter steam pipelines, (2) expand the exploitation area to the southeast and southwest, and (3) reduce the inlet pressure of the turbines to less than 4 bars.

1. Introduction

Exploration at the Ahuachapán Geothermal Field (AGF) began in 1968, and the first power plant (Unit I, the first geothermal power plant in Central America) came on line in 1975. The AGF is located in northwestern El Salvador in a weak tectonic zone where the movement of fluids occurs mainly along a fault system. The main production field, with an average surface elevation of about 800 m above seal level (a.s.l.), covers 4 km^2 with 53 wells drilled to depths ranging from 591 m to 1645 m. The initial reservoir salinity prior to exploitation was 22,000 ppm (Rogmagnoli et al., 1976), and the measured reservoir temperatures range from 214 °C to 250 °C. The entire Ahuachapán–Chipilapa area covers more than 50 km^2.

The geothermal power station incorporates both single- and double-flash steam cycles (low and medium pressure). Until 2004, most of the separated water was discharged to the Pacific Ocean via an 80 km long concrete channel; at present, all of the residual water is injected into wells in the Chipilapa area. The Ahuachapán and Chipilapa fields are shown in Fig. 1.

Currently 20 production wells are connected to the power plant. There are 8 injection wells and 25 monitoring or abandoned wells. Wells AH-25 and AH-30 are normally used to monitor reservoir pressure; some wells (AH-1, AH-7) are not able to provide steam to the power plant due to low well-head pressure which has declined over time.

2. Conceptual model of Ahuachapán system

The AGF is associated with the southern flank of the central Salvadoran graben and part of the northwestern sector of the Cerro Laguna Verde volcanic group. This group constitutes a complex extrusive structure developed during Quaternary time near the Pliocene tectonic block of Tacuba-Apaneca. There are regional and local structures controlled by fault systems of three main orientations: (a) E-W (the approximate trend of the main graven), (b) NE-SW, located in the western sector of the field, and (c) NNW-SSE, which is associated with surface hydrothermal activity.

The above geologic structure favors the ascent of deep hot fluid through a marginal set of faults, and further lateral fluid migration along a NW-SE-oriented transverse fault system. The most permeable horizon along the intersection of this system of faults consists of alternating andesitic lava and fine pyroclastic products. These andesitic rocks are known as the Ahuachapán Andesite, and they constitute the main hot-fluid-producing horizon for the geothermal field.

The first conceptual models of the Ahuachapán geothermal system were proposed in 1976 and 1982. They were based on limited

* Corresponding author. Tel.: +503 22116719; fax: +503 22116746.
E-mail addresses: memonterrosa@lageo.com.sv (M. Monterrosa), fmontalvo@lageo.com.sv (F.E. Montalvo López).

0375-6505/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.geothermics.2010.09.008

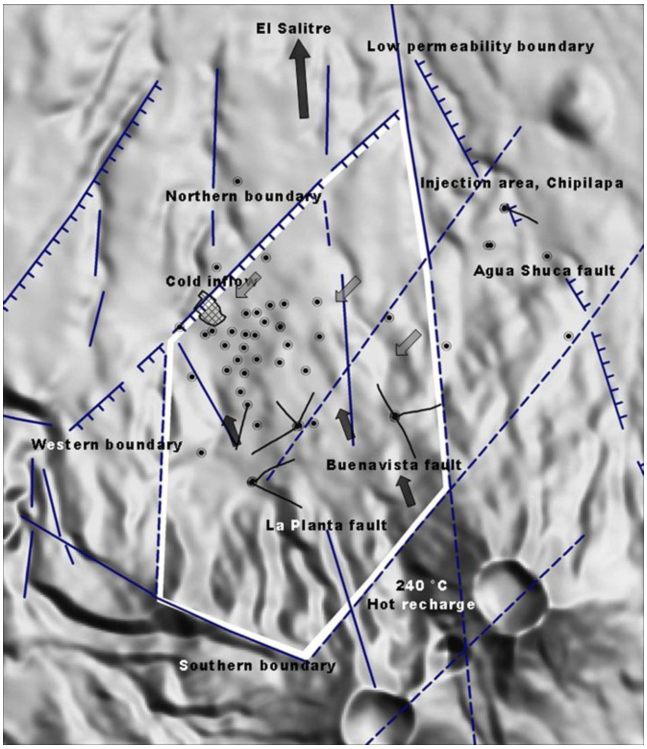

Fig. 1. Map of the Ahuachapán and Chipilapa geothermal fields, with well locations.

data about the well field area, and suggested that the Ahuachapán and Chipilapa fields were separate geothermal systems. During 1988–1989, Lawrence Berkeley National Laboratory (LBL, 1988) carried out a reservoir evaluation study of the Ahuachapán field, which included a hydrogeological model, examination of pressure and temperature histories, and a numerical reservoir simulation. An updated conceptual model was proposed suggesting that the Ahuachapán and Chipilapa fields are parts of the same geothermal system (Aunzo et al., 1989).

Later, ELC (1993) and ENEL-LaGeo (2004) confirmed the major features of the LBL model, as shown in Fig. 2. According to the conceptual model, the zone of hot recharge is located in the S-SE beneath the Laguna Verde complex. The hot fluid moves northeastward through major faults, flows laterally into the Ahuachapán andesites, and continues moving to the Chipilapa area. The final discharge zone is located at the El Salitre hot spring.

Interpretation of magnetotelluric (MT) resistivity data indicates that the andesitic geothermal environment of the Ahuachapán field is represented by a characteristic sequence of three layers (resistor–conductor–resistor). The reservoir, located between +200 m a.s.l. and −100 m a.s.l., coincides with the conductive layer, and its base is marked by the transition zone between the conductive and the deep resistive layers occurring at around 25 Ω m.

The geologic model indicates that three main faults (La Planta, Buenavista and Agua Shuca) are responsible for the up-flow into the productive reservoir, and that other faults control the outflow from the geothermal system. The geothermal reservoir is pressurized with respect to the overlying shallow aquifer and the saturated regional aquifer.

Geochemical data suggest dilution in a north-south trending zone that coincides with several major faults. Chloride concentrations and geochemical thermometers are higher in the western part of the production field (about 8000–9000 ppm and 260 °C) than in the eastern part (about 7000 ppm and 240 °C), suggesting that the dilution process occurs mainly from the N-NE direction. Dilute fluids supersaturated with calcite have also been found in the S-SE part, even though the highest measured temperatures (about 250 °C) have been recorded in this area.

In summary, the main features of the conceptual model are:

1. The depth of the main reservoir ranges from 900 m to 1200 m with measured temperatures of 230 °C to 250 °C. In the center of the field, the reservoir is located at 500–800 m depth with temperatures of 210–220 °C.
2. The Ahuachapán reservoir is located on a structural high (forming the core of the field).
3. The MT data suggest that the base of the reservoir occurs at the transition zone between the conductive and the resistive layers (25 Ω m).
4. Fluid temperatures increase in a NW direction, and measured temperatures and geochemical estimates do not exceed 260 °C.
5. The natural-state numerical model (LBL, 1988) suggests that inflow of cold water occurs from the N-NE part of the field. Production history indicates that the reservoir fluid has been diluted by no more than 20% of less-saline water (Montalvo, 1994).

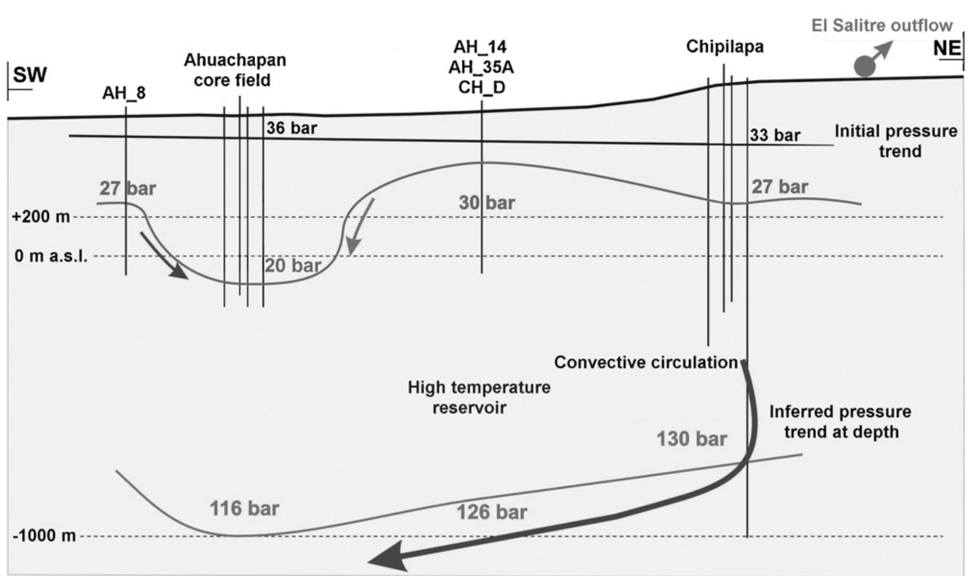

Fig. 2. Cross-section of the conceptual model (from ENEL-LaGeo, 2004).

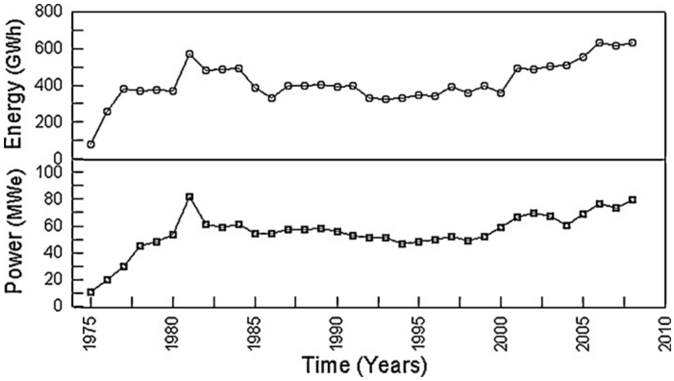

Fig. 3. Energy and power production at the Ahuachapán power plant.

6. Two important thermal manifestations are present in the area; El Salitre hot springs and El Playón.
7. The up-flow zone is located in the southern or SE part of the field, and out-flow takes place towards the NE.

3. Production history and reservoir response

The Ahuachapán geothermal field has been monitored systematically since 1975 when continuous exploitation for power generation began. Fig. 3 shows the history of energy production at the AGF, indicating a trend of increasing power generation in the last nine years.

3.1. Field developments and historical highlights

In order to maximize production, optimize costs, and sustain long-term generation, several different field management strategies have been implemented during the 33 years of operation as described below.

I. The initial period of commercial exploitation (1975–1983) was characterized by a rapid pressure decline that correlated with the extracted mass (pressure drop > 15 bars). Some injection experiments were carried out with negative results causing cooling in some wells; therefore injection was stopped. During this period, the total mass extraction was 22 Mtonne (the cumulative mass extracted to date since 1975 has been 80 Mtonne) and the total mass injection was 2.6 Mtonne (of a total to date of 33.6 Mtonne).
II. The period 1984–1994 was characterized by a slow pressure decline. Power production was coordinated with hydro generation, greater during the dry season and lower during the rainy season. No injection was implemented during this period, though there was some temporary test injection. The total pressure decline was around 1.5 bar.
III. During 1994–1999, continuous production from high-enthalpy wells was used to reduce the mass extracted. With this strategy, the pressure decline was quite low (<0.5 bar). No injection was carried out during this period.
IV. Power production was increased in 2000–2005 using more production wells and injecting in the Chipilapa area. Ten new wells were drilled in the center of the field (AH-4B, AH-16A), to the southwest (AH-34's), and to the southeast (AH-33's and AH-35's); a new 24-in. injection line was built to Chipilapa; and a pumping system was installed in order to increase the injection capacity. The pressure decline was around 1.5 bar, with a 15 MW increase in power production.
V. Since 2005, power production has increased from 65 to 80 MW, with a pressure decline of almost 1 bar.

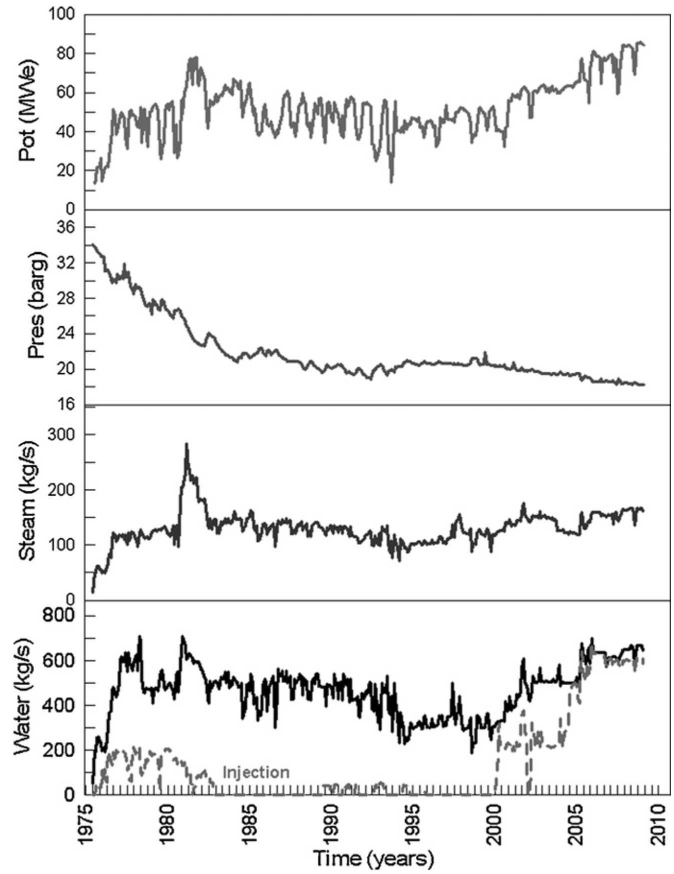

Fig. 4. Production history of AGF.

Fig. 4 presents the entire 33-year history of the AGF, showing that the total fluid production from the Ahuachapán field varied between 300 kg/s and 700 kg/s during the period 1978–1989.

The higher rate of mass extraction in recent years has not caused extensive boiling and steam production (steam cap expansion), indicating that the reservoir is still liquid dominated. Fluid recharge and especially injection have been important to the sustainability of the resource. This is in agreement with forecasts from reservoir modeling (ENEL-LaGeo, 2004).

Down-hole pressure has been monitored since 1978 in well AH-25 at 200 m a.s.l. The initial reservoir pressure was 36 bar g (245 °C); by October 2008 it had declined to 18.48 bar g. Since 2005, injection rates have at times exceeded production rates of separated water (from production wells), due to the addition of steam condensate (from the cooling tower system) and water from the emergency water tank. Fig. 5 shows steam quality and weighted average enthalpy, which average 30% and 1,048 kJ/kg, respectively, over the history of the AGF.

3.2. Production monitoring

At present, 16 wells are in production to supply the steam for the three units. Fig. 6 shows the water and steam flow rates for selected wells. The water flow rate is declining with time; only wells AH-20, AH-23 and AH-4B show an increase. Well AH-4B was initially operated with one separator, but in 2006 a second separator was installed to accommodate its higher flow rate. The steam flow rate per well was initially scattered, but in general it shows a declining trend, and at present ranges mostly between 6 and 10 kg/s; only well AH-4B produces about 30 kg/s of steam. Table 1 presents the

Table 1
Production characteristics of wells (2008).

2008	WHP (bar g)	P_{sep} (bar g)	Steam (kg/s)	Liquid (kg/s)	*h* (kJ/kg)	*X* (%)	MW_e
AH-4b	9.12	6.72	30.07	83.13	1233	0.27	13.76
AH-6	5.72	5.72	8.74	2.71	2254	0.76	3.55
AH-16A	6.67	6.46	7.95	47.05	975	0.14	4.16
AH-17	11.72	11.72	13.49	0.40	2723	0.97	5.40
AH-19	7.93	6.17	5.49	36.12	942	0.13	2.95
AH-20	6.36	5.98	11.31	65.72	968	0.15	5.89
AH-21	8.76	6.08	7.14	43.86	957	0.14	3.77
AH-22	6.69	6.16	4.88	24.86	1009	0.16	2.47
AH-23	5.93	5.93	6.67	26.01	1087	0.20	3.21
AH-24	6.04	6.04	3.10	27.50	875	0.10	1.81
AH-26	5.89	5.89	7.59	10.77	1524	0.41	3.26
AH-27	5.79	5.79	9.72	40.79	1059	0.19	4.74
AH-28	5.96	5.96	5.30	41.73	896	0.11	2.96
AH-31	6.47	6.47	9.79	59.39	969	0.14	5.15
AH-33B	7.62	6.59	9.14	47.33	1014	0.16	4.64
AH-33C	7.64	6.75	7.17	49.75	943	0.13	3.90
AH-35A	7.89	7.27	8.96	58.79	967	0.13	4.81
AH-35B	7.70	7.33	4.38	17.00	1119	0.20	2.13
AH-35C	10.33	7.46	21.54	100.15	1064	0.18	10.96

Average data 2008. WHP: well head pressure; Psep: separator pressure, Steam: steam flow rate; Liquid: liquid flow rate; *h*: enthalpy; *X*: steam fraction; MW_e: electrical megawatt.

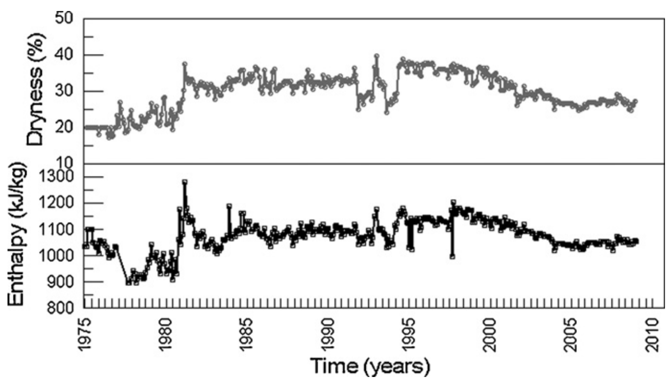

Fig. 5. Average dryness and enthalpy history of AGF.

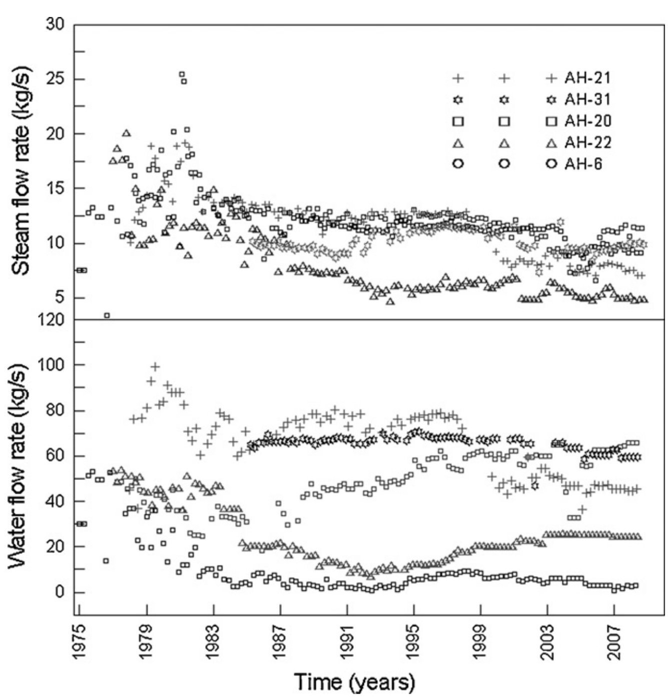

Fig. 6. Water and steam flow rate for production wells.

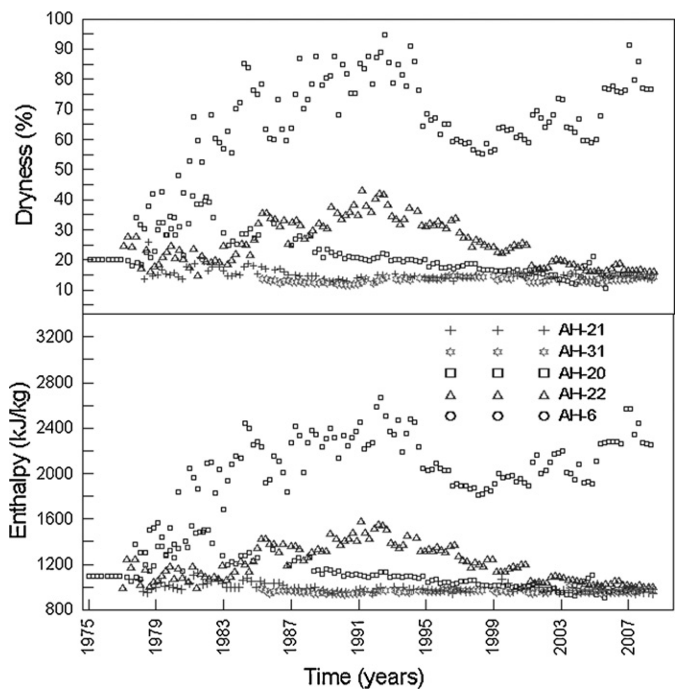

Fig. 7. Dryness and enthalpy evolution for production wells.

production characteristics for active wells (annual average data for 2008).

Fig. 7 presents the dryness and enthalpy history for selected wells. The highest enthalpies are observed in wells AH-6, AH-17 and AH-26, where a steam cap is present in the shallow part of the reservoir. Wells can be classified according to discharge enthalpy: (a) excess enthalpy wells (AH-6, AH-17 and AH-26), which are affected by boiling in the reservoir; (b) moderate enthalpy wells (AH-4B, AH-22, AH-23 and AH-27), which are also affected by boiling in the reservoir; and (c) low enthalpy wells (AH-16A, AH-19, AH-20, AH-21, AH-24, AH-28, AH-31, AH-33B, AH-35A and AH-35B), which are affected by colder fluids.

3.2.1. Pressure and temperature evolution

The wells located in the S-SE part of the main well field (AH-35B/AH-33A) are hotter (250 °C) than in the center (210 °C).

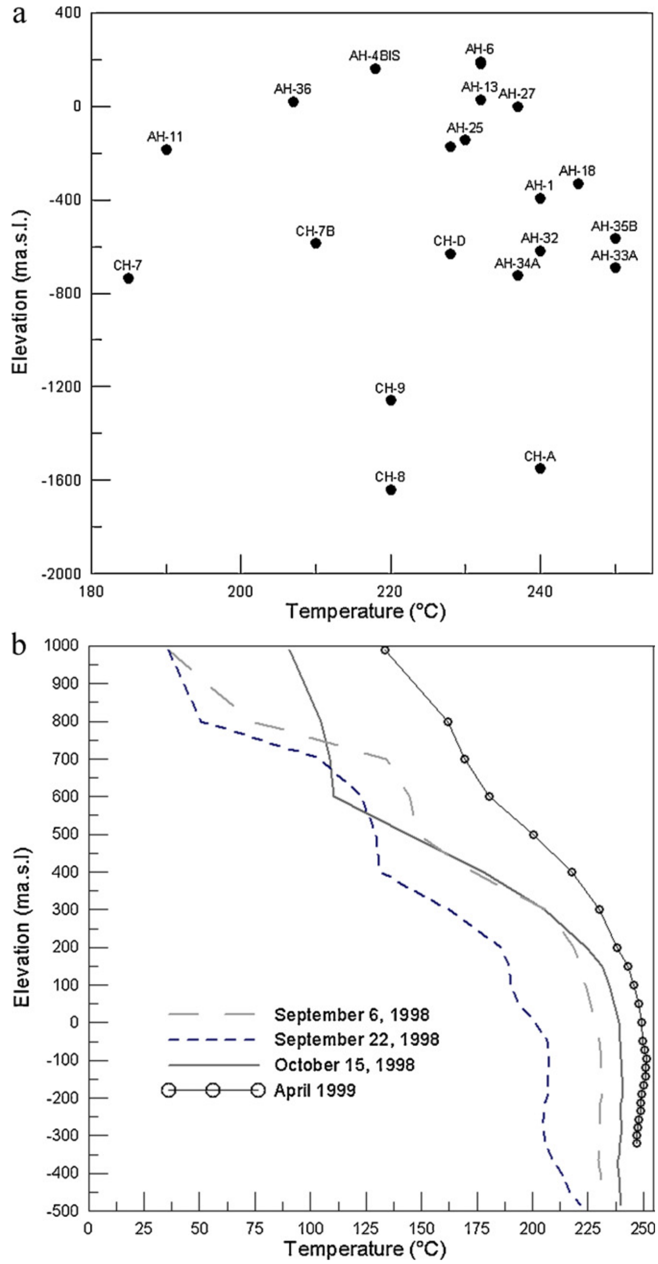

Fig. 8. Maximum temperatures at AGF and temperature recovery for well AH-35B.

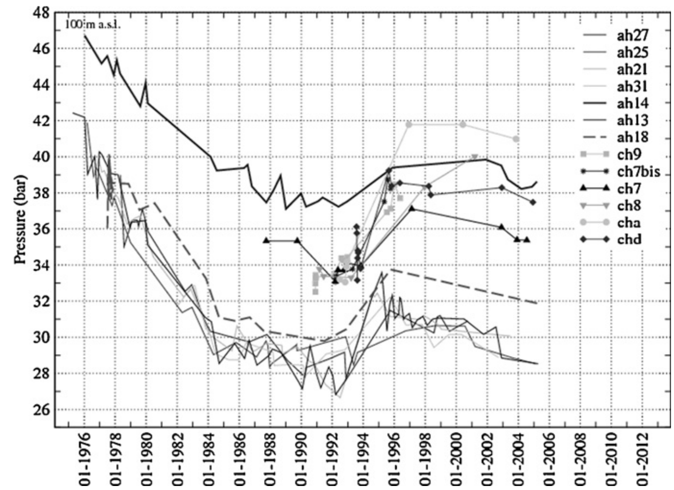

Fig. 9. Pressure comparison between Ahuachapán and Chipilapa wells at −100 m a.s.l.

Maximum temperatures recorded in various wells are presented in Fig. 8. In several wells the initial pressure at 100 m a.s.l. was close to 40 bars, but it has decreased to 20–25 bars in response to production as shown in Fig. 9.

Fig. 10 shows the temperature distribution based on 2005 data. These results and available pre-exploitation contours (Truesdell et al., 1989) confirm that the highest reservoir temperatures (235–240 °C) are located in the S-SE of the steam field zone; whereas the measured temperatures diminish to 205–215 °C towards to the north.

3.3. Chemical monitoring

The initial fluid chemistry at the Ahuachapán field indicates mixing in the reservoir between saline, high-temperature water and less saline, cooler water (>130 °C). The cooler water is probably from the regional saturated aquifer that overlies the geothermal reservoir (Steingrimsson et al., 1991), and enters the reservoir from above or laterally. The natural-state temperature (or liquid enthalpy) and chloride display a linear correlation suggesting mixing of hot saline water with cooler, lower chloride (steam-heated) waters at about 160 °C, which may also correspond to waters from the regional saturated aquifer (Aunzo et al., 1991). Currently, the chemical composition of the fluid does not show large variations.

Table 2 indicates reservoir chloride ranges mostly from 5000 to 9000 ppm; only wells AH-17, AH-35A, AH-35B and AH-35C show lower values. The silica temperature ranges from 208 to 245 °C, and

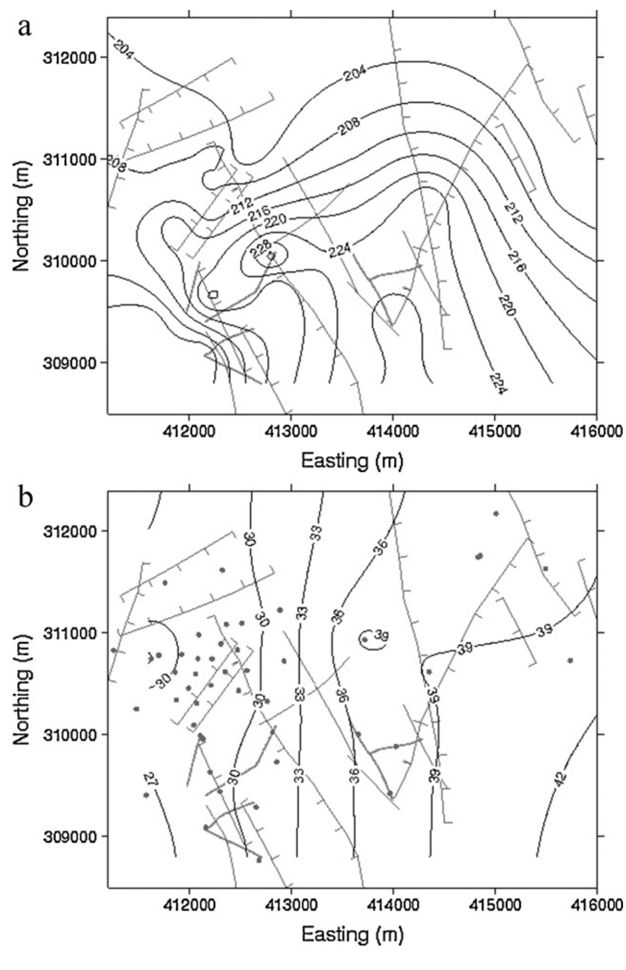

Fig. 10. Temperature and pressure contours at +100 m a.s.l (based on 2005 data).

Table 2
Chemical data of wells (2008).

2008	Clres (ppm)	Cl/B	T_{SiO_2} (°C)	T_{NaKCa} (°C)	CO_2 (mmol/100 mol)	NCG (wt%)	$T_{D\&P}$ (°C)
AH-4B	5327	66	227	231	268	0.71	260
AH-6	8972	66	216	236	430	1.06	266
AH-16A	7671	75	240	255	172	0.43	264
AH-17	151	2	208	184	304	0.76	237
AH-19	5114	70	221	231	86	0.22	249
AH-20	6031	68	220	239	131	0.33	252
AH-21	7890	75	224	250	218	0.54	255
AH-22	5095	65	221	234	145	0.36	251
AH-23	5181	64	226	236	532	1.30	266
AH-26	6497	65	219	236	368	0.91	261
AH-27	7145	65	244	257	304	0.75	270
AH-31	7535	69	245	257	73	0.19	265
AH-33B	5816	67	233	246	246	0.61	262
AH-35A	3615	65	224	227	219	0.55	256
AH-35B	3946	64	236	222	186	0.47	261
AH-35C	3981	64	240	221	154	0.39	206

Average data 2008. Clres: reservoir chloride; Cl/B: chloride–boron ratio; T_{SiO_2}: Fournier, 1977; T_{NaKCa}: Fournier and Truesdell, 1973; CO_2: carbon dioxide; NCG (wt%): weight percent non-condensable gases; $T_{D\&P}$: D'Amore and Panichi (1980).

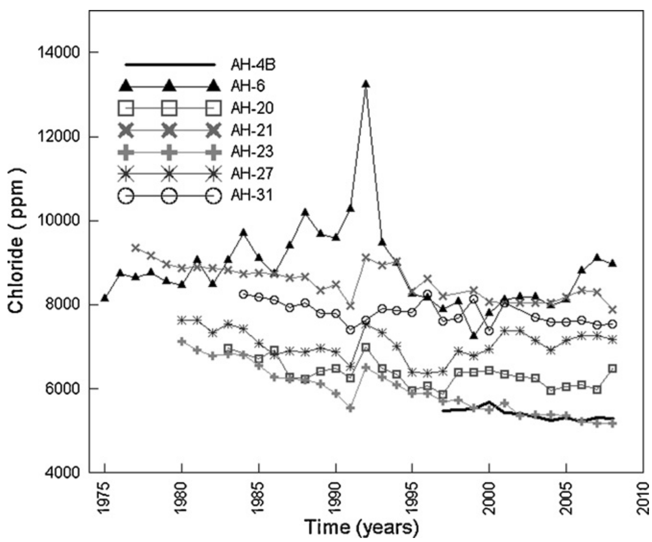

Fig. 11. Reservoir chloride evolutions for selected wells.

the Na-K-Ca geothermometer from 184 to 257 °C. Wells AH-6, AH-17, AH-21, AH-23, AH-26 and AH-27 show relatively high amounts of non-condensable gases, ranging from 0.54 to 3% by weight. The AH-35 wells have NCG between 0.39 and 0.61% by weight.

Wells with enthalpy less than 1000 kJ/kg show almost constant gas contents over time, whereas the two-phase high-enthalpy wells show a marked increase in gas concentration (up to 1.3% by weight).

In order to provide a general overview of the evolution of water and gas chemistry in Ahuachapán, several wells were selected to represent the different types of observed reservoir behavior. The variations in water chemistry over time show a trend of dilution for almost all of the wells. Only well AH-6 shows a tendency of increasing salinity for the first 15 years as shown in Fig. 11.

The reservoir chloride concentration for well AH-23 declined from 6600 to 5600 ppm, corresponding to a dilution of approximately 15%. The decline was gradual until 1992, but chloride has shown some increase and stabilization in the last few years. On the other hand, well AH-6 shows some scattered data with a clear trend towards increasing reservoir chloride concentration; 2008 values were similar to the initial ones.

The geothermal field is recharged mainly by two types of fluids: a hot, deep fluid rich in gas and sulfates with a low pH, and natural cold-water recharge from above. The cold-water recharge, after interacting with rock, acquires moderate salinity and temperature (1000 ppm, 160 °C; Montalvo, 1994).

The dominant reservoir processes of the Ahuachapán field under exploitation (excluding injection) are dilution from the cold water recharge from NE and boiling. However, the inflow of deep fluid also influences the chemistry and thermodynamic equilibrium for some wells. Dilution is the main process that governs the fluid chemistry in the reservoir; the second important process is boiling due to pressure drawdown in the reservoir.

3.3.1. Enthalpy-geothermometry comparison

Due to differences in reequilibration times, various chemical geothermometers respond differently to changes in thermodynamic conditions in a reservoir. If the fluid has specific enthalpy higher or lower than that for the liquid at the prevailing temperature, then comparison of geothermometer temperatures may indicate reservoir processes, such as boiling, mixing with hotter or cooler fluids, etc. (Truesdell et al., 1989). Table 3 classifies the wells according to their enthalpy evolution, as determined by comparing measured enthalpies with those determined from chemical geothermometers. Fig. 12 presents a comparison of the enthalpy histories of wells AH-6 and AH-31 to illustrate the boiling and dilution processes occurring in the reservoir.

3.3.2. Gas content

The wells with liquid enthalpy show a constant gas content over time, whereas the two-phase high-enthalpy wells show a significant increase. The initial concentration of NCG reservoir gases ranged between 0.1% for well AH-21 and 0.8% for well AH-6; in late

Table 3
Main reservoir processes in AGF based on chemical-physical indicators.

Wells		Process
AH-1, AH-7, AH-16A, AH-19, AH-20, AH-21, AH-24 AH-27, AH-28, AH-31, AH-33B, AH-35B, AH-35C	$H_{NaKCa} > H_{SiO_2} > H_m$	Dilution
AH-6, AH-4B, AH-17, AH-22, AH-23, AH-26	$H_m > H_{NaKCa} > H_{SiO_2}$	Boiling

H_m: measured enthalpy, H_{NaKCa}: enthalpy from NaKCa geothermometer, H_{SiO_2}: enthalpy from quartz geothermometer.

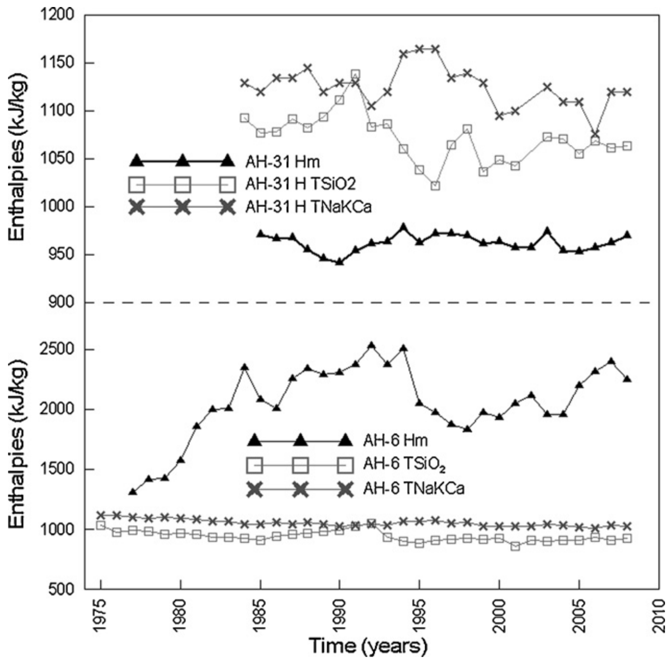

Fig. 12. Enthalpies comparison for well AH-6 and well AH-31.

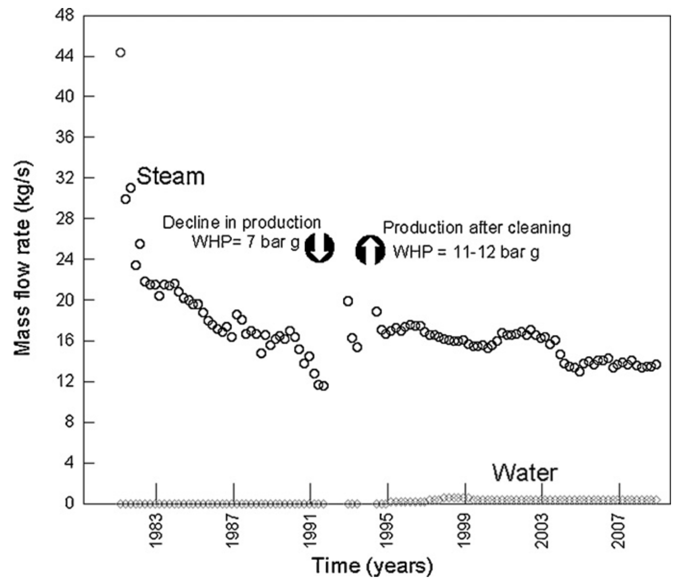

Fig. 14. Steam flow rate for well AH-17 before and after silica scaling.

2008, well AH-6 was at about 1% and well AH-23 was at 1.3%. The produced fluid in all the wells initially averaged about 0.2 wt% of non-condensable gases in the steam, whereas now the average is 0.56 wt% (Fig. 13).

The long term increase of the gas content is caused by boiling; however, migration of gases from the deepest part of the reservoir could also account for some of the increase.

3.3.3. *Silica scaling problems and actual mineral state*

No silica scaling problems were observed at AGF from 1975 to 1989; however, in 1990 well AH-17 was plugged by silica scaling. Since being cleaned out in 1992, well AH-17 has operated at a higher well-head pressure without any recurrence of the scaling problem. Fig. 14 shows the decline in steam flow rate due to pressure drawdown and silica scaling problems in well AH-17.

At present, all the production wells show no evidence of silica deposition problems. Continuous monitoring is performed with go-devil tools and chemical analyses in order to prevent future silica scaling problems.

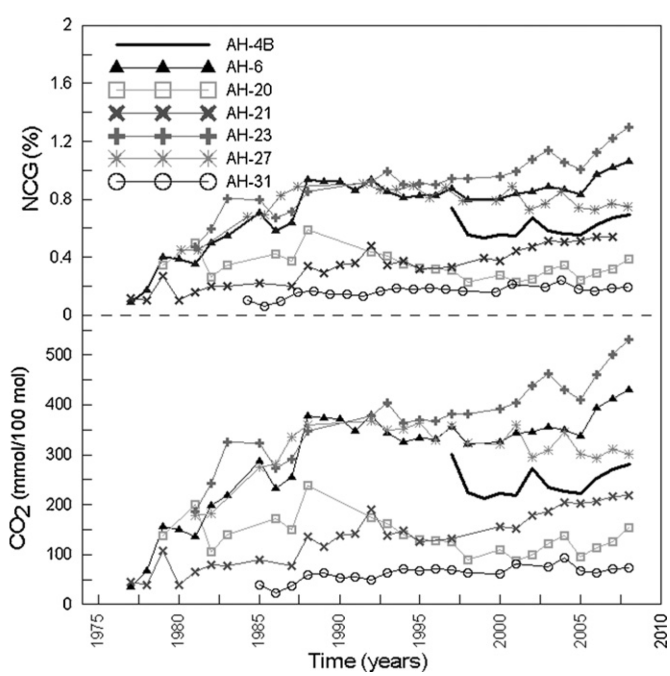

Fig. 13. CO_2 and NCG history trend for selected wells.

3.3.4. *Calcite scaling*

Well AH-32 was the first to be affected by calcite scaling (1990); it is located at the southern part of the field and is perhaps close to the up-flow zone. This well developed calcite scale after four months of production. Due to a lack of stable representative chemistry data, it was not possible to predict the scaling potential of the produced fluid. In 1994, during a work-over, tight-hole problems were observed and the original hole was lost and a side-track well was drilled. The well was later cleaned with acid and now is on standby; producing less steam than the original AH-32.

Wells AH-33B and AH-35A, both located in the S-SE part of the field, showed calcite scaling during 2001 and were plugged. Following mechanical cleaning and the use of inhibitor, both have been producing since 2002.

Currently five production wells: AH-33B, AH-33C, AH-35A, AH-35B and AH-35C are operating with scale inhibitor injection systems. All of them are located in the expansion area in the S-SE part of the field.

3.3.5. *Injection*

Between 1975 and 1983, approximately 47% (about 277 kg/s) of the produced brine was injected into wells AH-2, AH-29, AH-8 and AH-17, all in the center of the field (Cuéllar et al., 1981). The injection was stopped in 1983. A pumping station system (RTA) 2008 two 24-in. pipelines transport the brine to Chipilapa wells for injection. The first pipeline (LR1) began operation by gravity in December 1999, using wells CH-7, CH-7B and CH-9; later (in March 2005), CH-10 was put in operation. After six years, an inspection of LR1 showed a silica scale about 6 mm in thickness, but the line is still in operation.

The second line (LR2) started to operate in March of 2007, and in 2008 injection well CH-9A was put in service. Fig. 15 shows the injection parameters for Chipilapa wells; the total brine flow rate in 2008 was more than 550 kg/s.

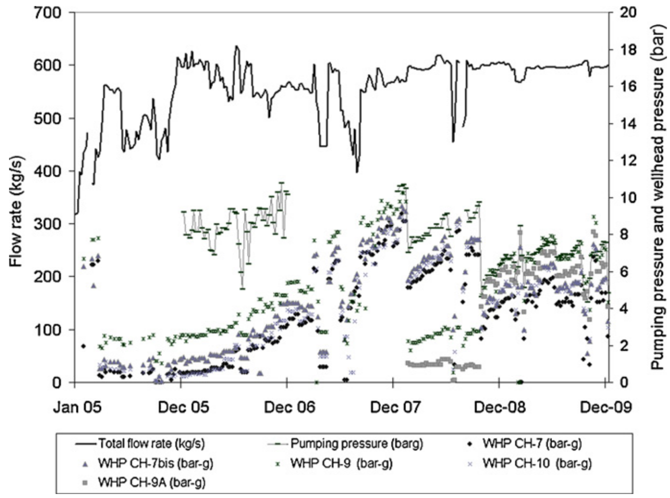

Fig. 15. Injection flow rate and wellhead pressure for Chipilapa wells, 2005–2007.

3.3.6. Tracers

Nine tracer test experiments using I^{131} and one using I^{125} were carried out in the AGF field during 1987 to 1992. Tracer recovery was observed in six tests, ranging from 0.1% to 28% for individual wells. In eight of the experiments the tracer was injected into wells AH-2, AH-5 and AH-29, located in the NNE sector. Only three tracer injection experiments have been carried out in the S-SE part of the well field, into wells AH-32, AH-18 and AH-33A.

The results indicate very rapid tracer breakthrough times for some wells, ranging from one day to a week. The results of the tracer experiments in the S-SE and N-NE sector of the field are in agreement with the structural natural-flow model, showing that the fluid moves from the southern part through the center of the field at velocities more than ten times higher than in the northern part. This could mean that a significant mass of fluid, mainly from the up-flow zone in the S-SE (lateral recharge), reaches the reservoir center more rapidly than the colder water recharge from the N-NE.

A tracer-test using I^{131} was conducted in September/October 2001. The test involved injection of about 100 kg/s of separated water from nearby production-well separators into well AH-33A. The recovery of the tracer was monitored in several nearby wells for a few weeks. The results indicate that well AH-33A is directly connected to wells AH-4bis, AH-19 and AH-22. A tracer recovery corresponding to 1–3% of injection return back to the wells was observed. Flow velocities are rather high (up to 60 m/day). These wells are all located along the Buenavista fault, which is believed to play an important role in the hydrology of the AGF. No recovery was noted in any other wells, except for a minor tracer recovery in well AH-20.

3.3.7. Natural manifestations

The main outflow zone for the Ahuachapán system is the El Salitre area, located about 7 km north of the geothermal field. More than 1000 l/s at 68–70 °C were discharged prior to the exploitation at Ahuachapán; since then the flow rate and salinity have decreased considerably. The fluid discharged at El Salitre was a mixture of geothermal water (10–20%) and shallow aquifer fluid (Glover, 1970). Fig. 16 shows the chloride, temperature and flow rate history of El Salitre spring correlated with the reservoir pressure of AGF.

There are numerous fumaroles on the northern flank of the volcanic range, but only the El Playón fumarole, located in the main field (300 m south of the power plant building and surrounded by wells AH-6, AH-7, AH-17 and AH-24), has a gas composition similar to the reservoir fluid, and its discharge history clearly

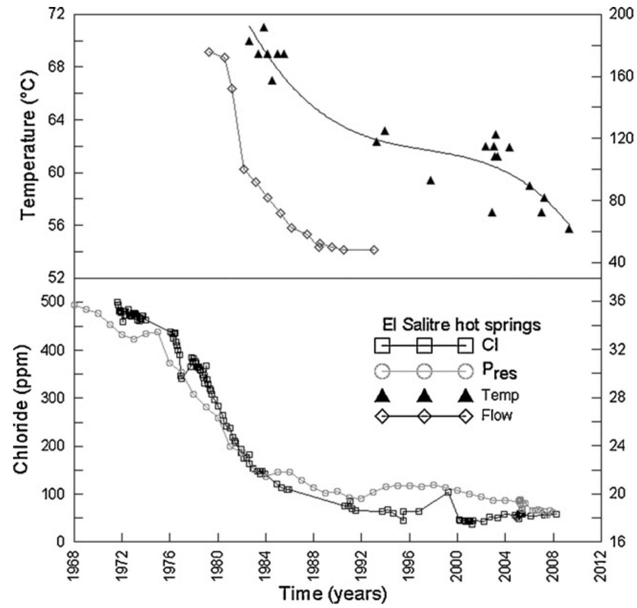

Fig. 16. El Salitre spring: chloride, temperature and flow rate history.

shows the effect of the exploitation of the field. With the drawdown in the reservoir pressure, the gas temperature (D'Amore and Panichi, 1980) decreased from 280 to 240 °C and the mass discharge declined from 50 kg/s to almost 0 by 1982 (LBL, 1988).

Hydrothermal (phreatic) explosions are relatively common phenomena within and near fumarole areas of high temperature geothermal systems. Several small hydrothermal explosions have occurred at Ahuachapán in historic times, and a large one occurred in October 1990 at the Agua Shuca thermal area located approximately 1 km S-SW of El Playón (Bruno et al., 1992). According to the physical and chemical evidence recorded before and afterward, the event was probably caused by over-pressurizing of a shallow aquifer by geothermal gas. Changes in heat and mass flow and an underground self-sealing process were probably the factors responsible for the explosion.

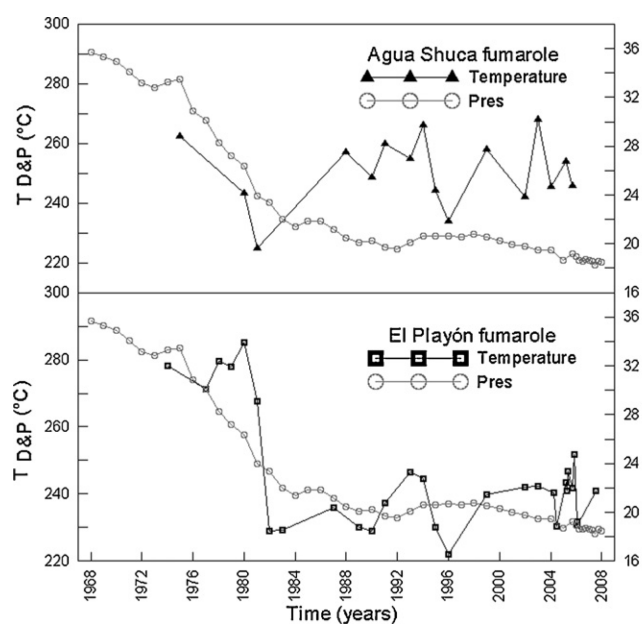

Fig. 17. El Playón and Agua Shuca history.

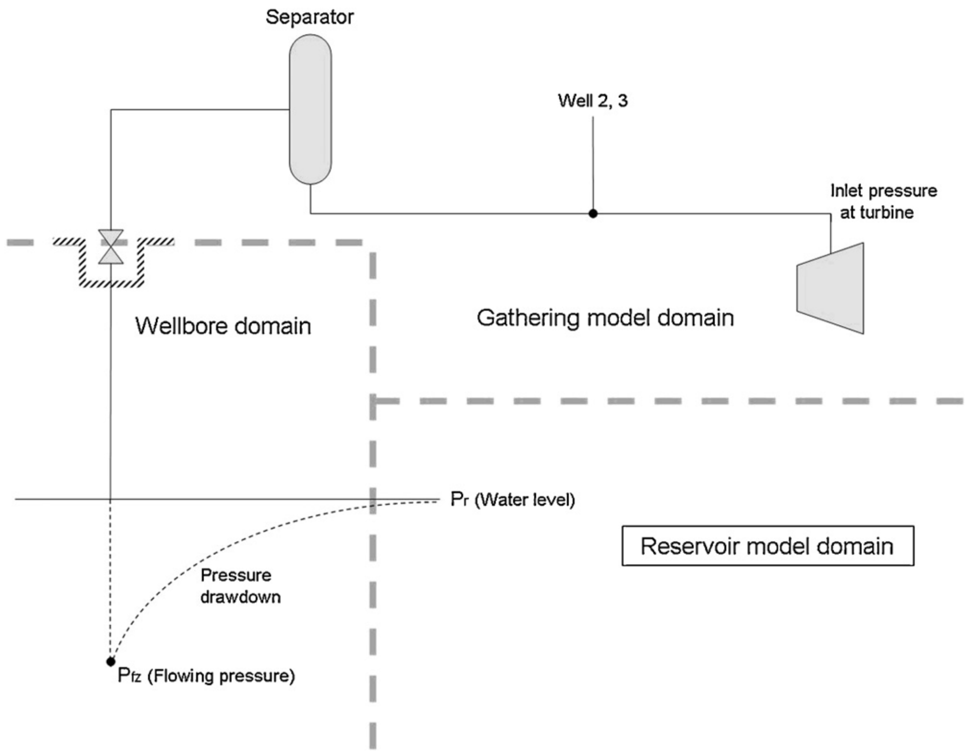

Fig. 18. Model domains for establishing sustainability.

Fig. 17 shows the evolution of gas temperatures at the Agua Shuca and El Playón fumarole calculated by D'Amore & Panichi (D&P) geothermometer.

4. Increasing the power generation

Two important projects were carried out at the AGF in order to increase the power generation capacity. The first was the stabilization project (1995–2000). In the course of this project ten production wells were drilled, mostly in the S-SE part of the field (only five of the wells became producers, among them AH-4B; and one well, AH-33A, was used as injection well).

Later on, in 2005, the optimization project was focused on improvements to surface equipment, the construction of a new injection pipeline (4.8 km long), and the expansion of the productive area with the drilling of two production wells (AH-35C and AH-33C) and one injection well (CH-9A). All the wells were successful.

The projects to increase and optimize the power production of the Ahuachapán geothermal field and power plant have yielded the following results:

1. A mass extraction rate of 800–850 kg/s was sustained from 2005 to 2008, increasing the electricity generation by 20–25 MW_e. This result is in agreement with the numerical model developed by ENEL and LaGeo during 2004.
2. Gross power generation increased from 65 to 85 MW during 2005, and in October 2008 the maximum power reached 88 MW. The average during this period (including overhaul periods) was 78 MW. The pressure drawdown was 1–1.5 bar and the reservoir pressure was almost stable (in 2008) at around 18 bar g.
3. No significant negative effects were observed in the field to this point with a total mass extraction rate of 800–830 kg/s.

5. Methodology for assessing sustainability

Several authors have discussed the sustainability and renewability of geothermal resources (Hanano et al., 1990; Hanano, 2003; Stefansson, 2000; Wright, 1999; Cataldi, 2001; Axelsson et al., 2004; Rybach and Mongillo, 2006; Rybach, 2007). According to Stefansson (2000) the concept of "renewable" describes a property of the energy resource, whereas "sustainable" describes how the resource is utilized. Sustainable operation is characterized by equilibrium as it is not possible to extract more energy out of the system than the amount of the energy entering into the system. Therefore, sustainable exploitation can only be achieved with a renewable energy resource. Also, the rate of energy recharge to geothermal systems is the most critical element for the classification of geothermal energy as a renewable resource.

A renewable energy source is linked in one way or another to some continuous, natural energy process. The conditions must be such that the action of extracting energy from the natural process will not influence the process. A simple definition of renewability is that the energy extracted from a resource is always replaced by a comparable amount of energy. Furthermore, we require that the replacement take place on a time scale similar to that of the extraction. Cataldi (2001) points out that sustainability and renewability both depend on the following specific factors: (a) temperature, (b) heat-transfer processes, (c) resource and reserves (d) heat-extraction technology, (e) carrier fluid and water recharge, (f) injection technology, (g) nature of the reservoir fluid and (h) time constant heat resupply. Renewability depends on deep geological processes that are beyond any human control, whereas sustainability depends on decisions by the field developer concerning: (a) the duration of the project, (b) the rate and quantity of heat extraction, and (c) the technology to tap, transport and use the natural heat. Therefore, if an appropriate limit is established for the quantity of heat to be tapped during the project period, geothermal can be considered a sustainable form of energy. However, the sustainability level may differ significantly from case to case depending on the field conditions.

Hanano et al. (1990) state that six factors strongly influence the longevity of a geothermal reservoir: (a) power output, (b) well density, (c) injection strategy, (d) initial reservoir pressure, (e) initial fluid temperature and (f) permeability in and around the reservoir. The first three factors can be managed by the field operator, but the last three are fixed by nature and are specific to the area. Economic and engineering factors influence the first three factors, with economics having perhaps the most profound consequences.

The time period for sustainable exploitation has not yet been clearly defined. Some authors such as Wright (1999) and Axelsson et al. (2004) cite times as long as 300 years, whereas Rybach and Mongillo (2006) point out that the regeneration of a geothermal resource is a process that occurs over various time scales depending on the type and size of the production system, the rate of extraction, and the attributes of the resource. The key issue is how long the production time can be for sustainable development. For the purposes of this study, we consider the "long term" production to mean 100 years of constant rate energy production. Regeneration processes during resting periods are not considered, and the load factor is taken to be as high as possible for economic reasons despite the depletion of the reservoir.

The approach adopted here is similar to that used by Hanano et al. (1990); it consists of three integrated models: (1) a reservoir model, (2) a wellbore flow model, and (3) a gathering system model that is connected to the power plant (Fig. 18). All three models have been developed for a liquid dominated reservoir. The reservoir model uses TOUGH2, which is coupled to the wellbore simulator HOLA (Bjornsson and Arasson, 1993), and the EES solver (a pipeline pressure-loss model).

The TOUGH2 model was calibrated using natural state conditions and the production history up to the year 2006. The forecast was carried out for 100 years with a power production of 85 MW.

For each well, the observed well-head conditions and estimated feed-zone parameters (productivity index, feed-zone pressure and enthalpy, etc.) must be calibrated using measured values (WHP, mass discharge rate and enthalpy, etc.). For the forecast, the average reservoir pressure drawdown is given by the TOUGH2 model, with mass discharge rate and WHP computed using HOLA. The well-head pressure must be adequate for the inlet pressure at the turbine. If the WHP is lower than the inlet pressure at the turbine, a well cannot supply steam to the power plant.

A gathering-system simulator (EES) for steam flow is used to calculate the pressure losses in the gathering system between the wellheads and the power plant.

6. Sustainability modeling

Fig. 19 shows the numerical grid used for the 3D reservoir model developed in 2004 for the Ahuachapán field to predict reservoir performance and assess the feasibility of increasing power production from 65 to 85 MW.

Fig. 20 shows the steam gathering pipeline systems. Eighteen cyclone separators, with capacities from 350 to 550 t/h, are installed. The steam-pipe diameters range from 16 to 28 in. (41–71 cm). Just one 1.2 km two-phase pipeline is still used (AH-19/AH-22). The shortest steam line is 300 m (AH-17) and the longest is 3.6 km (AH-35). Well AH-4bis uses two separators. Three interconnected steam collectors are used for each turbine. The inlet pressure at the turbine is 4.5 bar g; the minimum inlet pressure is 4 bar g, and constitutes the main constraint on the operation of the wells. In this paper, the sustainable use is evaluated only for the current plant conditions; any new, low-pressure turbine would need to be evaluated separately. The current efficiency and load factor are kept unchanged.

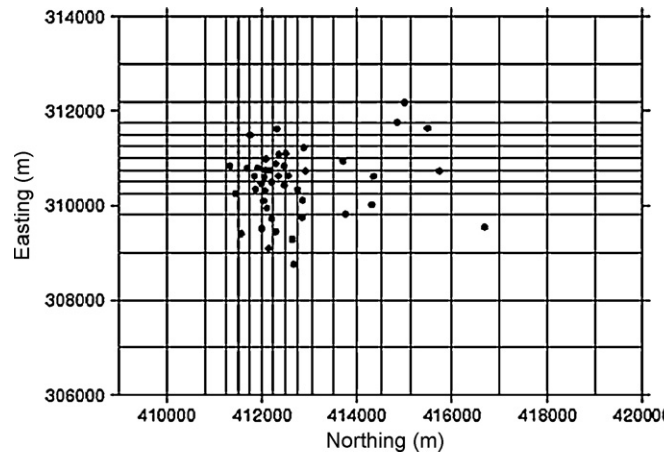

Fig. 19. Numerical grid used for the Ahuachapán model.

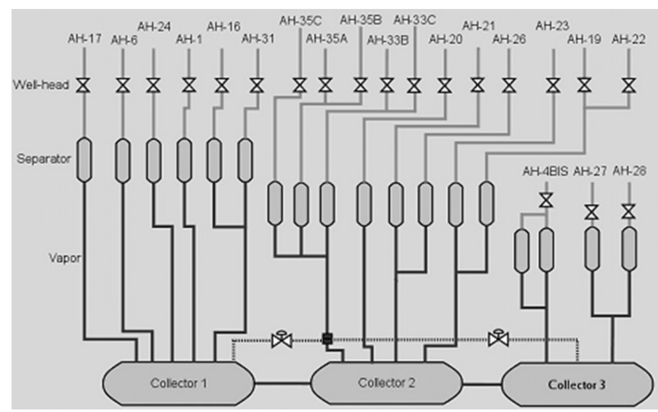

Fig. 20. Gathering systems at the Ahuachapán field.

7. Modeling results

The numerical model is constrained by matching the natural state conditions and the production history, and is used to forecast the reservoir response to future production operations for 50 and 100 years. In order to simplify the forecast calculations, the wellhead pressure and enthalpy for each well are assumed to be nearly constant. The wellhead pressure must be high enough to maintain the inlet pressure at the turbine. The flowing enthalpy is considered to be constant because it is rather difficult to simulate enthalpy changes, and there is no evidence for a large change in the enthalpy (200 kJ/kg). The elevation differences and the distances between the wells and the power plant are more than 200 m and 3000 m, respectively, and therefore play an important role in the simulation due to pressure loss.

Fig. 21 shows the computed pressure drawdown at well AH-25 over 100 years which is used to predict the wellhead conditions for the well. As shown in Fig. 21, the reservoir pressure will reach 5 bars at −200 m a.s.l. after 100 years. Table 4 presents similar performance forecasts for 50 and 100 years for five selected wells, located at five different topographic levels. The results indicate a decline of about 30% in steam flow rate in all the wells compared with the 2008 steam flow rate.

In order to achieve sustainable operation, the pressure and the steam flow rate for every well must be sufficient to have reliable and profitable power plant operation. The assumed well head pressure

Table 4
Well production forecast.

Well	WHP (2008) (bar g)	Steam (kg/s)	WHP (2025) (bar g)	Steam (kg/s)	WHP (2075) (bar g)	Steam (kg/s)	Elevation (m a.s.l.)
AH-6	5.5	8.7	5.2	5.0	5.2	3.6	783
AH-19	7.9	5.5	7.9	5.2	7.8	4.0	873
AH-28	6.3	4.5	6.1	4.0	6.4	3.5	829
AH-33B	7.1	8.6	7.6	6.5	7.6	5.8	917
AH-35A	7.9	8.0	7.9	6.2	8.0	5.1	989

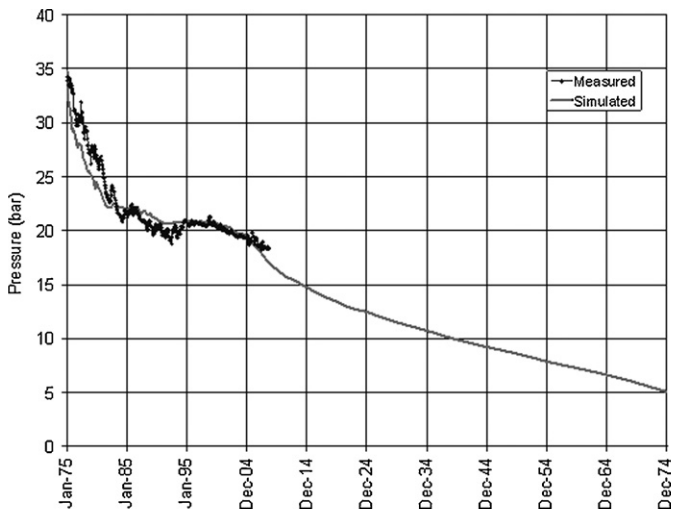

Fig. 21. Forecast of reservoir pressure at well AH-25 forecast for 100 years.

allows delivery of steam to the plant in spite of a decline in steam flow rate over time. The temperature at the center of the field is quite low (210–215 °C), but the wells located in this area are very close to the power plant and the pressure loss is quite low. However, the wells located 2 km away from the plant experience a higher pressure loss; these wells have a higher temperature (240 °C). The integrated model computes the optimum conditions required to maintain flow to the turbine.

According to the modeling results, the current (2008) production wells will not be able to sustain the 95 MW operations for 100 years; therefore, it will be necessary to expand the production area to the southern part of the field. The possibility of moving the power plant closer to the southern wells and perhaps to use low-pressure turbine or binary type units will also have to be considered.

8. Conclusions

I. Over the last 33 years the Ahuachapán geothermal field (AGF) has been in commercial operation, and sustainably managed despite some operational problems. Detailed and continuous monitoring has been carried out, providing good data for reservoir evaluation.
II. The AGF is still in a liquid-dominated condition, in spite of boiling and dilution processes that are occurring in certain wells (e.g., AH-17 has encountered boiling in the shallow part of the reservoir). The main up-flow zone is located in the southern part of the field, where temperatures of 240–250 °C have been measured (wells AH-35B/AH-34A). The main out-flow zone is located in the Chipilapa area, and the main discharge area is at the El Salitre spring.
III. Some silica and calcite scaling has been observed in a few wells. Well AH-17 was worked over due to silica scaling, but it is now in stable operation. Calcite scaling is still observed in the southern part of the field, and injection of inhibitor must be used to prevent plugging of production casings.
IV. The injection strategy implemented at the AGF is considered successful, and the steam production rate has been increased to generate about 850 kg/s with only a small pressure decline.
V. Results of numerical simulations predict a decline in steam production, even though production enthalpies are expected to remain fairly constant. This situation (i.e. constant production enthalpy) does not hold for all wells; some show enthalpy increases due to boiling, while others have declining enthalpies that reflect cooling due to injection or influx from surrounding aquifers. The change in enthalpy must be carefully evaluated on a well by well basis.
VI. The field management strategy should consider a reduction in power production to reach the level of sustainability for at least 100 years, the expansion of the actual steam field, and periodic upgrades to the gathering systems and the power plant, while taking into account economic considerations.
VII. More effort must be made to improve the knowledge of the rate of hot recharge to the reservoir, the thermal breakthrough effects due to injection, the type and location of the boundaries of the system, and, finally, the boiling and cooling processes that are affecting the wells.

References

Aunzo, Z., Bodvarsson, G.S., Laky, C., Lippmann, M.J., Steingrimsson, B., Truesdell, A.H., Witherspoon, P.A., 1989. The Ahuachapán geothermal field, El Salvador. Reservoir analysis. Report No. LBL-26612, Earth Sciences Division, Lawrence Berkeley Laboratory, Berkeley, California, USA, 199 pp.

Aunzo, Z., Laky, C., Steingrimsson, B., Bodvarsson, G.S., Lippmann, M.J., Truesdell, A.H., Escobar, C., Quintanilla, A., Cuéllar, G., 1991. Pre-exploitation state of the Ahuachapán geothermal field, El Salvador. Geothermics 20, 1–22.

Axelsson, G., Stefansson, V., Bjornsson, G., 2004. Sustainable utilization of geothermal resource for 100–300 years. In: Proceedings 29th Workshop on Reservoir Engineering, Stanford University, Stanford, California, USA, January 26–28, 9 pp.

Bruno, C.A.E., Burgos, J.A., Ayala, M.S., 1992. Agua Shuca hydrothermal eruption. Bulletin Geothermal Resource Council 21 (11), 361–369.

Bjornsson, G., Arasson, P., 1993. The Wellbore Simulator HOLA User Guide. National Energy Authority, Iceland.

Cataldi, R., 2001. Sustainability and renewability of geothermal energy. In: International Scientific Conference on Geothermal Energy in Underground Mines, Ustron, Poland, 4 pp.

Cuéllar, G., Choussy, M., Escobar, D., 1981. Extraction-reinjection at Ahuachapán geothermal field. In: Rybach, L., Muffler, L.J.P. (Eds.), Geothermal Systems, Principles and Case Histories. John Wiley, London, UK, pp. 321–335.

D'Amore, F., Panichi, C., 1980. Evaluation of deep temperature of hydrothermal systems by a new gas-geothermometer. Geochimica Et Cosmochimica Acta 44, 549–556.

Electroconsult (ELC), 1993. Report of resource evaluation. Feasibility of stabilization program for the Ahuachapán geothermal field. Draft Report, Electroconsult, Milan, Italy, pp. 3-9 to 3-15 (in Spanish).

ENEL-LaGeo, 2004. Feasibility study for the Optimization and Developments of the Ahuachapán, Chipilapa and Cuyanausul Geothermal System. LaGeo Internal Report, LaGeo, Santa Tecla, El Salvador, 264 pp.

Fournier, R.O., 1977. Chemical geothermometers and mixing models for geothermal systems. Geothermics 5, 41–50.

Fournier, R.O., Truesdell, A.H., 1973. An empirical Na-K-Ca geothermometer for natural waters. Geochimica Et Cosmochimica Acta 37, 515–525.

Glover, R.B., 1970. Geochemical Investigation of the Ahuachapán Geothermal Field. Draft Report, United Nations, San Salvador, El Salvador, 40 pp.

Hanano, M., 2003. Sustainability steam production in the Matsukawa geothermal field, Japan. Geothermics 32, 311–324.

Hanano, M., Takahashi, M., Hirako, Y., Nakamura, H., 1990. Longevity evaluation for optimum development in a liquid dominated geothermal field: effect of interaction of reservoir pressure and fluid temperature on steam production at operating conditions. Geothermics 19 (2), 199–211.

Lawrence Berkeley Laboratory, 1988. The Ahuachapán geothermal field, El Salvador – Reservoir Analysis – vol. I: Text and Main Figures, and Vol. III: Appendices F through I. Draft Report, Lawrence Berkeley Laboratory, Berkeley, CA, USA, 201 pp.

Montalvo, F., 1994. Chemical evolution of Ahuachapán geothermal field, El Salvador, C.A. Report No. 9, United Nations University Geothermal Technical Program, Reykjavik, Iceland, 26 pp.

Rogmagnoli, P., Cuéllar, G., Jiménez, M., Ghessi, G., 1976. Hydrogeological characteristics of the geothermal field of Ahuachapán. In: Proceedings 2nd U.N. Symposium on the Development and Use of Geothermal Resources, San Francisco, CA, USA, pp. 571–574.

Rybach, L., 2007. Geothermal Sustainability. Geothermal Heat Center Bulletin 28 (3), 2–7.

Rybach, L., Mongillo, M.A., 2006. Geothermal sustainability, a review with identified research needs. Geothermal Resources Council Transactions 30, 1083–1090.

Stefansson, V., 2000. The renewability of geothermal energy. In: Proceedings 2000 World Geothermal Congress, Kyushu-Tohoku, Japan, pp. 883–888.

Steingrimsson, B., Aunzo, Z., Bodvarsson, G.S., Truesdell, A.H., Cuéllar, G., Escobar, C., Quintanilla, A., 1991. Changes in thermodynamic conditions of the Ahuachapán reservoir due to production and injection. Geothermics 20, 23–38.

Truesdell, A.H., Aunzo, Z., Bodvarsson, G.S., Alonso, J., Campos, A., 1989. The use of Ahuachapán fluid chemistry to indicate natural state conditions and reservoir processes during exploitation. In: Proceedings 14th Workshop on Geothermal Reservoir Engineering, Sanford University, Stanford, CA, USA, pp. 273–278.

Wright, P.M., 1999. The sustainability of production from geothermal resources. In: Lectures presented at the United Nations University Geothermal Training Programme, Reykjavik, Iceland, September, 42pp.