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Production and Re-injection Strategies at Celikler Holding First 45 GPP on Pamukören-Aydin Geothermal Field

[1]Cetin Karahan, [2]Nazim Yildirim, [1]Tarik Atac

[1]Çelikler Holding, Ankara-Turkey

[2]Yildirim geothermal, Ankara-Turkey

Cetin.karahan@celikler.holding.com.tr, nazimy@gmail.com, 1tarik.atac@celiklerholding.com.tr

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ABSTRACT

Pamukören Geothermal Field of Celikler Holding Company is located at Middle section of Büyük Menderes Graben. It is a hidden geothermal system without any surface manifestations. With one or two spare wells, ten production and seven re-injection wells have been drilled to supply and re-inject the approximately 2700 t/h flow for already installed 45 MW GPP. The production wells, with bottomhole temperatures ranging from 178-191 ^oC, were drilled on the N-S intersection of northern Flank E-W directional Menderes Graben Fault, while the reinjection wells are located downstream of the catchment area to avoid possible early interference among production and reinjection wells. By applying this strategy, no negative interference has been experienced in at least three months time of continual exploitation and reinjection. The beginning capacities of the reinjection wells have almost increased twofold as a result of acidizing each well with 30 tons of 28.5 % HCl. The counter pressure of the reinjection wells declined 3-4 bars while the pressure at the production wells increased 1-3 bars for the same amount of reinjection and production capacities after stimulations. In this paper, the production-reinjection management strategies and the applied improvement studies for sustainability of the wells to avoid interference will be discussed.

1. INTRODUCTION

Since the beginning of the project at the end of 2010, a total of 30 wells with 900-2200 m ranging depth have already been drilled with the aim of supplying a 90 MWe capacity in licensed area borders. The first 45 MWe capacity binary geothermal Plant (GPP) has been in operation since October 30, 2014. The approximately 2700 ton/h of required flow has been being produced from eight production wells with bottomhole temperatures ranging from 168-191 ^oC and depths ranging from 900-2200 m. After being used, the 2700 ton/h disposal fluid is being reinjected back to the reservoir by seven reinjection wells at 80 ^oC. The locations of the production and injection wells are illustrated in Fig. 1.

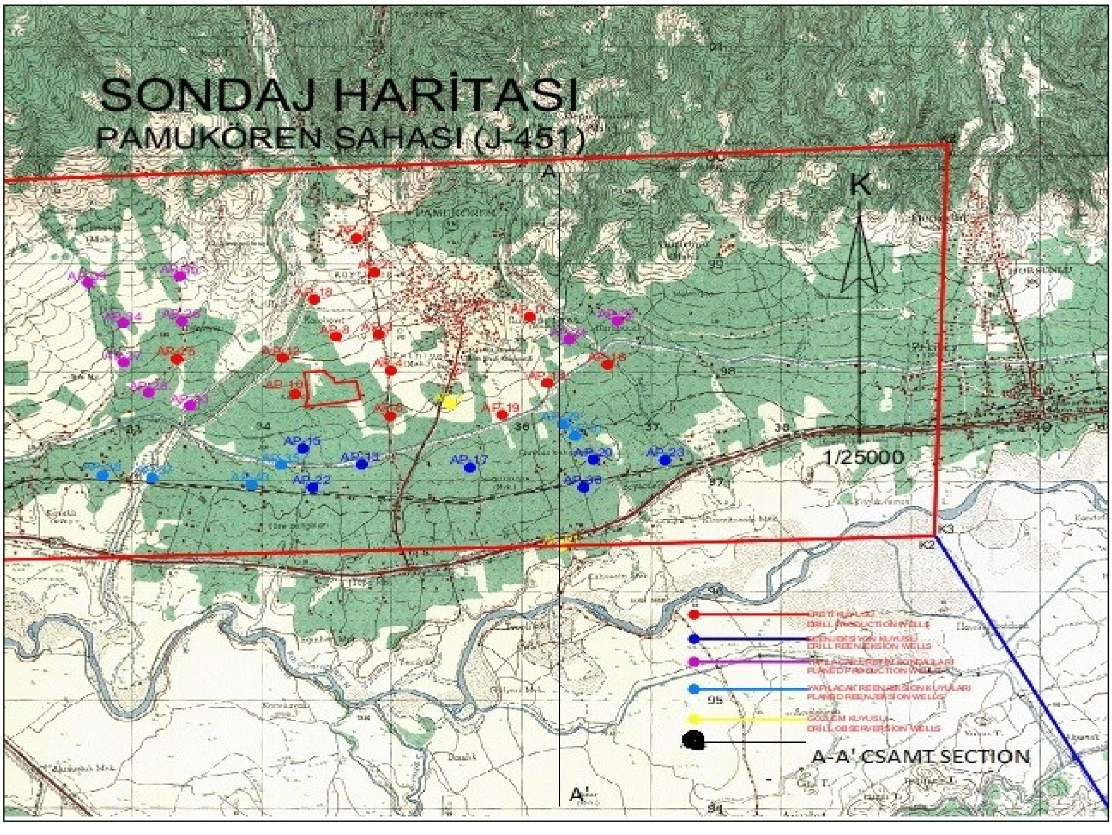


Figure 1. The production, reinjection and observation wells locations on topographic map.

As can be seen on the above map, all the production wells take place in the upflow zone, while reinjection takes place at the actively diminished zone which surrounds the area as an arc. The plan for a complete reinjection of the produced geothermal fluids is obviously a sustainable and environmentally friendly approach. The suitable value of well spacing for the production and reinjection wells depends on many parameters (Gringarten, A.C. 1975). It can be estimated from simulations, if permeability values are available. In the study, the following spacing has been defined as minimum between production and injection wells:

• 500 m (minimum) between production or injection wells

• 1000 m between production and injection wells.

Optimal well spacing between production wells and injection is considered to be as large as possible, while still making a connection. Narrow well spacing could cause an early thermal breakthrough and, therefore, was avoided (Buning et al, 1997) Temperature and pressure declines are important factors with respect to sustainability of the development. The plan is proposed with all new injection wells located further away from the production wells, but within the zone of permeability.

2. THE BASE GEOLOGY, TECHTONIC AND FLUID CHARACTERISTICS IN THE FRAME OF FIELD MANGMENT

2.1 Base geology, tectonics, and drilling

Pamukören geothermal field is located at Eastern North flank of East-West trending Büyük Menderes Graben developed by normal faults. In the region, the basement units are represented by Menderes massif metamorphic (Fig. 2) composed of Paleozoic para and ortho gneisses, chloride-schist, mica-schist, quartz-schist, quartzite, phyllites and intercalating marble layers. The stratigraphy of the region is mainly represented by metamorphic rocks of the Menderes Massif (Atmaca, I. 2010). The gneisses are thrusted over schist and marble units. In these units, the fractures and joints are filled by calcite and quartz minerals in addition to dense pyrite occurrences in geothermal active levels (Karahan, C. 2011).

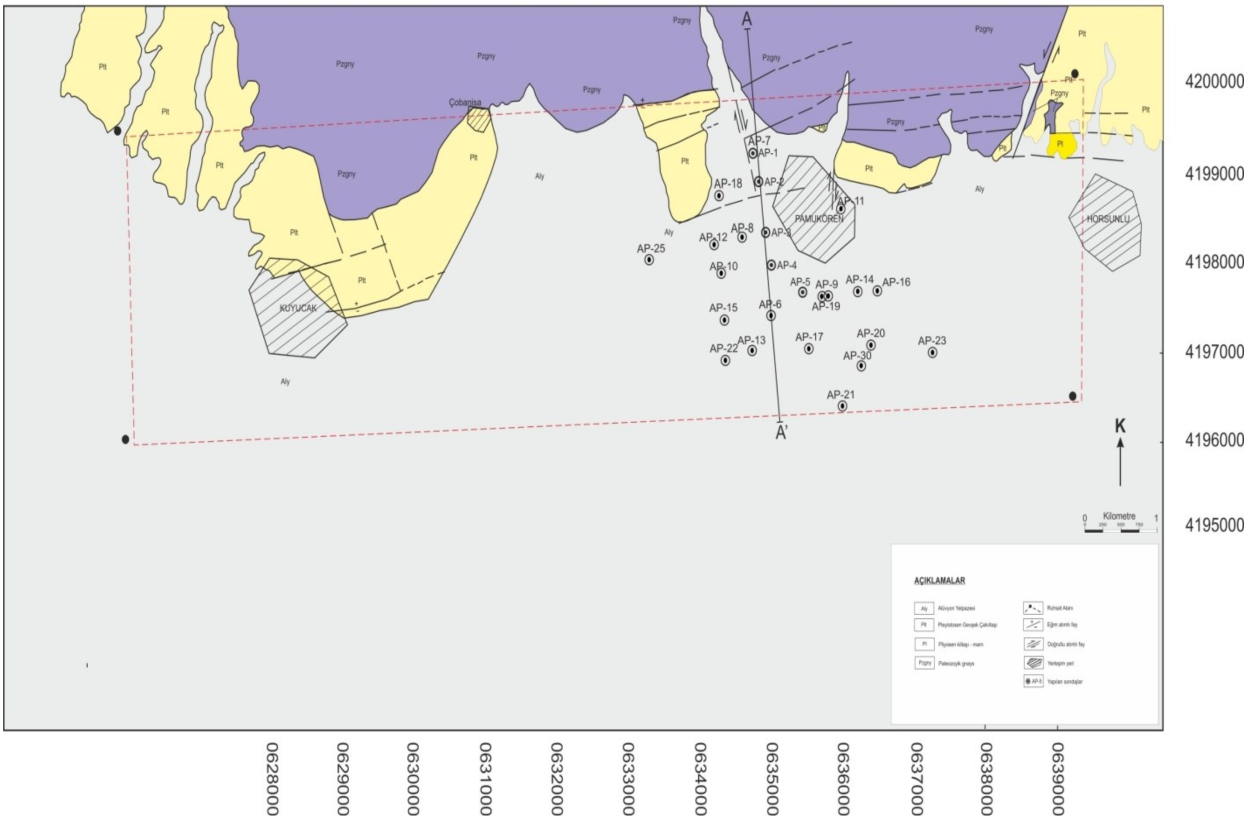


Figure 2. The Geological Map of Aydın-Pamukören geothermal field.

In all of the geothermal fields in the Menderes Massif, the oblique and normal faults having strikes in N-S, NW-SE, NE-SW intersects E-W trending major normal faults. These faults play an important role for the geothermal system in Pamukören geothermal field. So the crossing zones of faults are taken into consideration for the selection of the well locations. The CSAMT studies results of the area are illustrated in (Fig. 3). The production wells (AP-11, AP-14) and reinjection well (AP-20), which is seen on the CSMT cross-section, struck the E-W fault zones (Karahan, C. 2011). The wells were located according to geological indications and geophysical anomalies on the determined trending faults. The production wells were located on the north of N-S strikes faults, while the reinjection wells were located on south part of the same faults. Some of the present well locations are shown on the NW-SE geological section (Fig. 4). The reinjection well AP-13 struck the southern antithetic fault in the licensed area. By doing this, the reinjection wells were aimed to be placed downstream of the field. Therefore, the reinjection of relatively cold waste water (80 oC) strikes an impermeable wall at the south, builds up a high pressure zone, and indirectly feeds the production wells situated further north. This phenomenon in the reservoir has as a positive effect on the production wells by pressure increment. After injection of approximately four months, wellhead operational pressure of the wells has increased 1-2 bars at the same flow rates.

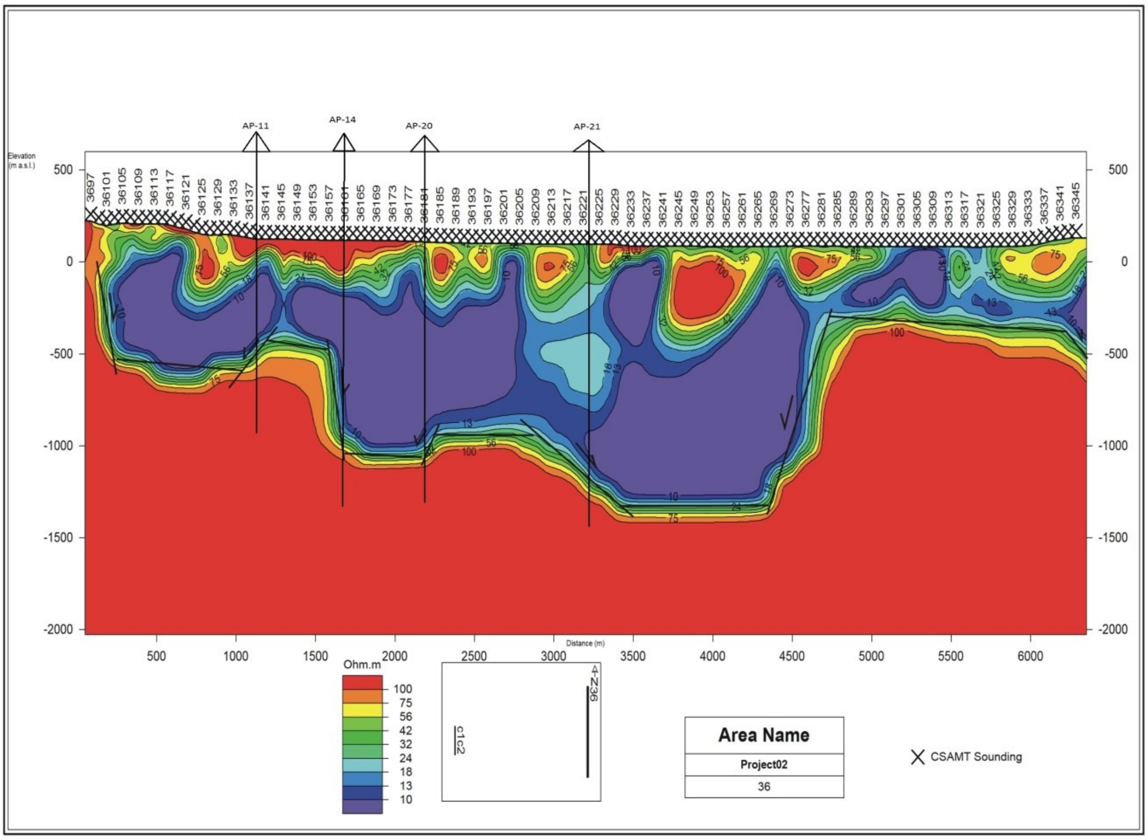


Figure 3. Two-dimensional cross-section (profile 36) and N-S trended structural model.

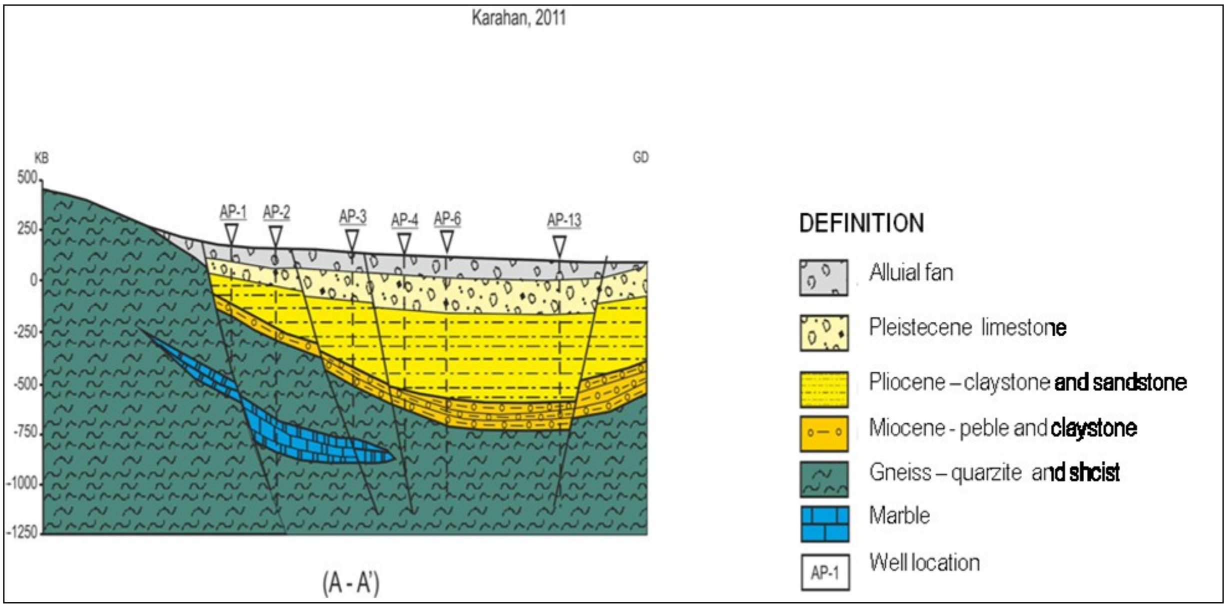


Figure 4. Geological cross-section of Pamukören geothermal field.

2.2 The well designs

The wells in Pamukören geothermal field were completed to a total depth (T.D.) ranging between 850- 2001 m. Some of the wells start with 13 3/8-inch casing and continue with 9 5/8-inch casing, all tied back to the surface. Only four wells start with 20-inch casing and continue with same orders as others. The well is completed with a 7-inch uncemented liner from 9 5/8 casing shoe to (T.D). Table 1 summarizes the design specifications of all of the drilled wells related to the installed 45 MWe GPP (Celikler Holding well completion reports).

Table 1. Well completion specifications.

	Drilling status	Casing Depth (m)	Hole (Inch)	Design (Inch)	Total Depth m	Max measured downhole ^{o}C	WHP bars-g	Flow rate Ton/h
AP2	vertical	0-329 0-552 545-1150	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1150	165	7.0	400
AP3	vertical	0-255 0-674 654-1052	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1047	183	9.0	500
AP4	vertical	0-145 0-775 775-1250	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1250	178	8.0	400
AP6	vertical	0-146 0-915 955-1457	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1457	168	7.0	360
AP7	vertical	0-42 0-146 0-482 0-680 665-880	26 17 1/4 12 1/4 8 1/2 6 1/2	20 13 5/8 9 5/8 7 casing 5 slotted	880	191	7.5	100
AP8	vertical	0-147 0-771 771-1480	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1480	182	7.0	288
AP12	vertical	0-146 0-853 837-1492	17 1/2 12 1/4 8 1 /2	13 3/8 9 5/8 7 slotted	1492	178	6.5	320
AP18	vertical	0-71 0-275 0-650 650-850	26 17 1/4 12 1/4 8 1/2	20 13 5/8 9 5/8 7 slotted	850	190	12.0	385
AP13R	vertical	0-149 0-962 962-1533	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1533	159	3.5	165
AP14R	vertical	0-222 0-841 788-1390	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1427	177	7.5	280
AP15R	vertical	0-179 0-944 944-1660	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1660	159	4.0	340
AP17R	vertical	0-228 0-960 960-1822	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1822	163	5.0	105
AP20R	vertical	0-71 0-243 0-903 903-1757	26 17 1/4 12 1/4 8 1/2	20 13 5/8 9 5/8 7 slotted	1771	160.7	7.0	280
AP22R	vertical	0-71 0-680 0-963 963-2001	26 17 1/4 12 1/4 8 1/2	20 13 5/8 9 5/8 7 slotted	2001	166	3.5	185
AP5Ob	vertical	0-135 0-805 805-1670	17 1/2 12 1/4 8 1/2	13 3/8 9 5/8 7 slotted	1681	168.5	7.0	140

2.3 Base chemistry

Commercialization of a geothermal resource requires that several different perspectives be pursued in regards to what happens when the reservoir fluids are moved around by production and disposal (Bodvarsson G 1969). Emphasis on reservoir management through hydraulic principles currently tends to dominate the issue despite where permeability changes are due to chemical reactions of injected fluids, mainly involving silica. Silica concentration is not as high as to cause problem around the reinjection wells vicinity in Pamukören geothermal field. $CaCO_3$ deposition has generally been regarded as a production problem, but successful inhibitors displace that concern to the context of injection.

The production in Pamukören geothermal wells can be achieved by means of injecting inhibitor to certain depth in production wells. Since the functional mechanism of the inhibitor does not affect the thermodynamic drive for scale deposition, one should anticipate deposition whenever the residual inhibitor in the brine diminishes to below a critical minimum concentration. Although the inhibitor has long-term stability at the temperature of flashed brine, its stability at rock temperatures in the injection zone is less. Additionally, the large rock surface area of the injection zone will absorb some inhibitor from the injectate. Furthermore, a slow, but finite overgrowth of $CaCO_3$ on inhibited crystals also consumes some of the inhibitor (Yildirim N 1989). Thus, the injectate progresses to an uninhibited condition so that $CaCO_3$ eventually will deposit in the rocks surrounding the injection well.

This negative effect on reinjection wells has been removed by acidification of the wells by 20 % HCl solution. The engineering questions raised by this eventuality are (1) how far is the fluid from the wellbore when the deposition occurs; and (2) how much $CaCO_3$ deposits compared to available space in the rock's porosity. The Table below is showing base line chemistry of individual wells and how the wastewater chemistry differs (Table 2 and Fig. 5).

Table 2. Base line chemical characteristics and gas content of the present production and reinjection wells (Yildirim, 2013).

Location	Production Wells								Re-injection wells						Observ well	Waste Wate
Wells	AP2	AP3	AP4	AP6	AP7	AP8	AP12	AP18	AP13	AP14	AP15	AP17	AP20	AP22	AP5	Total
Temp °C	182	183	178	166	191	182	178	190	159	177	145	163	161	166	168	80
pH/°C	8.50	8.71	8.71	8.56	8.86	8.48	8.84	8.07	8.69	8.87	8.25	8.76	8.78	8.73	8.62	8.5
EC µS/cm	5100	5000	4928	5030	4970	5051	4710	5140	4960	4840	4885	4796	4715	4963	4980	4200
Na mg/l	1272	1240	1270	1190	1225	1186	1162	1165	1174	1290	1112	1025	1005	1052	1190	1300
K mg/l	196	170	190	122	148	123	117	132	140	130	118	122	104	118	115	150
Ca mg/l	3.3	1.90	4.5	6.1	2.45	4.0	5.7	3.2	6.5	7.6	4.8	6.8	6.0	12	6.1	14
Mg mg/l	0.1	0.1	0.8	3.4	0.2	1.68	0.3	2.9	5.7	0.98	1.68	3.2	2.6	3.8	0.8	3.0
SiO_2 mg/l	336	356	352	392	395	417	320	436	312	361	343	256	273	257	300	330
HCO_3mg/l	2519	2306	2490	2100	2293	2080	2190	2307	2210	2160	2196	1795	1787	1087	2096	2550
CO_3mg/l	178	175	150	292	186	240	152	90	145	216	95	217	228	180	164	196
SO_4 mg/l	180	318	320	204	222	208	288	261	226	238	95	280	171	233	368	260
Cl mg/l	276	290	289	274	335	315	267	275	296	276	266	174	270	326	273	310
B mg/l	30	36	36	38	34	39	29.5	43	30.5	29.5	34	35	34	34	31	36
Fe mg/l	-	0.38	012	0.035	1.6	0.028	0.13	0.04	0.92	0.83	0.034	0.24	0.17	0.13	0.92	-
TDS mg/l	4446	4501	4733	4152	4411	4158	4158	4236	4203	4307	4041	3623	3304	3269	4228	4200
CO_2 wt %	-	1.58	1.61	1.59	1.70	1.31	1.57	1.49	1.26	1.38	1.28	0.78	1.16	1.24	1.48	0.008

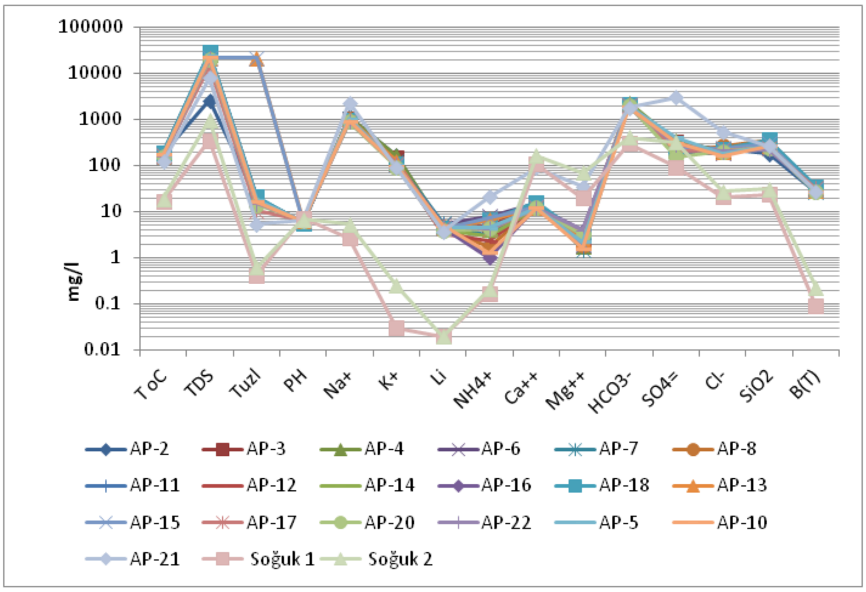


Figure 5. Baseline chemical data of the wells present in the production and reinjection zones.

The sampled liquid from Pamukören geothermal field wells at the surface, is Na-(K)- HCO_3- Cl in character, and contains 3500-4500 ppm TDS and 5-10 ppm Ca^{++}, with pH ranging from 8.0-9.0, depending on separation pressure (Yildirim 2013). All the wells of this water-dominant geothermal field produce a fluid containing a large amount of CO_2. The non-condensable gases (NCG) in steam, separated at approximately 6.5 bar (a), range from <20 to 33% by weight. When converted to reservoir conditions, all the wells in the reservoir contain 1.2 to 1.7% NCG). Recent measurements suggest that the NCG content of the reservoir has decreased slightly over the last 8 months. This decline can be attributed to several processes: influx of low gas fluid such as injectate or cold water, or possibly degassing by boiling. The main gas in the bulk non condensable gas is CO_2 with more than 98% by volume for all representative wells. The field determination gave values closed 99% CO_2. Hydrogen sulfide (H_2S) is very low in Pamukören; the field has nearly homogenous chemical characteristics, which show a large liquid-filled reservoir spread wide in the licensed area. The study states that the source water for the geothermal system is meteoric water similar to modern cold water from the higher elevations of the North Mountain (Yildirim and Simsek 2003).

The gas concentration of reinjected wastewater in this geothermal field is less than 0.0018 mol/l as CO_2. After emission to atmosphere, the H_2S concentration in the reinjected wastewater is not high enough to be determined. Therefore, the reinjected water is depleted of gases. This means the gas concentration in the reservoir has been lowered over the duration of operation. Chemical characteristics and gas concentration of the field is under control in the frame of monitoring work.

3. RESERVOIR ANALYSES AND MONITORING

3.1 Monitoring activities

The monitoring has been carrying out according the data in the Fig. 6. The types of data considered were water level in observatory wells (AP-5), chemical and gas concentration of the fluid from production wells, heat balance, pressure balance at production and reinjection wells (Satman et al 1981, 1997). The monitoring has been carrying out according the data in the Fig. 5. The criteria are to keep the reservoir conditions without disturbing changes after a long term exploitation and reinjection period in the monitored area.

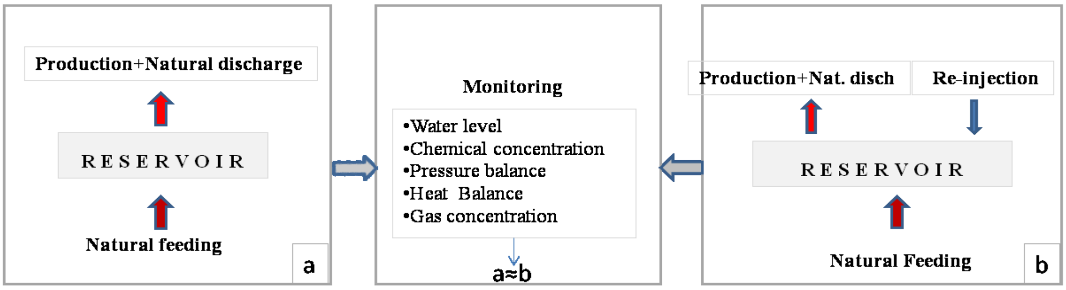


Figure 6. Monitoring of the reservoir data according to non-reinjection and reinjection period.

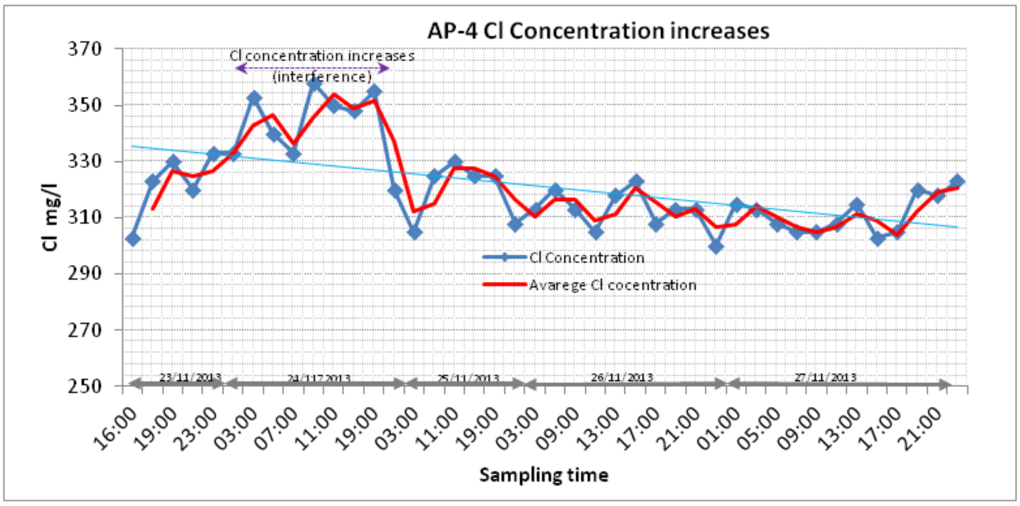
The sustainability of the planned development has been analyzed by means of numerical simulations. Several tests, including NaCl and hydrochloric acid injections, showed that northern and western blocks of the reservoir display better permeability than eastern and northern blocks where low transmissivity explains that the wells drilled in the western and northern blocks displays better production and reinjection. During the period of simultaneous production of AP-3, AP-4, AP-6, AP-8, AP-12 wells combined with reinjection going on AP-13, AP-15, AP-17 AP-20 and AP-22, pressure and chemical monitoring were performed.

As a tracer, 15 tons of NaCl was injected from reinjection well AP-13 with simultaneous 420 ton/h of water. The interference between AP-13 and some production wells including AP-3, AP-4, AP-6, AP-18 and AP-12 was observed in a couple of days while no interference effect was recorded between AP-13 and far distant production wells over an approximately 15 day observation period. As an example, chloride increase is shown in one of monitored well (Figure 7). The chemical front that showed itself in Cl concentrations increment had reached to nearest well, but had not reached thermal breakthough. This can be attributed to the large volume and huge heat source of the related reservoir. But, we must take into account that the period of the observation was short to make such evaluation about the field. The use of only four wells at production and two wells at reinjection is not enough to get good results due to the strong anisotropy of the permeability distribution in the reservoir where permeability is mainly of secondary origin and controlled by fracture systems. Limited data available does not allow obtaining a mathematical reservoir model. These limitations were due to actual conditions of some of the existing wells and the strong environmental restrictions which did not allow to test the well in full scale flow for long discharging period.

3.2 Well improvements by acidification

To enhance the production and reinjection capacities of the drilled well in Pamukören geothermal field acidification operations were commissioned. During the acid operation, retarders were not used due to the difficulty in supplying them. So, to avoid wormhole reaction in the formation of slotted liner vicinity, dilute HCl (20 wt. %) at the acidification both production and reinjection wells of the field. The solutions used for each well were prepared according the below depicted figure (Figure 8)

Well acidizing in a geothermal field is used for the reservoir development or to treat formation damage caused by drilling mud, drilling cuttings and scaling (mineral deposits) in geothermal wells (1995; Buning et al, 1997 al., 1999, Barrios et al., 2002, Malate, R.C.M. et al 1998, Serpen and Tureyen, 2000, Jaimes-Maldonado 2003). Acidification operation were performed with drill collar to the desired depth in production wells and from the spool in reinjection wells. After injection of the solution, the acid was forced by cold water injection to spread into the fractures. After waiting at least 8 hours for reaction time with the formation in the reservoir, the resulted solution was discharged from the wells by back flow in the production wells and sequestered with reinjection water in reinjection wells, as planned. At the end of acidification operations, the following successes have been achieved from both production and reinjection wells of the pamukören geothermal field (Table 3).



. **Figure 7. Cl concentration increases in AP-4 fluid after injection of NaCl as a tracer from AP-13.**

Table 3. The improvement rate of the production and reinjection wells after acidification.

WELLS CODE	Kind of utilization	Production Capacity (tons/h)		Reinjection Capacity (tons/h)		Improvement rates
		Before acidification	After acidification	Before acidification	After acidification	
AP-5	Observatory					
AP-6	Production	280	390			39 %
AP-8	Production	270	340			26 %
AP-10	Production	180	220			22 %
AP-11	Production	230	320			39 %
AP-12	Production	280	330			18 %
AP-13	Re-injection			350	500	43 %
AP-14	Re-injection			240	300	25 %
AP-15	Re-injection			280	320	14 %
AP-17	Re-injection			120	160	33 %
AP-18	Production	not acidized	550			
AP-19	Re-injection	320	380	280	300	7 %
AP-20	Re-injection	280	360	420	450	7 %
AP-22	Re-injection	180	220	130	160	23 %

4. CONCLUSION

There have been some changes in the production and injection strategies in the field. At the beginning, from October 2013 to March 2014, all of the total waste brine was injected to the southern part of the field (distributed in wells AP 13, AP-15, AP-17, and AP-22) and the rest in the eastern part of the field (wells AP-17 and AP-20). From March 2014, the production was doubled, and so too were the extraction and injection rates. Upon interference effect of AP-13 on production wells, the injection to the south was decreased to half the previous rate, and the balance was shifted to the wells in the eastern part of the field (AP-14, AP-17, AP-19 and AP-20). This injection strategy was done to mitigate the interference effect on production wells and to minimize the pressure drawdown observed in the field based on the reservoir monitoring conducted and the results of small-scale tracer test with NaCl injection from the well AP-13. Based upon the problems experienced since the commission date of the power plant, the new strategy is to drill far distance reinjection wells to southern and eastern part of the field according to the planned seismic and MT studies result. By injecting the wastewater in wells with large distance to production wells, the expected thermal breakthrough will be extended over a longer period of time. A tracer test with at least three different tracers should be conducted in the field to see the speed and pathway of the injected wastewater in the reservoir.

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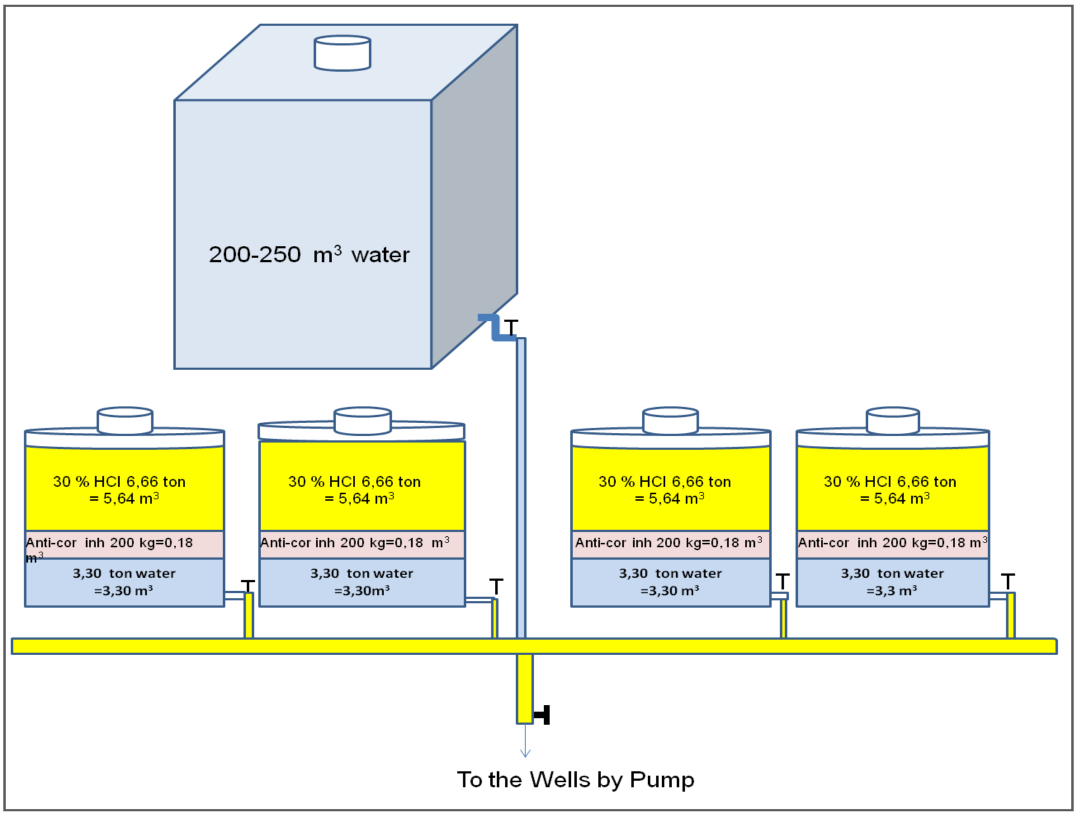

Figure 8. Used acidification solution in Pamukören geothermal field wells.