RESERVOIR MODELING STUDY OF THE AHUACHAPAN GEOTHERMAL FIELD (EL SALVADOR) IN THE FRAME OF A GENERATION STABILIZATION PROJECT

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ABSTRACT

The energy production of the Ahuachapan power plants (95 MW installed capacity) is presently reduced to 375 GWh/year (45% average load factor), due to the decreased pressure in the exploited reservoir. With the aim of investigating possible remedial measures, a new simulation model has been implemented to analyze the reservoir response to alternative exploitation strategies. The model study shows that a substantial improvement in the steam production can only be achieved through the adoption of a large-scale reinjection program. The poor production characteristics of several wells drilled in nearby Chipilapa area suggest the opportunity of utilizing it as the main reinjection sector for Ahuachapan: the distance (a few kilometers) and the existence of hydraulic connection between the two areas represent promising conditions for the success of this strategy. The expansion of the wellfield towards the South is also envisaged, increasing the availability of production wells. The power generation could be stabilized at a level approaching the rated capacity of the installed plant.

1. INTRODUCTION

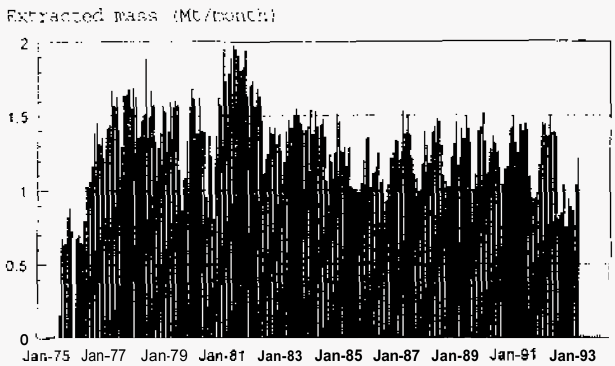
The commercial exploitation of the Ahuachapan geothermal reservoir started in 1975 with the first 30 MW condensing unit, followed in 1976 by a second unit of the same size. In 1981 an additional, double-flash unit of 35 MW was put on line, increasing the total installed capacity to 95 MW. During the exploitation period, a general productivity decrease of the field was observed, related with declining reservoir pressure and limited drilling of make-up wells. As a consequence, the power plant is presently utilized at an average load factor of only 45%. The Electric Agency of El Salvador (CEL) recently started a project aiming to stabilize the electricity production of the Ahuachapan power plant at the highest possible level, compatibly with the resource availability. In the frame of this project, a reassessment of the resource was carried out (ELC,1994a), focused on the development of a new numerical model of the reservoir, with the aim of providing insight into the probable reservoir response to new exploitation schemes and of supporting the techno-economical feasibility study of the proposed interventions (ELC, 1994b).

2. PRODUCTION PERFORMANCE AND RESERVOIR EVOLUTION

A total of 32 wells have been drilled in Ahuachapan in the period 1968-1981, out of which 17 have resulted to be producers, and 14 are presently in operation. Although the drilled wells are distributed over a 6 km2 area (see Figure 2), the productive wellfield is limited to about 1 km2

After an initial extraction rate increase from about 1,520 kt/month in 1977 (2x30 MW in operation) up to 1,840 kt/month in 1981 (commissioning of the 3rd unit), the average extraction rate progressively decreased to a nearly stabilized value of 1,100-1,300 kt/month in the last years (see Figure 1). The electricity generation accordingly decreased after the peak value reached in 1981, and since 1992 is being programmed to be limited to 375 GWh/year, corresponding to an average plant load factor of only 45%, and requiring an average extraction rate of about 440 kg/s). Initially, reinjection of residual water was carried out at variable rates (25-30% of the extracted fluid) in 5 wells (AH-2,8,17,29, and marginally AH-19). Due to observed thermal breakthrough effects in nearby wells, reinjection was suspended in 1982 , and since then almost all residual fluid is disposed of to the Ocean through a canal.

The present production performance of the wells is characterized by total flowrates ranging between 12 and 84 kg/s (at wellhead pressures 6-8 bar abs), with steam flowrates between 5 and 17 kg/s. The peak total production presently amounts to about 700 kg/s of fluid, providing 145 kg/s of medium-pressure steam and 42 kg/s of low-pressure steam. However, this extraction rate cannot be maintained continously, because it would lead to an unsustainable pressure drop in the reservoir. In fact, the adopted exploitation strategy is aimed to maintain a nearly constant reservoir pressure at the critical level of about 23 bar (at elevation +150 m asl), through the limitation of the mass extraction to 13,500 kt/year, corresponding to an average rate of 430 kg/s. This is obtained modulating the extraction on seasonal basis through the temporary shut-in of some wells, particularly those with lower enthalpy, having a higher total fluid specific consumption.



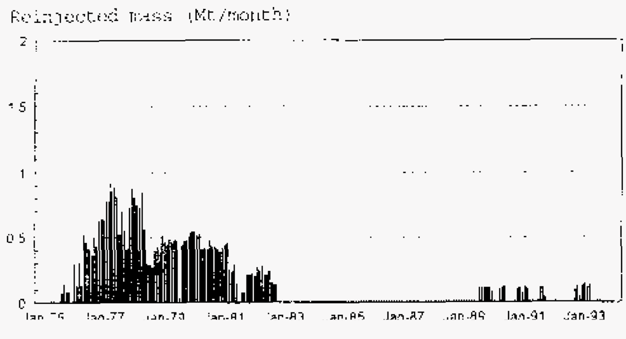


Figure 1 - Monthly extraction/reinjection (all wells)

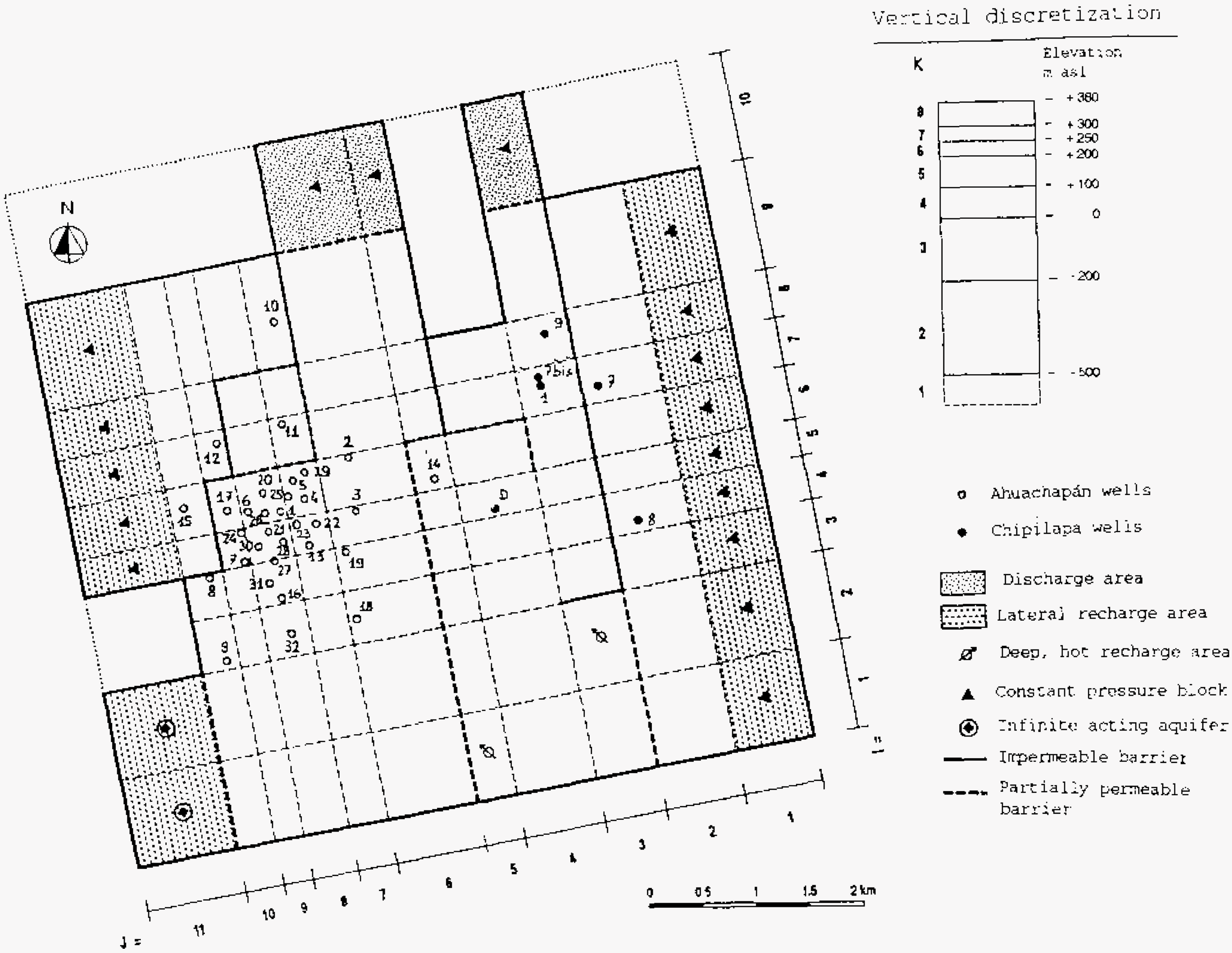


Figure 2 - Wells location, mesh geometry and model boundary conditions

The exploitation-induced reservoir evolution is mainly characterized by a strong decrease of the reservoir pressure in the period 1975-1982, followed by a tendency to stabilize at low level after 1982-1984, mainly as a consequence of the imposed extraction limitation (see Figure 3). Due to the high permeability of the reservoir, the evolution trend is nearly the same throughout the productive wellfield.

Disregarding localized cooling related with the reinjection activity in the period 1975-1982, the temperature evolution does not evidence severe cold water invasion until now, apart from possible indications in the northeastern part of the field ; however, geochemical variations in the fluid composition suggest the progressive draining of originally lower temperature waters from the East, heated up along their flow path towards the exploited area. For more details on the thermodynamic evolution of the reservoir during exploitation, see Steingrimsson et al. (1991).

The evolution trend of the discharge enthalpy is not homogeneous, and the wells can be grouped into a few groups of similar characteristics, related both to the location in the field and to the depth of the feeding horizons, namely:

. wells with constant or slightly decreasing enthalpy, with no or very limited excess steam (AH-1,7,19,21,24,28,31)
. wells with increasing enthalpy, up to conditions of high excess steam (AH-6,26,22,23)
. wells with irregular evolution (typically transient increase in the discharge enthalpy) and/or moderate excess steam (AH 20,27)
. wells producing nearly dry steam throughout the operation period (AH-17).

In the nearby Chipilapa field, about 3 km to the E-NE of Ahuachapan (see Figure 2), several exploration wells of commercial diameter were drilled in the period 1989-1992, encountering a reservoir of rather low temperature (ranging between 180 and 220°C); some of the wells (CH-7bis, CH-9 *and CH-D) exhibit* production characteristics of marginal interest, particularly due to the low wellhead pressure (< 5-6 bar); on the other hand, together with the sterile well CH-7, they show a moderate to high injectivity (in particular CH-7 and CH-D), which calls for their possible utilization as reinjection wells.

3. CONCEPTUAL MODEL

The heat source of the geothermal system relates mainly with the magmatic chamber of the volcanic complex Laguna Las Ninfas-Laguna Verde, some 3 km to the SE of the exploited field (see Figure 2). Along deep reaching faults, probably pertaining to the regional E-W/WNW-ESE system, an upflow of 250-260°C water takes place in an area located between the volcanic axis and the southern part of the exploited area. The reservoir is mainly constituted by a propylitized horizon, closely related with the lithologic unit of the Ahuachapan Andesites and exhibiting a marked lateral continuity. The thickness of this horizon ranges between 300 and 400 m in the exploited area, with its top laying at elevation +300-400 m asl in the central sector, deepening to +100-0 m asl towards the South and the East. Some permeability appears to extend also to the underlying Old Agglomerates. A sequence of volcanic agglomerates, affected by strong hydrothermal alteration constitutes the cap-rock of the system. For a discussion of the geological features of the field, refer for example to Aunzo et al. (1991).

The fluid circulation is basically controlled by faults and fractures, mainly related with the NNW-SSE neotectonic system, which act as preferential conduits. On the other hand, faults of the E-W and

NNE-SSW systems seem to limit the reservoir extension to the North and the West respectively.

Apart from fumarolic manifestations in the Ahuachapan and Chipilapa areas, the main natural discharge of the system is represented by the thermal manifestations of El Salitre, some 7 km to the North of Ahuachapan, which before exploitation start discharged 1,000-1,500 l/s of 68-70°C water, with an estimated 10-20% component of deep geothermal fluid (Aunzo et al., 1991).

Some degree of communication between Ahuachapan and Chipilapa seems to exist, although the deep hot recharge of the latter could originate from a different source, also located in the South, as suggested by geochemical data.

Reservoir temperatures are in the range 230-240°C in the center of the exploited area, with a small inversion in the deeper part of the reservoir, particularly in the SE sector (towards the assumed recharge zone), where the maximum temperature tends to increase, and to be encountered at greater depth. Pressure values in the undisturbed state were about 40 bar at a reference level of +150 m asl, without major horizontal gradients within the productive area, suggesting high horizontal permeability. Initially, the reservoir was essentially in liquid conditions, with the exception of a limited zone in the NW (around well AH-17) where a two-phase/steam cap already existed in the undisturbed conditions. This cap progressively extended due to the fluid extraction, and presently covers most of the northern part of the exploited area.

4. MATHEMATICAL MODEL

Extensive reservoir engineering activity has been carried out in the past on the Ahuachapan reservoir, including mathematical modeling (ELC, 1983; Ripperda et al., 1991). A new numerical model of the Ahuachapan reservoir, particularly oriented to the study of exploitation schemes, has now been implemented, based on the simulation code GEMMA, developed by ELC-Electroconsult. Figure 2 shows the adopted three-dimensional mesh, covering both the Ahuachapan and the nearby Chipilapa area, and extending to the South to include the assumed zone of deep, hot recharge (northern slope of the volcanic chain). The reservoir top is modeled at variable elevation, with a maximum of +380 m asl in the central part of the exploited reservoir, whereas the reservoir bottom is set to -500 m asl throughout the model: the total number of grid blocks amounts to 370.

At its E and NW borders, the geothermal reservoir is surrounded by a regional aquifer, with lower temperature and about 5 bar higher pressure potential, modeled by rows of constant pressure blocks, whose connection with the main geothermal reservoir is limited by hydraulic barriers of reduced permeability. On the other hand, at the SE corner of the model, the connection with an essentially "infinite-acting" aquifer has to be assumed, in order to match the observed behaviour during exploitation. Towards the North, a connection with constant pressure blocks represents the natural discharge of the system towards El Salitre. The other lateral model boundaries, as well as its upper and lower limits, are assumed to be impervious to both mass and heat flow: in particular, conductive heat exchange with the overlying cap rock is neglected.

Figure 2 also shows the location of the assumed totally and/or partially impervious hydraulic barriers. The essentially impermeable barrier limiting the Ahuachapan reservoir towards the North and the West can be noted, as well as the assumed barriers around Chipilapa, required to satisfactorily match the pressure distribution before and during exploitation, and creating a condition of "indirect connection" with the main Ahuachapan area.

The assumed permeability values are 160 mD for the main reservoir ("Ahuachapan Andesites"), 40 mD for the underlying formation ("Old Agglomerates"), and values as high as 1200 mD in the uppermost, central part of the reservoir, in order to match the behaviour of some wells with shallow feed horizons like the dry steam producing AH-17. Moreover, in the presently exploited zone and in its southern extension a 2x anisotropy factor in N-S direction has been assumed, in order to favour the recharge flow from S-SE. Apart from localized situations resulting from the matching procedure, the vertical permeability is set equal to the horizontal one. Porosity is assumed to be 12% throughout the reservoir.

The model has been brought to a "quasi-steady" state through stabilization runs of a few hundred years, leading to a steady state pressure distribution (Figure 4) coherent with the observations (about 40 bar at +150 m asl both in Ahuachapan and Chipilapa, small horizontal gradients within the drilled Ahuachapan sector). The temperature distribution is also essentially stable and fits the observed values. This represents the natural, undisturbed state of the geothermal system prior to exploitation, characterized by:

. two deep, hot recharges, located respectively to the SE of Ahuachapan (125 kg/s at 250°C) and to the South of Chipilapa (100 kg/s at 230°C);
. minor inflows from the SE and the SW (aprox. 50 kg/s each);
. a main discharge from Ahuachapan towards the N-NE (255 kg/s) and a minor one, also directed to the N, from Chipilapa (45 kg/s);
. minor surface discharges (about 20 kg/s) to account for the presence of hydrothermal manifestations in the modeled area.

The resulting flow path is shown in Figure 4: it is interesting to note that a part of the eastern hot recharge already flows towards Ahuachapan in the undisturbed condition: the flow towards Chipilapa results in fact from a mixing of the deep recharge with a lower temperature lateral inflow.

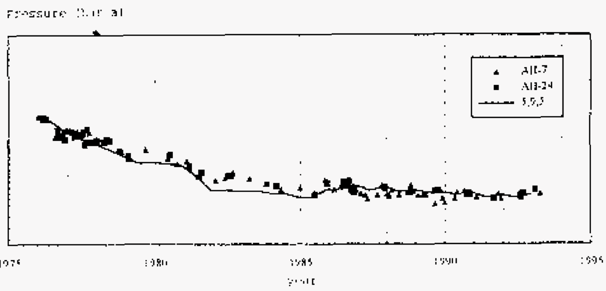


Figure 3 - Example of pressure history match

3. EXPLOITATION PHASE SIMULATIONS

5.1 Matching of past reservoir behaviour.

The model was calibrated matching the historical data from the exploitation period 1975-1993. The monthly data of mass extraction/reinjection of each well were utilized as input data, assigning the wells to the appropriate block (a maximum of two wells fall into the same block). Through variation of the hydraulic characteristics of the reservoir (permeability, barriers) and of the recharge/discharge conditions of the system (effect of the surrounding constant pressure and infinite-acting blocks), it was attempted to match the evolution of both the reservoir pressure and the discharge enthalpy of the producing wells: the latter essentially reflects changes in the reservoir temperature and/or the progressive extension of two-phase conditions in the reservoir.

The match of the pressure evolution resulted in general very satisfactory, with deviations between observed and computed values not exceeding 1-2 bar (see an example in Figure 3). The 1993 pressure distribution (Figure 5) shows a pressure low centered in the presently exploited area, with a good agreement with the observed values (about 24 bar at +150 m asl). On the other hand, the observed pressure trend between Ahuachapan and Chipilapa, with an intermediate high around wells AH-14 and CH-D, is correctly reproduced. This peculiar pressure distribution during the exploitation phase, together with the evidence of a pressure response in Chipilapa related with the extraction activity in Ahuachapan (present drop of about 10 bar with respect to the measurements in well CH-1 in the early '70), poses in fact an important interpretation problem about the kind of connection between both areas and about the flow path changes induced by the exploitation. It has to be assumed that the pressure drop in Chipilapa is related to a decrease of the fluid flow towards this field sector, after modification of the original, natural flow path, induced by the pressure drop in the exploited Ahuachapan area (see Figure 5).

The situation obtained for the year 1993 basically corresponds to a pseudo steady-state condition of the reservoir, with a mass balance between fluid extraction from the wells (about 440 kg/s), the hot recharge, the exploitation induced lateral recharge, and the strongly reduced natural discharge of the geothermal system.

The obtained match of the discharge enthalpy evolution of the single wells is considered acceptable, in spite of some inaccuracy in the reproduction of the behaviour of the wells with medium-high enthalpy (two-phase feeding of the wells). However, it is deemed

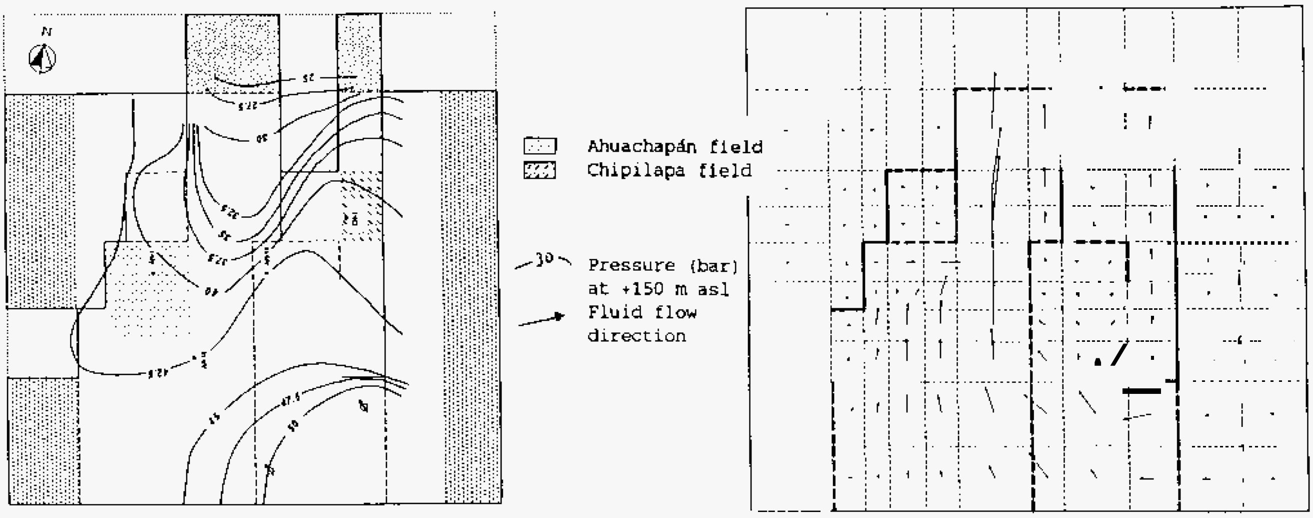


Figure 4 - Pressure distribution and schematic flow path (undisturbed state)

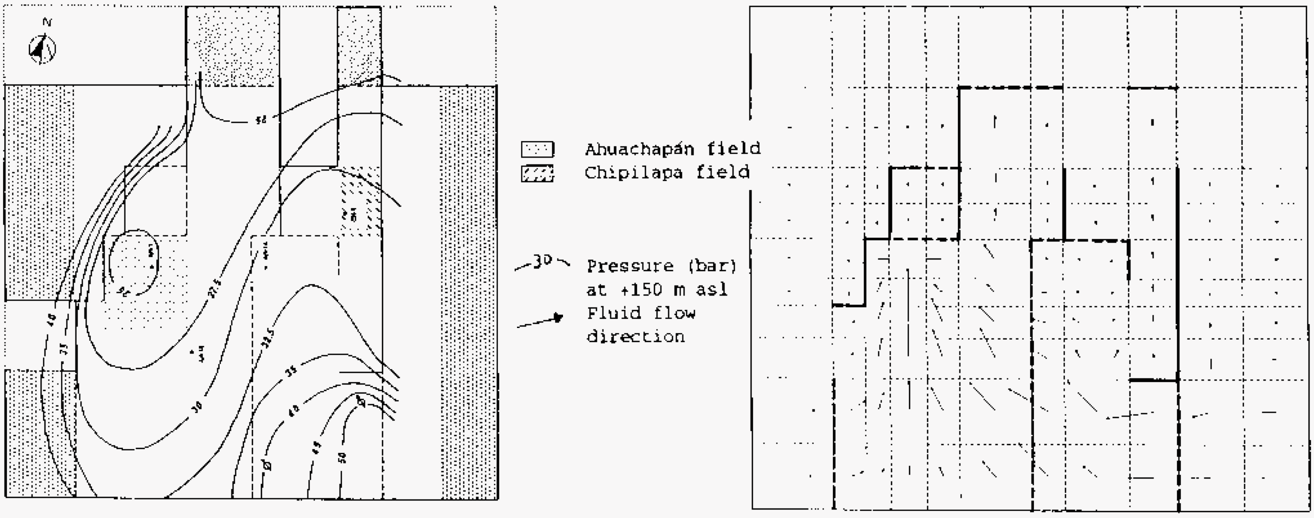


Figure 5 - Pressure distribution and schematic flow path (year 1993)

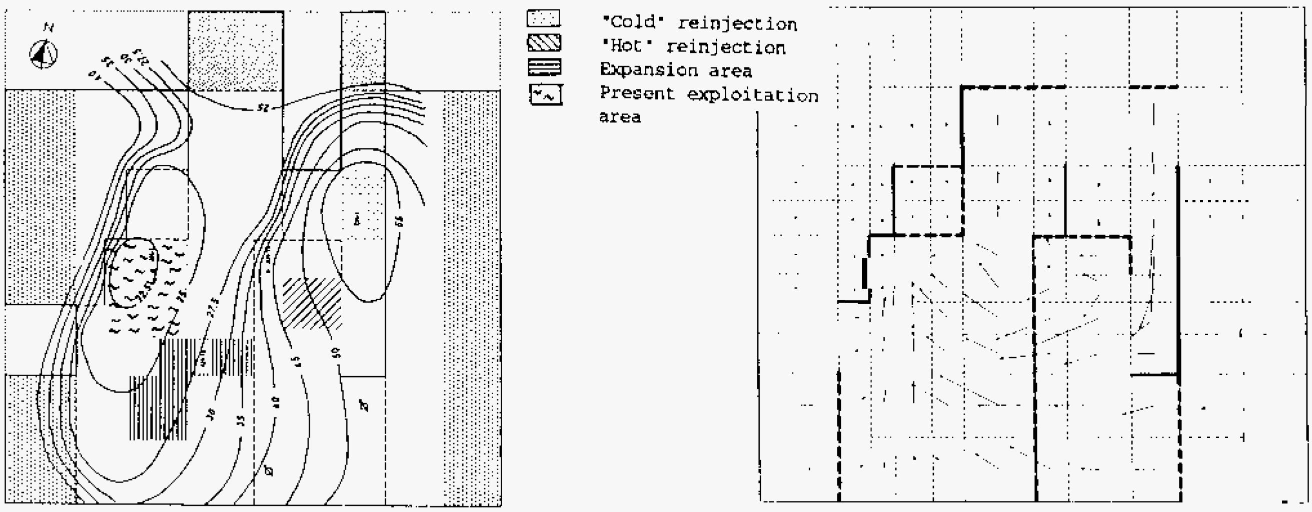


Figure 6 - Expected pressure distribution and schematic flow path (year 2010)

that this apparent limitation does not substantially affect the ability of the model to reproduce the future reservoir evolution, and its influence on the wells deliverability.

5.2 Forecasts of future reservoir behaviour

The calibrated model has been used to evaluate several alternative strategies for the future reservoir exploitation. For the forecast simulations, the extraction is defined in terms of available wells, rather than in terms of specified mass flow rate: to achieve this, the production characteristics of the existing wells and the expected characteristics of the future wells have been studied, examining with a wellbore simulator their relationship to changing reservoir conditions (pressure at feed level, enthalpy of the feeding fluid). Through appropriate interpolation tables and assigning each well to its specific reservoir block, the simulation model automatically calculates the deliverability of each well (at a prescribed wellhead pressure) and accordingly defines the related mass flow rate. The deliverability variation of the wells becomes therefore a direct output of the simulation runs, allowing a realistic evaluation of the future performance of the assumed wellfield.

Starting from the obtained thermodynamic conditions for the year 1993 (end of the matched period), following hypotheses were considered for the time span reaching the year 2010:
. continuation with the present exploitation strategy, without reinjection and without increase of the number of production wells or of their utilization factor (reference case);
. "cold" reinjection of the water from the second flash in the area of Chipilapa, with an increased extraction in the presently exploited zone (higher utilization factor of the wells);
. expansion of the extraction area towards the South, with drilling of new wells.

The simulation results suggest that:
. without the implementation of a large-scale reinjection program, the more intensive use of the existing wells or the drilling of new wells would only lead to a deliverability increase of very transient nature, being therefore unattractive. Only the replacement of existing, low enthalpy wells with new wells with higher steam fraction (maintaining basically the same mass extraction with a better energy conversion efficiency) could be envisaged;
. through the reinjection in Chipilapa of the second flash water (about 300 kg/s at 117°C), it appears possible to maintain in the future a nearly constant extraction rate of about 550 kg/s (about 20% more than the present rate), operating the existing wells with a higher utilization factor (80%, instead of the present 65%). The pressure level in the reservoir would remain essentially unchanged throughout the analyzed period.
Although the basic model could be rather optimistic in the evaluation of fluid return from Chipilapa (up to 80% of the injected water), sensitivity studies show that even a partial return as low as 25-35% of the injected water would limit the productivity loss until 2010 within 5-10% of the initial value (see Figure 7). Due to the large distance between the exploited area and Chipilapa and the type of hydraulic connection, avoiding a direct return of the reinjected water, no significant cooling effects are observed, so that the average discharge enthalpy would remain essentially unchanged;
. the expansion of the extraction area towards the South (see Figure 6) with the drilling of 6 new production wells would make possible an increase of the average production to 900-950 kg/s (with a wells utilization factor of 80%). However, maintaining this extraction level (with a decrease until 2010 limited to about 10% of the initial value) requires the total reinjection of the separated water (about 600 kg/s). The reinjection could partially be carried out in the conveniently located area of well CH-D (conveying there the water from the first-stage separation of the new wells, and reinjecting in "hot" conditions). However, with this exploitation scheme the simulation results (Figure 8) indicate a potential risk of adverse cooling effects in the production area. In fact, the most pessimistic cases analyzed to this respect (through the assumption of a finite coefficient of heat exchange between rock and fluid, corresponding to the hypothesis of a strong channeling of the returning fluid) show a parallel decrease of total flowrate (by 15-20%) and of the discharge enthalpy (by 50-100 kJ/kg), leading to a possible loss of steam production in the order of 40% at the end of the simulated period. This would be related in particular with the possible loss of some production wells in the expansion area, due to excessive wellhead pressure decrease. Although this represents extremely negative and rather unlikely conditions, a careful monitoring program should be set up, in order to face possible thermal breakthrough by modifications of the reinjection scheme (for example, moving all the reinjection to the northern Chipilapa zone). Make-up wells should be located in any case in the western part of the foreseen expansion area, in order to minimize the cooling risk due to the reinjection in the CH-D area.

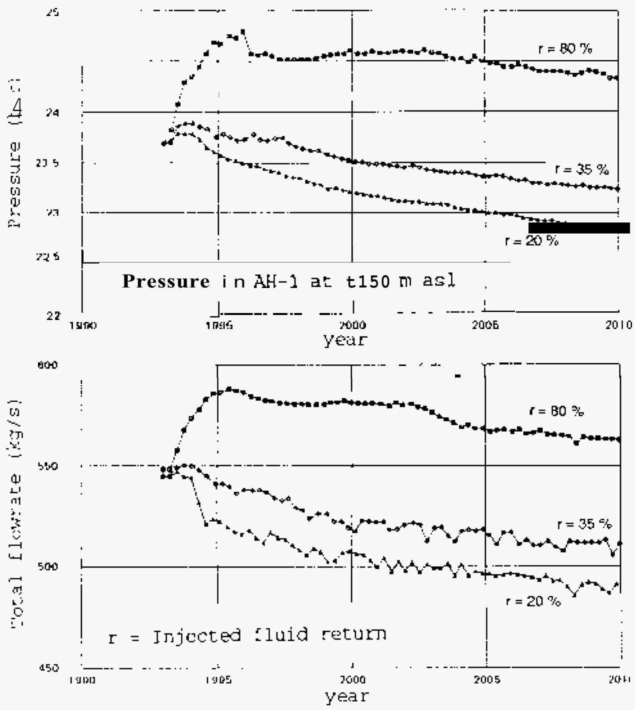


Figure 7 - Expected pressure and flow rate evolution with 300 kg/s reinjection in Chipilapa and 80% utilization factor of the present wells

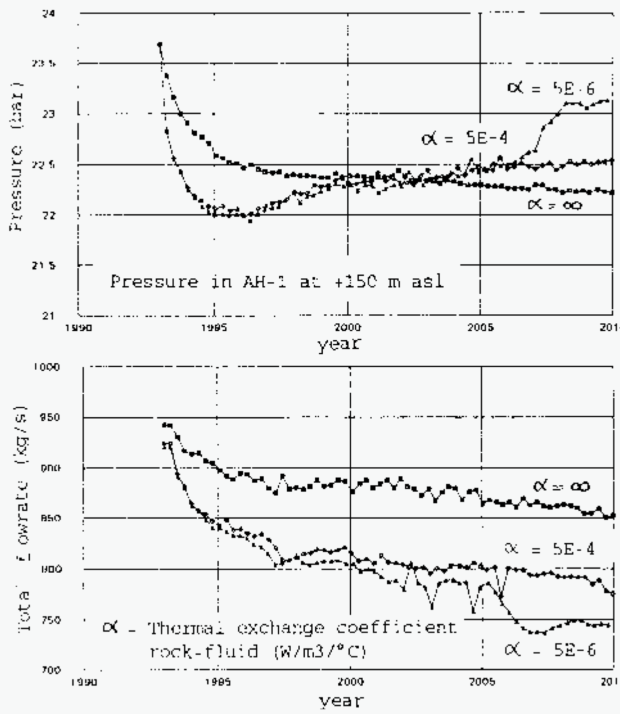


Figure 8 - Expected pressure and flow rate evolution with 600 kg/s reinjection (Chipilapa and CH-D area) and expansion of the extraction area

6. CONCLUSIONS

. The reservoir study has shown that only an exploitation strategy based on large-scale reinjection of the residual fluid will make possible an increase of the present extraction rate in the Ahuachapan field.

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The already available Chipilapa wells represent an excellent opportunity to implement the reinjection.

. With the presently available wells, a 20% improvement of the production could be obtained through reinjection of the second flash water in Chipilapa.

. A substantial increase of the extraction rate could be achieved through the southern expansion of the present extraction area, provided total reinjection of the residual water is carried out.

. If the positive expectations about pressure support through reinjection and productivity of the expansion area are confirmed, the power output of the installed plant could be substantially improved, approaching the rated capacity (up to 85-90 MW).

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