RESOURCE ASSESSMENT AT THE BERLIN GEOTHERMAL FIELD (EL SALVADOR)

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ABSTRACT

The drilling in the Berlin area of six deep, production diameter exploratory wells led to the discovery of a commercially exploitable geothermal field, with temperatures up to 300°C at a depth of 1800 to 2500 m. Conservative estimates of the reservoir potential, based on the results of simple mathematical models and on considerations about the "reservoir abandonment pressure", indicate a minimum proven potential of 55 MW. However, a probabilistic evaluation of the total field potential suggests that values as high as 150 MW can be considered as probable. Taking into account the results of the reservoir assessment, the installation of 2x25 MW, single-flash, condensing units has been decided. Moreover, a program of accelerated exploration is foreseen, aiming to a rapid development of any additional capacity in excess of the presently proven one.

1. INTRODUCTION

The Berlin geothermal field is located in the northern slope of the Berlin-Tecapa volcanic complex, 75 km to the ESE of San Salvador, capital of El Salvador.

Six deep wells, mostly drilled in the years 1978-1981, out of which four turned out to be good producers, proved the existence of a reservoir of commercial interest. In the beginning of the nineties, in the light of the accelerated growth of demand for electric power in El Salvador, CEL, the electric executing agency, decided to pursue the development of the field. To this aim, it installed two back-pressure units of 5 MW each and entrusted the consulting company ELC-Electroconsult with updating the feasibility study for the installation of a condensing plant.

This paper describes the results of the assessment of the geothermal resources of the field (ELC, 1993), conducted in the framework of the feasibility study (ELC, 1994a). Additionally, it presents a strategy aimed at a global development of the resources.

2. GEOLOGY OF THE AREA

The area of potential geothermal interest is located within a 20 km wide graben which runs in a general W-E direction, parallel to and enclosing the active volcanic axis of Central America. In the late Pleistocene a calderic collapse took place, originating from a highly explosive eruption from a stratovolcano which overlay a Tertiary volcanic basement (Figure 1).

The caldera has a 7x4 km elliptical shape and has been largely filled by recent lavic and pyroclastic products, showing evidence of magmatic differentiation. It is assumed that the heat source of the geothermal system is related with the magmatic chamber responsible for the post-calderic activity, as well as with the residual heat of the chamber that originated the caldera.

Several tectonic systems were recognized in the area. The most outstanding one trends NNW-SSE and affects even the most recent formations, controlling the distribution of the hydrothermal manifestations. This system originated a 3.5 km wide graben that is visible in the northern sector of the caldera, cuts its northern rim and extends several kilometers in the plain outside the caldera.

The geothermal fluids are located within a sequence of andesitic to andesitic basaltic lavas and of tuffs belonging to the Tertiary basement. The hydraulic behaviour of these formations essentially depends on the degree of alteration induced by the circulating fluids: the reservoir occurs in the propylitic zone, formed at temperatures in excess of 220°C, while the phyllitic zone, characterized by the abundance of chlorites, acts as the cap-rock of the system.

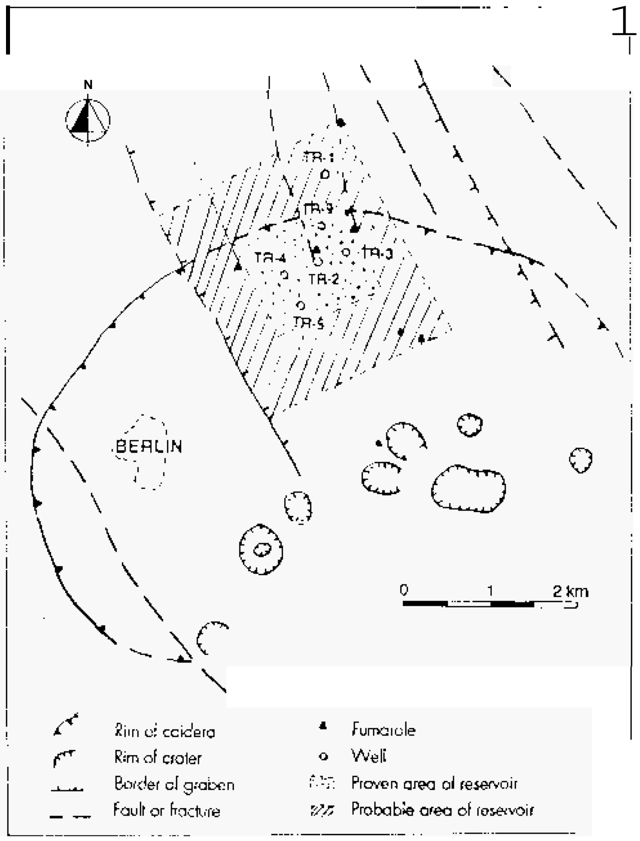

Figure 1 - Geological scheme

3. CHEMISTRY OF THE FLUIDS

The geothermal fluids exhibit a typical sodium chloride composition and, under reservoir conditions, have a content of TDS of 7,000 to 11,000 ppm and of silica of up to 700 ppm, with a pH of about 6. Non-condensible gases amount to 0.25-0.50% in weight of the steam for a separation pressure of 8 bar and contain 10% in volume of H_2S (Campos, 1990).

The high silica concentration constitutes a constraint for the exploitation of the field. It has been calculated that saturation conditions with respect to amorphous silica would occur for a separation pressure of 13-14 bar, while for a separation pressure of 10 bar the saturation index would amount to 1.1: this value was assumed as a threshold, beyond which significant phenomena of scaling in the separators, reinjection pipes and reinjection wells might take place. Accordingly, it was deemed advisable to adopt a single flash system, with a separation pressure of about 10 bar and hot reinjection of the residual water.

A weak oversaturation during flashing with respect to calcite occurs in some wells, pointing out the risk of calcium carbonate precipitation, to be verified by means of long term tests.

During the operation of the back-pressure units, magnetite and pyrite deposition was detected in the conveyance pipes and in the steam filters (Guidos, 1992). This deposition was interpreted as being related to corrosion phenomena within the producing well TR-2, due to the entrance of acidic shallow waters through a casing break. According to this hypothesis, the corrosion phenomenon would be local and temporary and would not affect significantly the commercial operation of the plant.

4. RESERVOIR CHARACTERISTICS

4.1 Thermodynamic Data

Within the investigated area, *temperature* increases rather regularly up to a depth of about 1 500 m, reaching at the top of the reservoir a value of 280-290°C. Further down, a moderate increase is observed up to the maximum values of 295-305°C, followed by a slight reversal in the bottom of the wells, with a decrease of 5-20°C with respect to the maximum temperature.

Both temperature and *pressure* tend to increase moving towards the SW of the field. In its undisturbed condition, the reservoir is in a *water-dominated* state.

4.2 Hydraulic-Textural Parameters

The main circulation losses during drilling usually took place in correspondence with the maximum temperature zones, although permeability extends beyond these zones. The following values of the hydraulic parameters were determined:

. Injectivity index: 1-2 (l/s)/bar
. Transmissivity: 1 D.m
. Productivity index: 0.4-3 (kg/s)/bar

These values point to an overall low permeability of the formations constituting the geothermal reservoir. However, the analysis of the field response to exploitation through the back-pressure units suggests a global transmissivity of the reservoir in the order of 25-35 D.m. This discrepancy might be due to the intersection by the wells of a few producing fractures, sharply limiting the useful thickness and hence the transmissivity of the individual wells.

An average porosity of 10.7% was determined in the cores, while the average grain density amounts to 2.6 g/cm^3 (Larios de Lopez, 1988).

4.3 Wells Productivity

The production characteristics of the 4 commercial wells are summarized in Table 1. It should be mentioned that the maximum discharge pressure of these wells is quite high, ranging between 20 and 40 bar.

Table 1 - Wells Productivity

Well	Total Flow (kg/s)	Enthalpy (kJ/kg)	% Steam	Steam Flow (kg/s)	Power (MWe)
TR-2	87	1350	28.9	24.8	11.9
TR-3	38	1280	25.0	9.5	4.6
TR-5	62	1370	29.5	18.3	8.8
TR-9	36	1300	26.0	9.4	4.5
TOTAL	223			62.0	29.8

5. CONCEPTUAL MODEL OF THE FIELD

The main heat source for the system is situated in the southern sector of the field. The heated fluids rise along deep fractures, probably belonging to the regional W-E system, and reach layers with widespread fracturing, being affected by intense neo-tectonic activity. The impervious phyllitic horizon restricts the movement towards the surface of the fluids, which tend to flow from the surge zone to the NNW, undergoing a gradual cooling (Figure 2).

The sector of maximum permeability, where the best conditions occur for the formation and development of the geothermal system, correspond to the intersection between the NNW-SSE graben of neo-tectonic origin and the caldera.

The area of potential interest was ranked in terms of probability for the existence of a commercially exploitable reservoir, on the basis of the results of the wells and of the geoscientific investigations (Figure 1). The *proven area*, identified as the zone directly tested by means of deep wells, covers a surface of 1.9 km^2. The *probable area*, identified as the zone associated with favourable structural conditions and with the presence of hydrothermal manifestations, covers a surface of 6.8 km^2. The *possible area*, identified as the zone included within the NNW-SSE graben, covers a surface of about 20 km^2.

Based on the evidences of permeable zones, the thickness of the reservoir is estimated to range between 800 and 1 000 m.

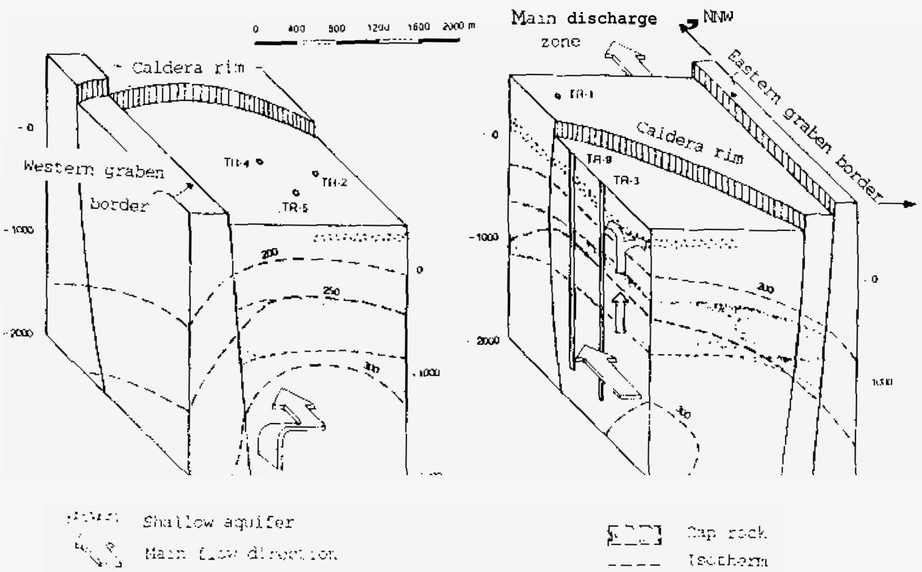

Figure 2 - Model of the field

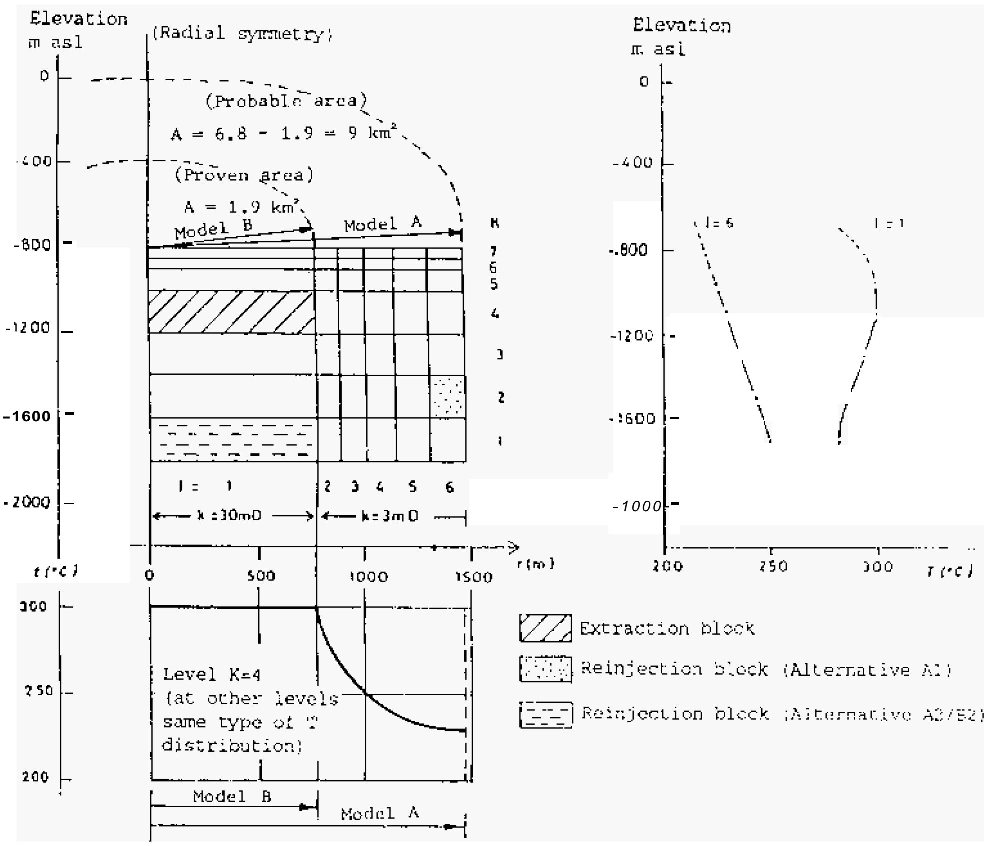

Figure 3 - Models for the evaluation of potential

6. FIELD POTENTIAL ESTIMATE

6.1 Proven Potential

The evaluation of the minimum proven potential was carried out through a simulation study, determining the maximum power whereby the reservoir pressure, at the assumed extraction level, exceeds throughout the useful life of the plant a specified pressure value ("abandonment pressure"). This value was established, based on the characteristics of a typical production well, as a function of the enthalpy of the fluid and of a M.D.P. adequate for guaranteeing the "operation of the wells" at a sufficiently high pressure. The adopted threshold value for the M.D.P. was 13 bar for the first 20 years of exploitation and 11 bar for the following period (20-25 years).

Two different, very simplified axisymmetric models were implemented in order to evaluate the reservoir response to exploitation (Figure 3); both models were very conservative in terms of productive volume and fluid reserves :

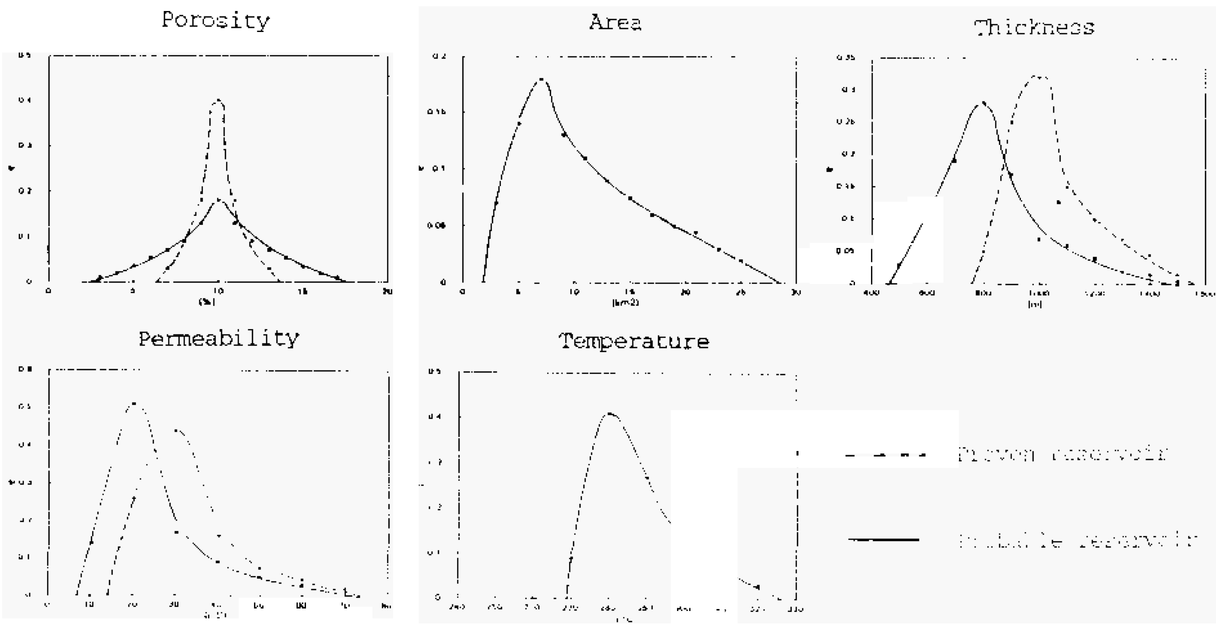

Figure 4 - Probability curves of the reservoir parameters

. Model A, covering an area equivalent to the probable reservoir extension, but with strong temperature decrease outside the presently proven area; and

. Model B, with an areal extension limited to the proven area.

Different reinjection schemes were hypothesized, including reinjection inside and outside the proven area, as well as the possibility that reinjection takes place in an unconnected aquifer (no return to the producing reservoir).
Through several simulation runs, the *minimum proven potential* was found to be 55 MW with a condensing plant, assuming a useful life of 25 years, a load factor of 85%, a specific consumption of steam of 7.5 kg/kWh and a separation pressure of 11 bar.

6.2 Probable Potential

The value of potential obtained through the above- mentioned models represents a minimum which can be substantially lower than the actual capacity of the field.

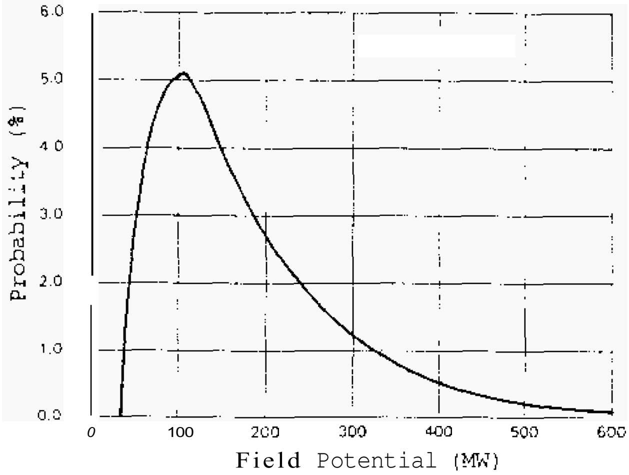

Figure 5 - Probability curve of the field potential

In order to evaluate the probable/possible potential, a probabilistic approach was adopted. On the basis of considerations on the possible extension of the reservoir (derived from the conceptual model) and on the parameters controlling its potential (essentially porosity, temperature and permeability), a probability curve of the global potential of the field was constructed, extrapolating the results of the simple models used for determining the proven potential by means of the Montecarlo method (Figures 4 and 5).

The study revealed a probability maximum around 100 MW ("expected value"), while there is a 50% probability that the total potential results to be in excess of 150 MW and only a 10% probability that it exceeds 350 MW.

7. FIELD EVOLUTION UNDER EXPLOITATION

7.1 Evolution of the Reservoir

The expected evolution of the reservoir under exploitation was investigated by means of a preliminary three-dimensional mathematical model, representing the conditions considered as "probable", in particular with respect to the areal extent of the reservoir (Figure 6). Therefore, this model differs from those adopted for assessing the proven potential of the field.

Initially, the model was adjusted to the *natural state* of the reservoir, establishing a thermodynamic undisturbed condition coherent with the actual observations (pressure and temperature distribution in the drilled area), varying the hydraulic parameters and the amount and location of the hot recharge and of the discharge of the system.

Several exploitation strategies were simulated (see an example in Figure 7), characterized by a different location of the reinjection zone in relation to the extraction zone. It was observed that the thermodynamic evolution of the area subject to exploitation essentially depends on the rate of extraction and only marginally on the reinjection strategy, provided that reinjection is carried out outside the caldera border, which seems to represent a barrier of limited permeability.

The risk of "thermal short circuiting", due to preferential flow along fractures of the reinjected water towards the exploitation area, was evaluated considering finite values of the heat exchange coefficient between rock and fluid. The analysis shows that, even in the most pessimistic cases, the negative effects of reinjection would be moderate, by virtue of the distance between the extraction and reinjection zones.

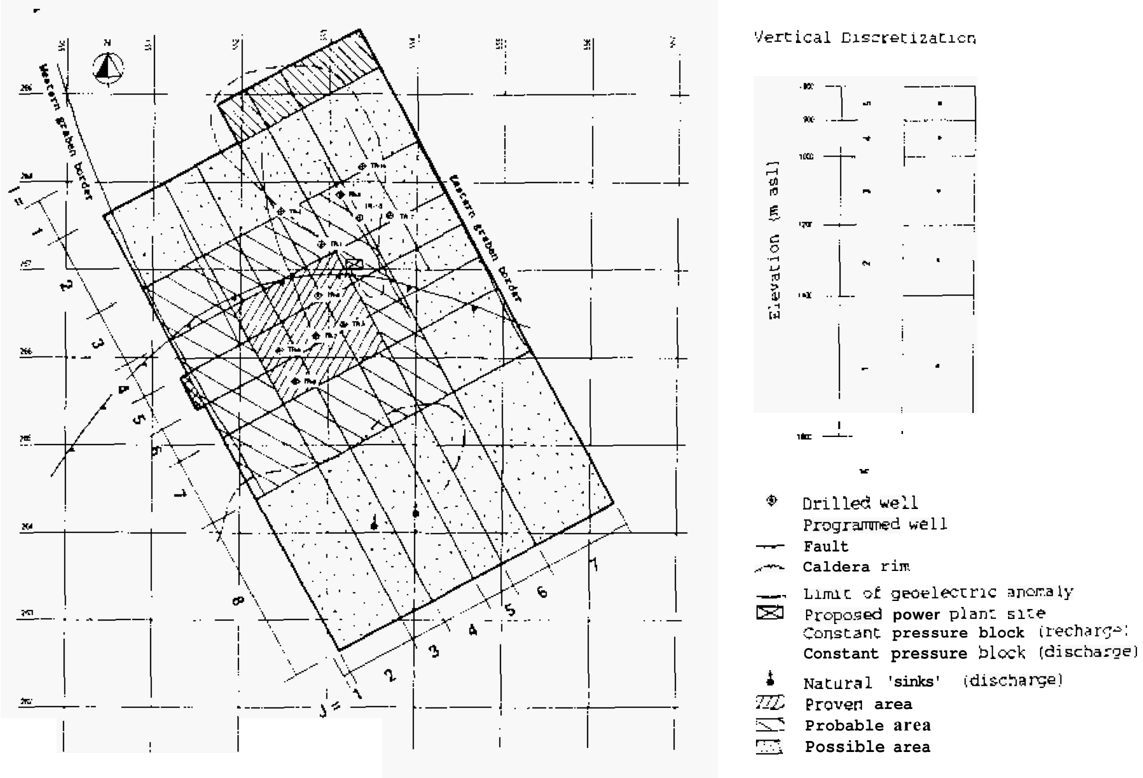

Figure 6 - Three-dimensional model

By assuming the installation and operation of a 50 MW power plant, the results of the simulation indicate that (Figure 8):

. The pressure drop in the reservoir remains within totally acceptable limits, being very sharp in the initial stage of exploitation (20 bar after one year), due to decompression of a single phase liquid, and quite gentle later on ("falling liquid level"). After a 25-year period of exploitation, the pressure drop in the reservoir within the exploited area is expected to amount to 35-40 bar.

. The average enthalpy of the extracted fluid remains almost constant, with no important phenomena of boiling at the assumed extraction level nor significant cooling due to reinjection.

7.2 Evolution of the Production Characteristics

The simulation of the reservoir behaviour under exploitation allowed to evaluate the future evolution of the production wells' characteristics.

It was assumed that the wells fall under two categories of high (type A) and medium (type B) productivity, for an average capacity of 6.5 MW, and that 10 wells are initially drilled to feed the 50 MW plant, thus allowing for a certain excess of available steam (3 wells in excess of the initial requirements). The simulation model indicated that (Figure 9):

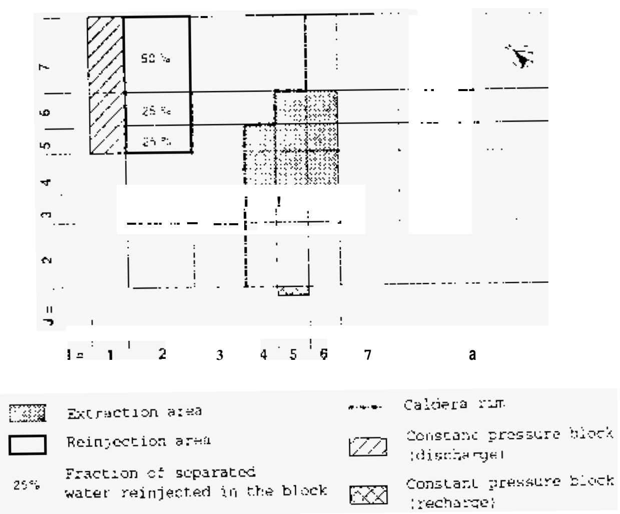

Figure 7 - Hypothesized exploitation scheme

. A pronounced loss of productivity, in the order of 15%, occurs during the first year of operation; later on, the productivity is substantially stable (average loss of 1%/year).

. The average enthalpy of the produced fluids slightly decreases with time, although this does not affect significantly the productivity of the wells.

. Two additional wells are to be drilled during the course of the plant operation, to make up for the productivity losses (not accounting for possible losses due to mechanical failures, or similar events not related with the reservoir performance).

8. CONCLUSIONS

The resource assessment that was conducted for the feasibility study of the Berlín geothermal field has proven a minimum potential of 55 MW. It also indicated a high probability for the existence of a potential of at least 100 MW.

On the basis of these results, the development of the resources is due to proceed along two parallel lines:

a. First Development

Large-scale exploitation of the proven potential in the shortest possible time is planned to begin by installing two single-flash modular units with a capacity of 25 MW each. The modular solution was selected in consideration of its higher flexibility of operation and the possibility of a further development of the field in smaller size steps.

The optimization of the units took into account, besides the environmental conditions, the thermohydraulic and chemical characteristics of the resource. In particular, an optimum range of 9 to 11 bar of turbine inlet pressure was identified, in view of the possible future installation of other units and of the constraints related with the high silica content.

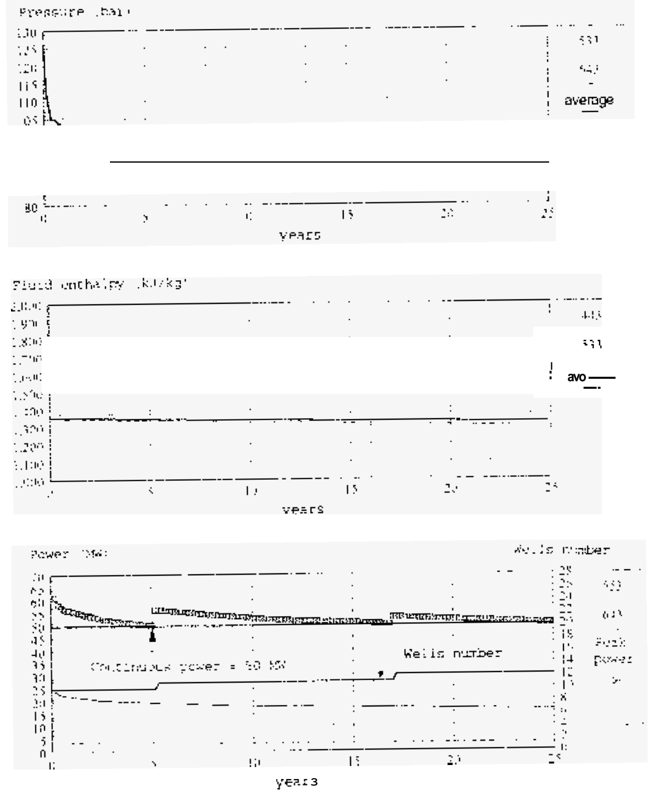

Figure 8 - Reservoir evolution with 50 MW capacity

Because of the rugged topography, and in order to minimize drilling related civil works and to optimize the well separation and gathering system, drilling of directional wells has been planned (3-4 wells per platform).

b. Future Development

The conceptual model of the field has singled out areas of priority interest, adjoining the sector of proven reserves, which are potentially suitable for the implementation of additional modular units with a capacity of 25 MW (ELC, 1994b). Within each one of these priority areas, 2-3 sites have been identified, suitable for drilling up to 4 directional wells.

It is proposed to drill exploratory wells in these selected sites. Should the outcome of any of these wells be favourable, the surrounding area has to be the object of a study aimed at verifying the technical and economical feasibility of installing a 25 MW modular unit. Any steam in excess to what is needed for the condensing units during operation can be profitably used for running one or more back-pressure units, until a new condensing unit comes on line.

This proposed strategy has the advantage of anticipating the electrical generation and of minimizing the risks and investments associated with the implementation of large-scale geothermoelectric projects.

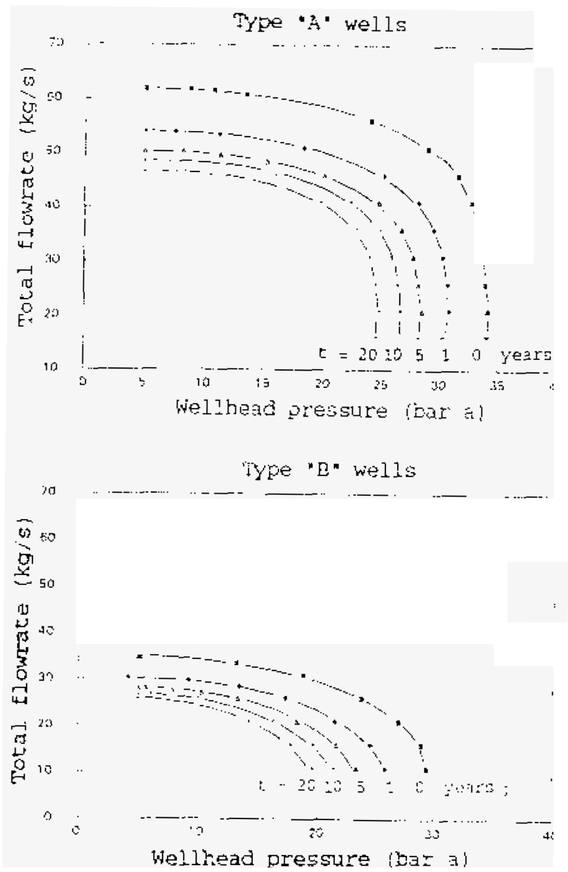

Figure 9 - Evolution of well production

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