ECONOMIC PLANNING AND DESIGN OF GEOTHERMAL ELECTRIC GENERATION IN EL SALVADOR

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ABSTRACT

Economic factors are the guiding principles for the ambitious development program of geothermal resources in El Salvador. The program includes the rehahilitation of the 95 MW Ahuachapan power plant. the installation of 50 MW at Berlin and the feasibility study for additional units at San Vicente. The accurate planning of the field-power plant system development. comhined with a design aimed at high efficiency, improve the economic competitiveness of geothermal vs thermoelectrical generation. in spite of the presently low cost of fuel.
The Ahuachapan study proved the technical and economical feasihility of the stabilization of the field production and rehabilitation of the plant efficiency, up to saturating the 95 MW total capacity of the three units The cosrihenefit ratio of the proposed interventions is particularly favourahle due to the availability of already amortized installed capacity, presently partially unexploited.
The Berlin field has a 50 MW proven and 100 MW probable capacity. The study showed that *the* optimum exploitation strategy involves the installation of 25 MW modular units. Flexible design is a determining factor to success. to he reached through the analysis of the unit performances during the field evolution. The optimum unit operation at variable pressure is defined hy design conditions identified as of "Maximum Efficiency". "Nominal Capacity" and "Maximum Capacity".

1. INTRODUCTION

The geothermoelectric generation in El Salvador dates hack to 1975, when the operation of the first **30** MW unit in the Ahudchapm field was started. **Three** units totalling 95 MW are presently in operation in Ahuachapan: however. the **actual** average capacity is limited to ahout 45 MW due to the decline of ihc reservoir thermodynamic paramerers. In the Berlin field two hack-pressure units of 5 MW each have been installed. and a third one is to he commissioned in 1994.

The economic planning and design of the exploitation of the country geothermal potential represents a **least** cost opportunity to increase the electric generation and meet the increasing energy demand. The following three geothermal power projects are underway:

. Stabilization of the production of the field-power plant system of Ahuachapan, including the recovery of the maximum eificiency and of the nominal generation capacity (95 MW):

Installation of 50 MW in the Berlin geothermal field:

. Exploration and feasihility study **of** the San Vicente geothermal field development, in order to rapidly install condensing unit/s.

The following design activities hare been fundamental to obtain the best economic results from the ahove mentioned projects:

Planning of the expansion of the electric system and assessment of the economic value of the geothermoelectric generation;

Analysis of the performance of the field-power plant system of Ahuachapan. study of new production/reinjection schemes and exploitation strategies. in order to obtain a stable long-term operation:

Optimization of the productivity and efficiency of the steam production in Berlin, including steam pressure **selection** and design of the fluid gathering system:

Selection of the turhine capacity and of the thermodynamic efficiency of the Berlin geothermal units: the units capacity depends on a co-ordinated planning of the field-power plant development. on availahle turhine standard sizes and on a capacity-efficiency balance;

Application of adequate flexibility criteria to the plant components design. in view of future adjustments of the plant operation **tu** cope with possible modifications in the fisld production characteristics.

High efficiency reduces the specific fluid consumption and contributes to reducing the environmental impact of the project.

There must he coordination hetween the reservoir engineering studies and the studies for the optimization of surface equipment to obtain a good quality project. A simulation program for the performance analysis of the combined system field-power plant was developed and adjusted during the performance analysis **of** the Ahuachapan plant. and was later utilized for the design of the Berlin power plant.

2. ELECTRIC GENERATION PLANNING AND ECONOMIC VALUE OF ENERGY

Effective **electric** capacity in El Salvador in 1994 is ahout 700 MW (total installed capacity 817 MW). of which 55% from hydro power plants, 35% from thermal power plants and 10% from geothermal power plants. To meet the estimated 7-9%/year demand increase in ihe next 10 years, ***the*** expansion of the generation system at a rate of 70-90 MW/year has been planned. The contrihution from geothermal sources should be about 115 MW, namely: 40 MW from the Ahuachapan rchabilitation: 50 MW from Berlin field: 25 MW from San Vicente field. Considering that utilization factor of geothermal plants is 0.9 on the average, the contribution of geothermal capacity to energy generation is almost twice as much compared to other power plant capacities.

The geothermal potential represents the least cost generating **source** for base energy; geothermal power projects are therefore planned with priority, reducing the construction time to the minimum allowed by the critical construction path. The second best alternative arc oil-firing steam thermoelectric plants.

The economic value of geothermd energy can he assessed through the avoided cost method. hy evaluating the overall cost of generation from alternative plants to he huilt in order to generate the same energy of the geothermal plant. In the electric system of El Salvador, fuel **oil** fired power plants constitute the **most** attractive alternative to geothermal plants. The average costs of thermoelectric base generation, shown below, represent the avoided **cost:**

Capital cost	US$/MWh	27.6
Operation and maintenance cost	US$/MWh	*6.2*
Fuel consumption **cost**	US$/MWh	21.2
Total generation cost	US$/MWh	55.0

Capital costs were calculated assuming a 25 years useful life and **a** 12%/year interest rate, plant factor 0.86. while the fuel consumption cost is hased on the present very low price of fuel oil (86 US$/ton). representing therefore a minimum prudential value

The optimum selection of the geothermal power plant capacity and efficiency. drilling strategy and planning of equipment installation is systematically based on the economic value of the capacity of generation and of steam production. Such value results from the avoided cost of 55 US$/MWh, considering a plant life of 25 years for Berlin and 15 years for Ahuachapan, a 12% interest rate and a plant factor of 0.90. The economic parameters calculated for each project are the following:

Project		Ahuachapan	Berlin
Geothermal power value	US$/kW	3000	3400
Value of M.P. Steam	US$/(kg/h)	338	230
Value of L.P. Steam	US$/(kg/h)	218	---

The differences in value depend on the different specific conditions; the value of the Ahuachapan medium pressure steam is higher since it can feed an already installed and presently unutilized power plant capacity. Investments to increase net capacity and steam production and to reduce steam specific consumption are justified when operation and maintenance costs are lower than the benefits ohlained. i.e. lower than the values indicated above.

3. PERFORMANCE AND REHABILITATION OF AHUACHAPAN

The stabilization project of the Ahuachapan geothermal system is aimed ai the expansion of the field pmduction and improvement of the plant efficiency.

Several interventions have been identified during the study. directed towards the achievement *of* the objective of increasing electric generation up tu the maximum installed capacity of 95 MW. These interventions include the rehahilitation of the power plant, the rehabilitation of some existing wells affected by severe mechanical or chemical problems. the adoption of massive reinjection of the residual fluid far to the East of the exploited zone. through which an artificial recharge hack tu the reservoir can he induced, and the development o f a new sector of the field. where prnduction wells are to he drilled.

Inefficiencies to be corrected hy plant rehabilitation are resulting from equipment wear. evolution of the *stem* characteristics (e.g. gas increase from 0.2% to 0.5% in weight of the steam). poor automation of the steam pruduction control, as well as from fined instead of variable steam pressure operation when the turbines arc operating at partial load.

The performance analysis has heen carried out with a computer program specially studied for geothermal projects. This program requires input data such as well production curves, characteristics of the separation and conveyance system, main parameters describing the equipment performance. The equipment design performances are utilized as a reference to calculate nominal performances and are later adjusted on the basis of specific tests. In this way actual equipment inefficiencies are singled out.

The program also allows fur the evaluation of the quality and reliability of the operation data indicated below and obtained at different times. in various plant conditions. hy different methods and sometimes with poorly calibrated equipment:

. periodical production tests of wells disconnected from the power plant:
. pressure. temperature and flow data measured on the separation and conveyance system:
routinarily measured power plant data and specific plant tests data.

The main identified inefficiencies causes are:

a. Steam entrainment in water lines between primary separators and flashers, presently amounting to ahout *2%* of water flow. with *stem* degradation from *6* bar to 1.6 bar. The rehahilitation pmcess provides for the adoption of manually adjustable variahle orifices for better control of the steam entrainment (less than 0.5% of water flow) and for the automatic control of the water level in the separators of the new wells to he drilled (total elimination of entrainment).

h. Pressure increase from 0.085 bar to 0.12 har (units 1 and 2) and to 0.095 (unit 3) in the condenser is due to the increased gas cuntent. A significant improvement can he achieved through the installation of a new hyhrid gas extraction system (liquid rinr pump combined with steam ejectors).

c. Steam throttling in the turbine regulating valves when the turbine is operating at partial load. The operation with reduced steam pressure while keeping the regulating valves fully open can improve the overall field-plant efficiency: pressure variation can he eased hy replacing the ejectors now in use. which arc not sufficiently flexible.

The proposed remedial measures hting about economic returns in a shun time. The overall efficiency increase has been assessed at ahout 2 MW/unit. when units are operating at full load.

Figure 1 shows the estimated benefits with respect to power generation, to he achieved through the implementation of the proposed interventions. The cumulative curves marked with a numher from 1 to 4 indicate the field productivity at different steam pressures:

1 - Present situation (average production capacity)
2 - Benefits uhtainahle from the plant rehahilitation in the present field conditions
3 - Benefits obtainable from reinjection and from reabilitation of the enisling wells
4 - Benefits ohtainahle from the expansion of the lield production

In the same figure power plant performance curves, with two or three units operating at the same time. are shown. The intersection of the power plant perfurmance curves with the field productivity curves indicate the best field-power plant equilibrium at variable inlet pressure

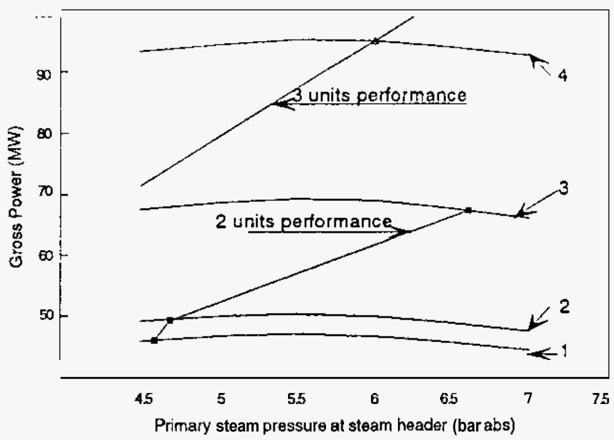

Figure 1 - Ahuachapan : Equilibrium between field productivity and units performance

4. BERLIN

4.1 Productivity and efficiency of steam production process

Silica content in the Berlin wells is relatively high (1000-1200 ppm in water separated at atmospheric pressure). so that saturation of amorphous silica is reached at ahout 13 har. To avoid silica scaling in the pipes and reinjection wells or to limit them to technically and economically acceptable levels, pressure ranges in normal operation conditions must always he higher than X har and preferably around 10 har: such a process involves one steam separation only. The impact of such constraint in the optimization of the steam production process is relatively small. heing prdctically limited to the loss of the second flash (ahout 15% of capacity), due to the fluid high enthalpy (1300kJ/kg) and high wellhead production pressures.

The study of the *stem* production process has taken into account hoth the initial conditions of wells production and the predicted evolution of the reservoir during the life of the field: as to the fluid gathering system. efficiency parameters in line with the results ohtained from the Ahuachapan plant have heen considered.

The pruductivity of 10 wells vs steam pressure in the most probable case of the field evolution is shown in Figure 2: the maximum production is ohtained at a steam pressure of X bar. Figure 3 shows productivity losses with steam pressure increase. Efficiency and efficiency variations (in terms of extracted mass specific consumption) vs steam pressure are shown in Figures 4 and *5:* it

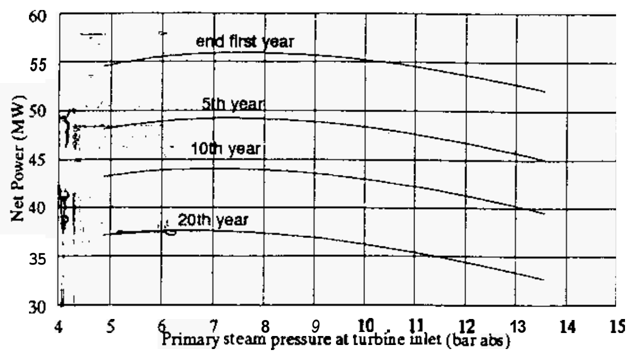

Figure 2 - Berlin : Steam productivity vs steam pressure

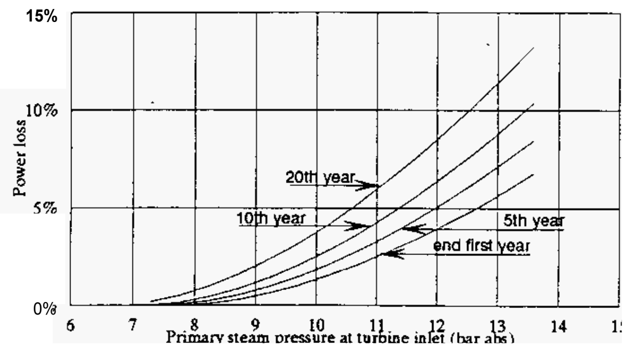

Figure 3 - Berlin : Productivity losses vs steam pressure

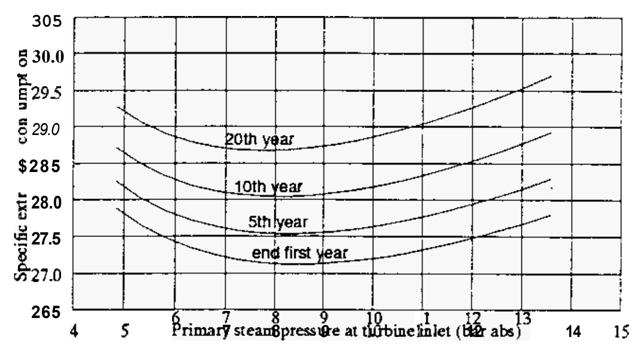

Figure 4 - Berlin : Power plant efficiency vs steam pressure

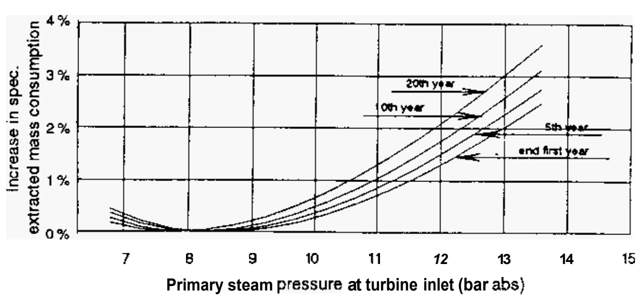

Figure 5 - Berlin : Power plant efficiency losses vs steam pressure

can he observed that the range of acceptable pressures (8-10 bar) falls close to the optimum **8** bar **value.**

The study proposed different layouts of separators according tu specific conditions: one separator for several directional wells placed on the same platform (Figure *6):* one separator for several wells on different platforms: one separator for each well. The automatic regulation of the water level in the separators and an optimum steam speed of **30** m/s in steam pipes are foreseen.

4.2 Unit types

The reservoir engineering study allowed to classify the field potential of Berlin as follows: 50 MW proven and immediately exploitable: 100 *MW* probable. to be verified with **future** feasibility studies. Such capacity can be profitably exploited by installing the following units. corresponding to standards proposed by different manufacturers:

. "modular unit" of about **25** MW capacity (Figure **7).** with single flow turbine, shop preassembled on steel skid. lateral condenser. simple buildings with one **floor:** (total of **4** units if 100 *MW* are exploited):

. "large sire unit" of about **50** MW. with two flow turbines mounted on concrete pedestal with condenser placed inside the pedestal, two floor powerhouse: (total of **2** units if **100** MW are exploited).

The first solution has following merits:

. better availability and reliability due to **the** higher numher of units, more operation flexibility. possibility of continued production in case of failure of one of the units;

. shorter delivery time and quicker assembling of the first two units. with possibility to plan further exploitation of the possible capacity in a gradual and modular way. Figure **8** shows three possible areas of field development according to the **25** MW modular units.

4.3 Modular units capacity, efficiency and flexibility

Both **25 MW** modular units and large size 50 MW units **are** among thc construction standards of most manufacturers. **A** reference solution based on modular turbine with exhaust size of ahout 3 m², last stage 22/23" bucket has been selected.

The optimization process of the unit can bc summarized in the following steps:

Definition of the steam nominal pressure at 10 har. with variation range 8-11 bar to allow for wide flexibility of operation at variable pressurc:

. Definition of the wet hulh ambient temperature for cooling tower design: **21** C corresponding to average values:

. Selection of the optimum volumetric steam flow at **the** turbine exhaust according to optimum exhaust losses: **630** m3/s at a 210 m/s speed;

. Calculation of capacity and efficiency (specific steam consumption in kg/kWh) with varying pressure in the condenser. **The** results are shown in Figures 9 and 10.

Each pressure value in the condenser implies a corresponding adjustment of the cooling system (water flow and cooling tower dimensioning) and of the gas extraction system, which have an impact hoth on the capacity and efficiency calculations and the cost estimates.

Efficiency improves (specific consumption decreases, **see** Figure 9) when the condenser pressure **goes** down to minimum values of abuut 0.07 bar. where consumption of the auxiliary system becomes predominant. On the contrary. the capacity **of** the selected turbine sire increases almost proportionally to the condenscr pressure (Figure 10).

The overall assessment has shown small economic differences in a range of **22 MW - 25** MW gross capacity values and of 0.085-0.1 bar condenser pressure. According to the economic results, it was deemed convenient to select flexible design criteria defining the operating range and the conditiuns identified as "Maximum Efficiency" (partial load), "Nominal Capacity", "Maximum Capacity" (overload).

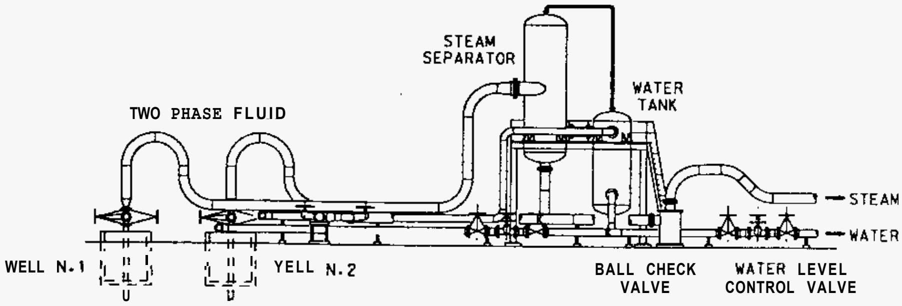

Figure 6 - Typical separation system arrangement for **two production wells**

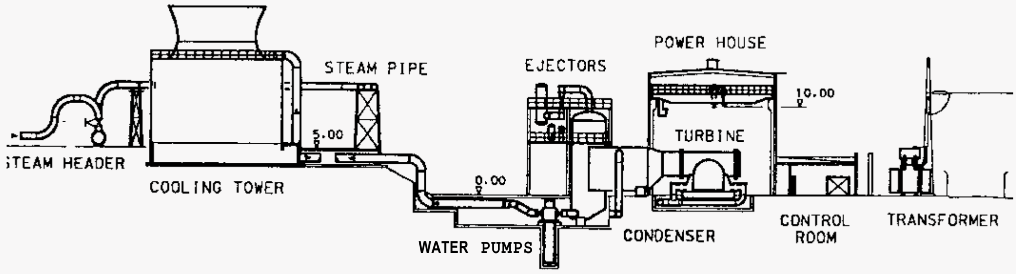

Figure *1* - Typical modular unit arrangement

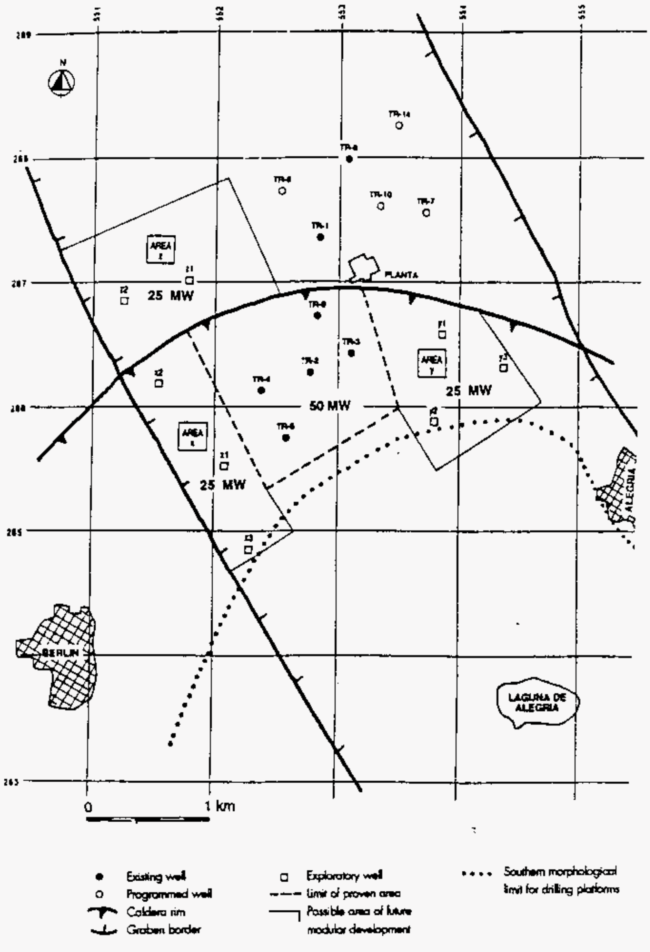

Figure 8 - Berlin : modular field development

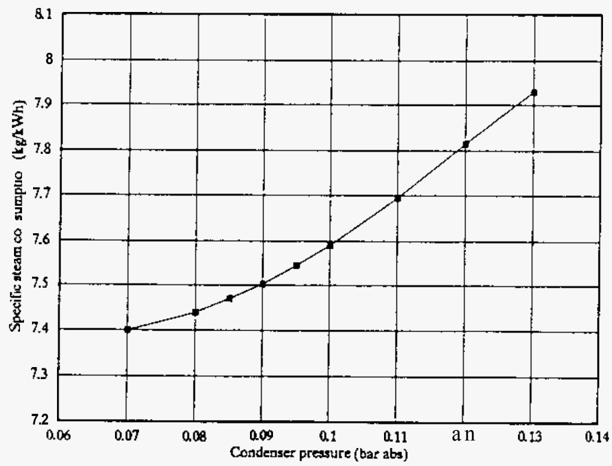

Figure 9 - Modular unit efficiency vs **condenser pressure**

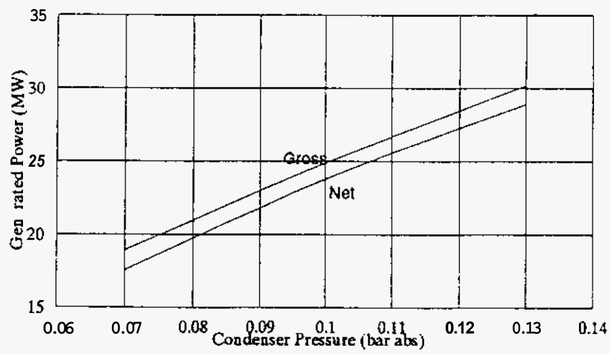

Figure 10 - **Modular unit** capacity vs **condenser** pressure

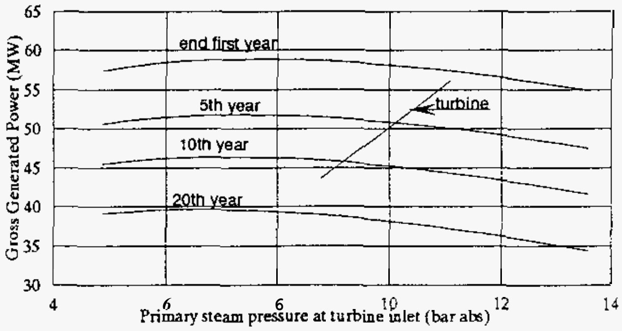

Figure 11 - Modular unit performance - Variable steam pressure

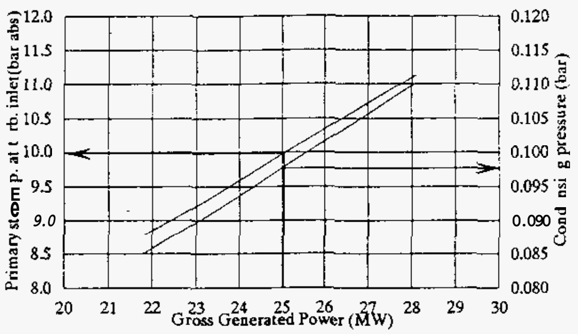

Figure 12 - Berlin : Equilibrium between field productivity and performance of 2 modular units

Table 1 - Units best operating range

Load		Partial	Nominal	Maximum
Gross Power	MW	22.3	25.0	28.0
Net Power	MW	21.0	23.7	26.7
Steam Pressure	bar	9.0	10.0	11.1
Steam Flow	t/h	160	177	200
Non Condensible Gas Content	%	0.4	0.4	0.4
Condenser Pressure	bar	0.087	0.980	0.110

The design data and the expected unit performance are indicated in Table 1 and in Figure 11. The design of all the plant components must comply with these conditions.

The advantages of flexible performance are indicated in Figure 12, where the field-plant equilibrium conditions at variable pressure are shown. During field exploitation the production from the 10 wells decreases: initially, the two 25 MW modular units can operate at maximum capacity, whereas in the following years the balance shifts towards nominal and partial loads with improved efficiency. After some years new wells are to be drilled, so that a well-balanced production is obtained again for overload conditions.