LATERADEVELOPMENTUPDATE

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ABSTRACT

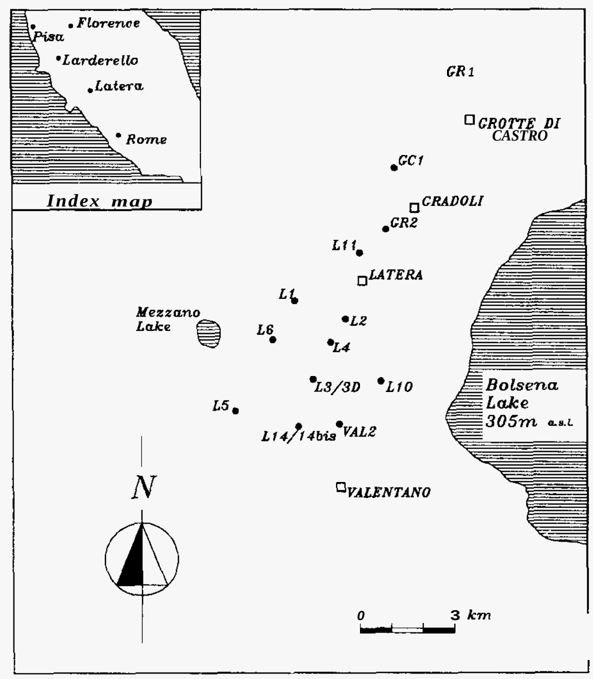
The development of the Latera water-dominated field is described in this paper, from the early exploration drilling to the commercial power plant design and construction (currently in progress).
The operation of a 4.5 MW power plant, supported by EEC financing, in the initial phases of the project allowed a good knowledge of the reservoir to be gained (areal extension, well connections and hydraulic bamers, ctc.), thus allowing further drilling to be addressed and the optimum exploitation strategy to be defined, e.g. production from the central par: of the field and reinjection to the northern margin.

1. INTRODUCTION

The Latera geothermal field is located in central Italy (about 100 km northwest of Rome), in the Monti Volsini volcanic region of northern Latium, west of Bolsena Lake. The water-dominated reservoir, mainly made up of carbonate and carbonate-siliceous formations of the Tuscan series, lies within a caldera of the same name and extends beyond its rim to the north-east.
The aquifer has temperatures in the range 190-230°C, with typical values of about 210°C. The enthalpy of the produced fluid (a two-phase mixture at wellhead) is around 900 kJ/kg, with a noncondensable gas (mainly C02) content of 3-6% by weight.
Details on the geology and the geochemistry of the field can be found elsewhere (Barelli et al., 1983; Gianelli and Scandiffio, 1989).
A map showing the location of the field and of the wells is reported in Figure 1.

2. FIELD DISCOVERY AND EARLY DEVELOPMENT

Geothermal research, carried out by ENEL, began in the early 1970s with regional prospecting that individuated a number of thermally anomalous areas, including the Latera caldera.
Subsequent studies and surveys led to the siting and to the drilling, started in December 1978, of two exploration wells (Latera 1 and Latera 2). The latter (with a total depth of 1395 m) was productive, thus demonstrating the existence of a water-dominated reservoir.
A production-reinjection test loop between these two wells was conducted to characterize the long-term injectivity (which unfortunately remained inadequate) of the Latera 1 well after a stimulation operation (both hydro-fracturing and acidification were performed) supported by the EEC.
Tests of scale inhibition were also performed, as the flashing brine showed a marked carbonate precipitation (Corsi et al., 1985).
A development project of the field was undertaken, with the aim of electricity generation. As a first step, two additional wells (Latera 3 and 3D) were dnlled in 1980 and 1981 with the financial conmbution of the EEC (contract GE 29/80/IT). The Latera 3D well was directionally drilled down to a total depth of 1369 m from the same pad site of the Latera 3 well (2485 m), whose temperature profile had suggested the presence of a nearby reservoir (Barelli et al., 1983). This well was highly productive.
It was thus decided, while the drilling of other wells was planned, to test the long-term behaviour of the reservoir with production and reinjection on an industrial scale. The installation of a power plant would allow the feasibility of electricity generation to be demonstrated and, at the same time, would offset the cost of the experimentation with the generated power.



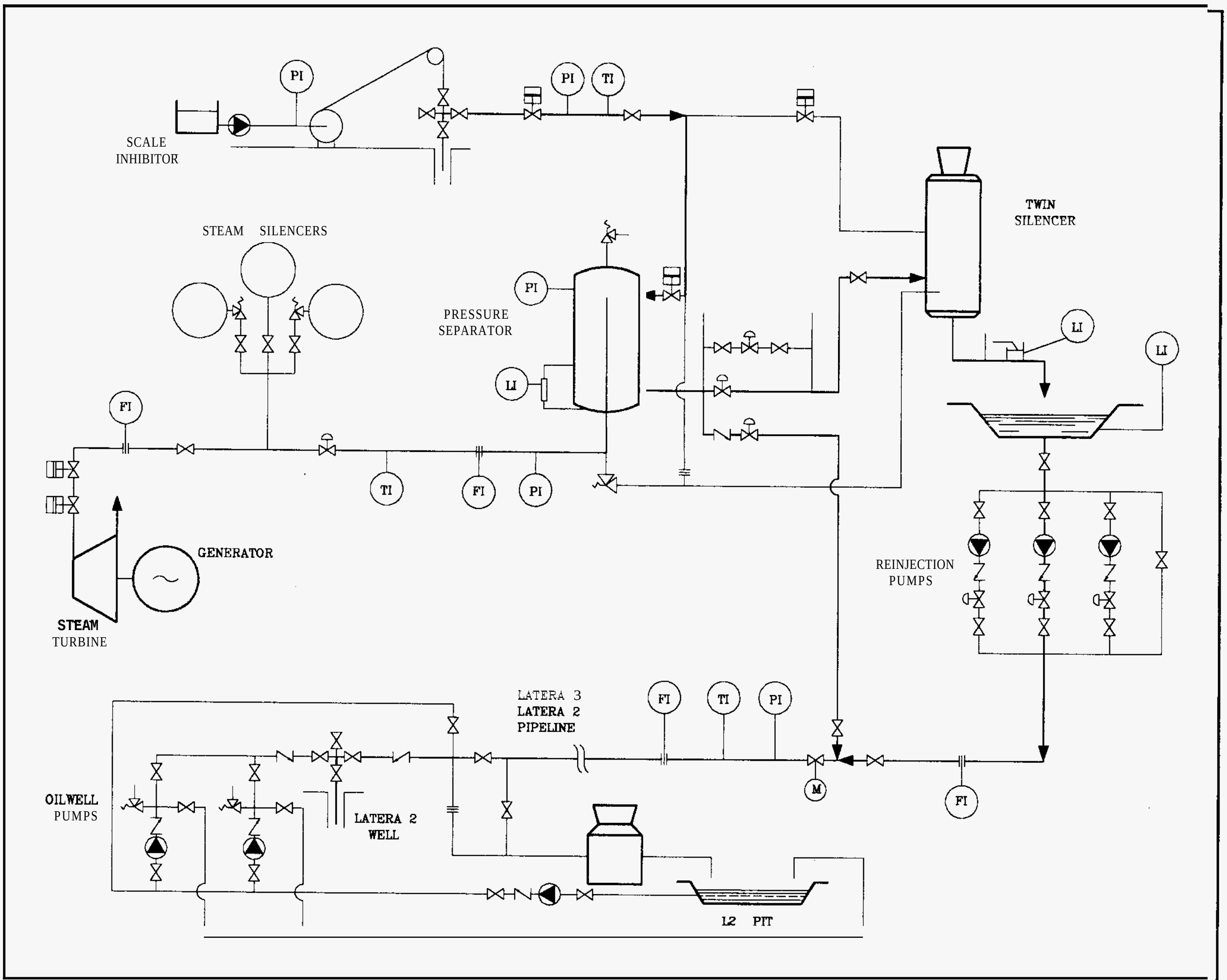
igure 1. Latera field and well locations

The Latera 3D well was preferred to Latera 2 for its higher flowrate capacity (due to the larger production casing at the wellhead, 13 3/8" vs. 9 5/8") and for the higher downhole temperature (230 vs. 210°C).
EEC financing was again obtained (contract GE/116/83/IT) for the construction of a 4.5 MW single-flash power plant and for the associated separation and reinjection facilities.

2.1 Latera 4.5 MW power plant

Various objectives had to be achieved with the operation of the plant, the most relevant being:
- resource characterization (both physical and chemical, including corrosion measurements);
- scale inhibition effectiveness and reliability;
- "hot" reinjection feasibility;
- equipment functionality and reliability.

Regarding this last point, it has to be noted that Latera was the first geothermal power plant installed in **a** water-dominated field in Italy and also the first outside Tuscany, where the "traditional" steam-dominated areas are being exploited.
The 4.5 MW power plant schematically represented in Figure 2 was installed in 1984 on the site of the Latera 3D well. It may be considered to consist of two interconnected main blocks: the equipment for the separation (with a bottom outlet cyclone) and the measurement of the geothermal steam-water mixture produced by the well; and the turbogenerator unit, featuring a discharging-to-the-atmosphere turbine which is fed by the separated steam.
These facilities were designed for a total geothermal fluid flowrate of 400-500 t/h.
The plant was monitored and operated by a control room, where the main measurements were continuously recorded.



gure **2.** Simplified flow diagram of the Latera 4.5 MW power plant

A scaling inhibitor downhole injection plant (with a capillary tubing) was installed and subsequently operated with satisfactory results (Pieri et al., 1988).

Latera tests, which followed those in Cesano, were the first successful operations of this kind reported, leading to the nowadays widespread practice of antiscalant injection in medium temperature water-dominated fields.

As there were no other suitable wells at the time, Latera 2 was chosen for the reinjection of the spent brine. It was connected to the pressure separator (via a pumping station) by means of an 18" diameter pipeline about 2.4 km long. High-pressure (10 MPa) pumps were installed to kill the reinjection well.

Through a bypass it was possible to reinject either the hot separated water or the spent brine after the atmospheric flash, or even a mix of the two streams.

2.2 Operational experience

Electricity generation began in November 1984. The maximum recorded gross power output was 3.2 MW, while the production **of** the first year totalled around 12 million kWh.

The pressure separator was operated between 10 and 12 bar (absolute), yielding a steam quality slightly over 10%. The separated steam had a high noncondensable gas content, as the produced fluid contained about 2.5-3% by weight of C02.

The scaling tendency of Latera 3D brine proved to be much less than that of Latera 2, so that, after the first tests, the inhibitor was injected at wellhead.

All of the three reinjection schemes (hot pressurized water, atmospherically flashed brine and a mix of these streams) were tested; continuous operation, however, was carried out with the mixed one, with approximately 80% of the flowrate coming directly from the pressure separator and 20% from the basin. The reinjection temperature was 160-170°C, thus minimizing the cooling of the Latera 2 well.

The reinjection was switched in May 1985 to a new well, Latera 14bis, specifically drilled to recover Latera 2 as a producer. The use of a provisional pipeline no longer allowed reinjection at high temperature, but rather only of the atmospherically flashed brine.

The reservoir behaviour was continuously monitored by means of the pressure interference with the field wells, where the static level was recorded.

With the aim of gathering further data, at the end of 1985 the surface installations were modified to allow the utilization of the Latera 2 well. Transportation of the two-phase mixture of this well to the power plant was thus possible by means of the pipeline previously used for reinjection (with minor adjustments). With this arrangement, the pressure separator could be fed by either the Latera 3D or Latera **2** wells, while reinjection was made into the Latera 14bis well.

The power plant was started again and operated for some months in 1986 and 1987.

Latera 2 proved to be fully recovered as a producer; successful downhole inhibition tests were carried out in this well (Pieri et al., 1988) and useful information (pressure drop, flow regime) was obtained by the operation of the pipeline in two-phase flow (Sabatelli, 1987; Andreussi et al., 1994).

Production from the Latera 2 well and reinjection in the southern part of the field (Latera 14bis) greatly increased the knowledge of the reservoir. It was in fact ascertained that the wells in the northern part of the field (up to Gradoli 1) were hydraulically well connected with the main body of the reservoir; at the same time the existence of a hydraulic barrier (between the Latera 4 and Latera **3D** wells), isolating the southem zone from it, was revealed. The Latera 3D well was

Table 1. Drilling results

Well	Depth [m]	Productivity [(t/h)/bar]	Injectivity [(m^3/h)/bar]	Max. flow rate [t/h]	Max. inj. rate with P_{wh}=0 [m^3/h]	Reservoir Temp. [°C]	Fluid	Electric Power [MW] (1)
L1	2796	0	0	0	0	—	—	0
L2	1394	70-300		500		210	—	9
L3	2485	~0.5	~1	30	50	210	water	0
L3D	1369	~70	~200 (2)	600		230		14
L4	1808	3	2-7	200		210	—	3
L5	2651	0	0	0	0	—	—	0
L6	2018	0	0	0	0	—	—	0
L10	2507	~0.1	1	~15		360	steam	1
L11	1399	>100		400		200	CO_2	0
L14	1790		~70 (2)		400	60-70	water	0
L14bis	455		>400	600	1000	170	CO_2	0
VAL2	1455		~70 (2)		~500	130	water	0
GR1	2260	40	~30	400	~600	190	water	5
GC1	3000	0	0	0	0	—	—	0
GR2	1901		60 (2)	600	1000	190	water	8

(1) Calculated for a double flash cycle
(2) After stimulation

found to be poorly connected with the other, more southern wells as well.
Moreover, the fluid produced from the Latera 2 well exhibited a higher NCG content, ranging around **4-6%** by weight, than the one from Latera 3D and (as was already known) a lower temperature (210°C, corresponding to an enthalpy of about 900 kJ/kg).
The interference measurements showed that the reservoir had a very poor recharge.
Microseismic control, continuously performed during the tests, did not show any problem associated with the reinjection of the spent brine in the wells utilized for that purpose.
As all the goals of the experimentations were considered satisfactorily met, including a comprehensive reservoir characterization, the plant was mothballed. This decision was taken because its operation was not as profitable as expected.
However, further field development was undertaken, together with the study of the power cycle to be adopted, in order to install a larger power plant of commercial size.

3. FIELD DEVELOPMENT AND POWER PLANT DESIGN

3.1 Drilling

As previously stated, the first two wells were Latera 1 (starting in 1978 and ending in 1979) and Latera *2* (1979-1980). They were followed by the two wells partly financed by the EEC, Latera 3 and Latera 3D (1980 and 1981).
With the aim of developing the field and checking the reservoir areal

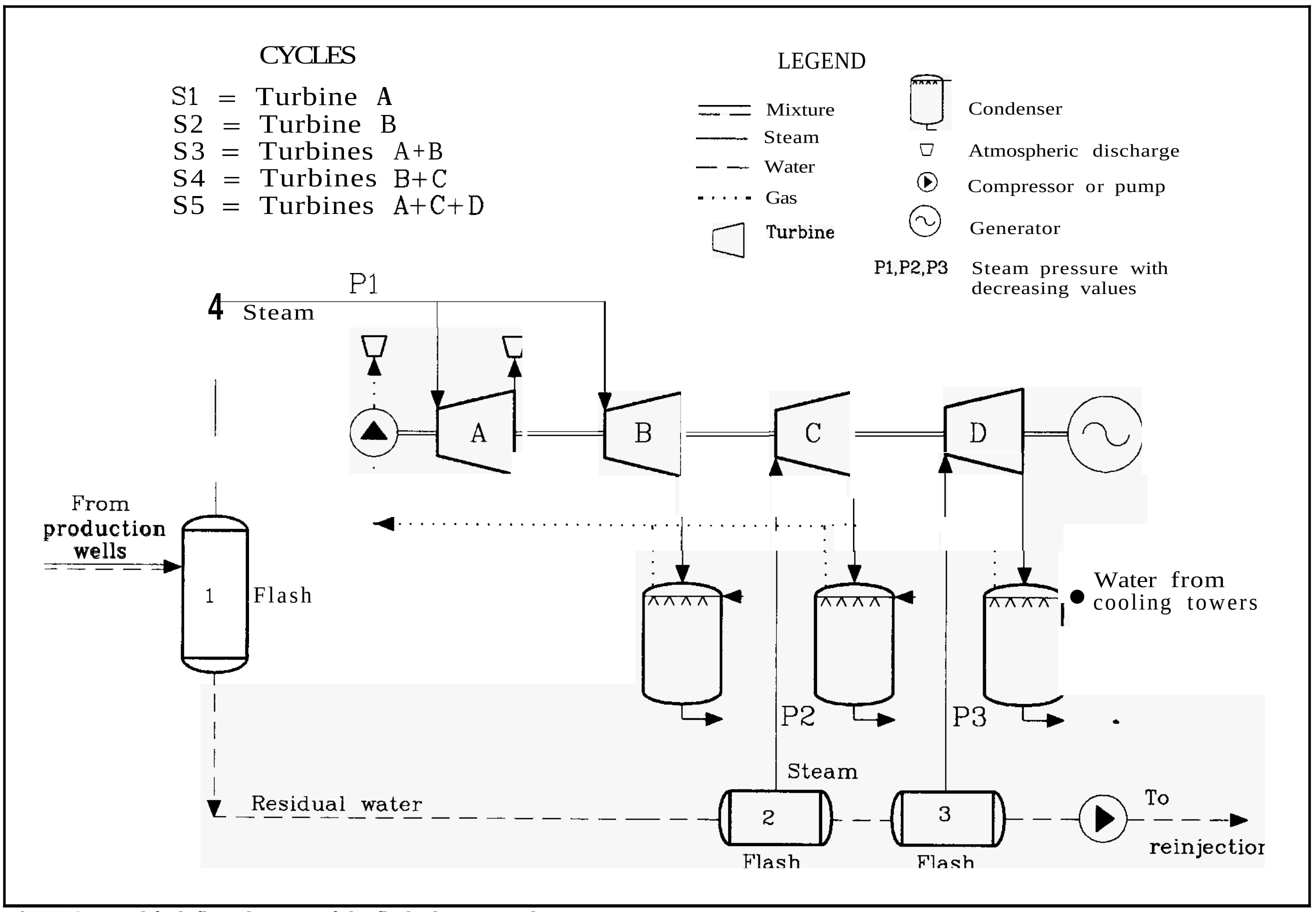
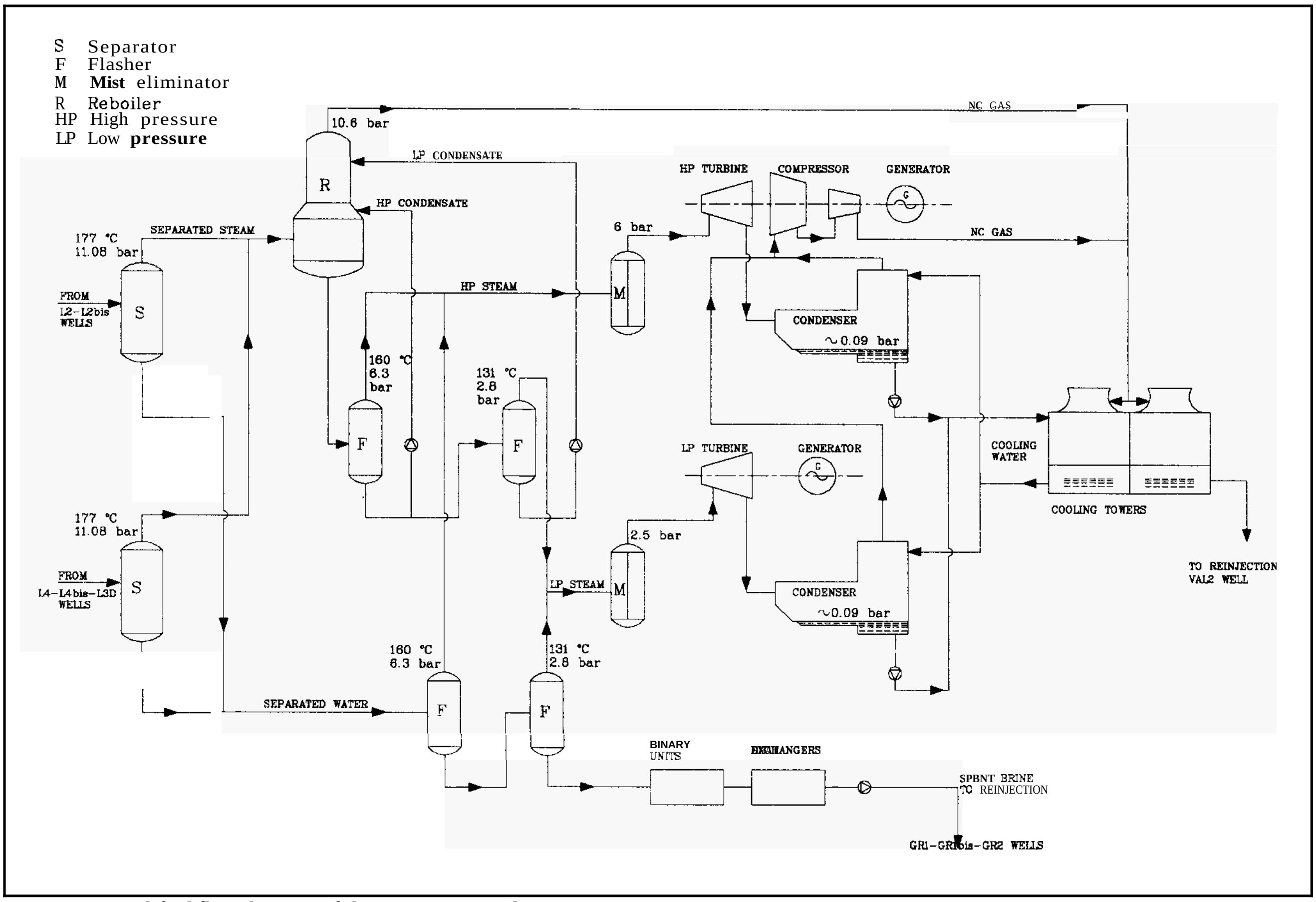


Figure 3. Simplified flow diagram of the flashed steam cycles



igure 4. Simplified flow diagram of the Latera power plant

extension, 11 additional wells were dnlled between 1981 and 198.5: Latera 5, Latera *6,* Latera 4, Latera10, Latera 11, Latera 14, Gradoli 1, Grotte di Castro 1, Latera 14bis, Gradoli 2 and Valentano 2 (see locations in Figure 1).

A total of 15 wells were thus drilled, with depths ranging from 450 to 3000 m, three of which were directionally drilled (Latera 3D, Gradoli 2 and Valentano 2). The dnlling results are summarized in Table 1.

10 wells out of 1.5 proved to be productive or suitable for reinjection. They were all located along the NNE-SSW axis of an uplifted structure constituted by a fold of the carbonate rocks (geological sections can be found in Carella et al., 1986). Latera 3 and Grotte di Castro 1 were in fact the only dry wells among those falling into this alignment.

The wells located in the southern part of the field (Latera 14 and 14bis, Valentano 2), shallower and colder than the others, are nevertheless permeable. Latera 4 was a poor producer, while Latera 11 produced only gas (mainly CO_2).

An attempt was made to check the existence of a deeper reservoir with hotter fluids near to the caldera rim, deepening a preexisting well, Latera 10 (and subsequently drilling Latera 10D) to a depth of over 3000 m, without success.

3.2 Reservoir studies

A feasibility study was undertaken (starting in 1986), together with reservoir assessment, in order to evaluate the sustainable production of the field and the optimum power cycle to be adopted.

On the basis of the knowledge of the geological structure previously mentioned, the reservoir was considered extending from Latera 14 to the south to Gradoli 1 to the north, with a width of about 1.5 km, thus covering a surface area of around 20 km^2.

The reservoir volume was discretized into blocks of different permeability, with estimates based on the results of the production-reinjection operations and interference measurements.

The highly permeable zones were characterized by a strong anisotropy, the permeability being much higher along the major axis (directed NNE-SSW) of the structure and in the vertical direction than trasversally (in the WNW-ESE direction).

Preferential flow paths thus exist along the structure axis.

Initially, it was planned to produce from the wells placed in the central part of the field and to reinject in the wells located both at the southern and northern ends.

The results of the 4.5 MW power plant operation that were being obtained in the same period, in terms of reservoir characterization, as these findings were incorporated in the model, made some changes necessary, however. The major change, due to the discovery of the hydraulic barrier mentioned in the previous chapter, was the decision to switch the reinjection of all the spent brine to the north, the wells at the southern end of the field being usable for the separate reinjection of the aerated excess condensate from the cooling towers.

In order to avoid thermal breakthrough, taking into account also the marked anisotropy of the reservoir, it was decided to reinject the spent brine in the area of the Gradoli 1 well.

The results of the modelization (carried out using SHAFT79 and MULKOM codes) showed that an overall production rate of 1500 t/h of water was considered sustainable by the field for at least 25 years, the economic life of the plant. In order to make this flow rate available, it was planned to use the Latera 2, Latera 3D and Latera 4 wells and to drill two more wells (to be named Latera 2bis and Latera 4bis) near to them, both to be completed with a $13^{3}/_{8}$" casing.

The Latera 3D well, drawing from a smaller and hotter reservoir substantially isolated both from the main body of the reservoir and from any potential reinjection zone, was expected to exhibit a marked decline of production, making it usable for perhaps only ten years, when the possibility of drilling make-up wells will be evaluated.

A further well, Gradoli Ibis, had to be drilled similarly to allow the reinjection of the overall spent brine flow rate, due to the injectivity limitations of the Gradoli 1 well (caused by its casing layout and local permeability).

3.3 Cycle selection and power plant design

The brine produced by the Latera reservoir is characterized by an unusual high NCG content which, despite enhancing the production rate of the wells (by gas-lifting effect), is a substantial drawback in the power cycle.

The estimation of the NCG production trend was thus of paramount importance for the selection of the optimum power cycle, even if major uncertainities might affect this kind of evaluation.

The result of the reservoir study was an expected mean flow rate of NCG of around 70 t/h for at least 8 years, i.e. the average time expected for the reinjected water to again reach the production wells.

Moreover, the selected cycle had to be flexible enough to deal with the notable changes in the characteristics of the produced fluid (mainly NCG content) which are possible during the exploitation of the field and affected by major uncertainities.

The feasibility study took into consideration the following flashed steam cycles (binary cycles being considered at that time appropriate for "bottoming", i.e. cascade utilization of the flashed water only):

S1 - single flash, noncondensiug;
S2 - single flash, condensing;
S3 - double flash, noncondensing *HP* turbine and condensing LP turbine;
S4 - double flash, condensing;
S5 - triple flash, noncondensing *HP* turbine, condensing MP and LP turbines;
S6 - double flash with upstream NCG removal by means of a direct-contact reboiler.

***Table* 2.** Comparison among cycles performances (values relative to the scheme S4)

CYCLE	S1	S2	S3	S4	S5	S6
Specific power	41	67	83	100	91	105
Specific equipment cost	97	103	84	100	94	96

The simplified schemes of cycles **S**1 to S5 are reported in Figure 3, while cycle **S6** is shown (in greater detail) in Figure 4.

The performances were evaluated for all the cycles, taking into account the reservoir evolution (Allegrini et al., 1989). Table 2 summarizes the results obtained, in terms of specific power (the reciprocal of the total fluid specific consumption) and equipment cost (surface equipment and power plant), expressed as a percentage of scheme S4 (taken at a value of 100). A cycle employing surface reboilers was also considered and discarded, as its power output was comparable with that of cycle S6, but it required a much higher investment cost.

It can be seen that cycles S1 and S2 are characterized by a poor thermodynamical efficiency (as expected), while the greater complexity and cost of cycle S5 with respect to S4 are not reflected by a comparable increase of power output. A more detailed analysis of cycles S3, S4 and **S6** was therefore performed, considering the characteristics of the standardized machinery used by ENEL in steam-fed geothermal power plants (Allegrini et al., 1985).

Table 3. Thermodynamic analysis (with standardized machines)

CYCLE	unit	S3	S4	S6
Total flow	t/h	1500	1500	1500
NCG amount	t/h	33.5	33.5	33.5
Separation pressure	bar	10.7	10.7	10.7
HP turbine inlet pressure	bar	10.3	10.3	6.1
HP steam flow	t/h	107	107	138
HP gas flow	t/h	33.5	33.5	2.0
HP steam + gas flow	t/h	140	140	140
LP turbine inlet pressure	bar	2.8	2.8	2.3
LP steam flow	t/h	125	125	105
Gross electric power	MW	22.8	27.0	29.4
Net electric power*	MW	21.2	24.6	26.3

* Including the auxiliaries of the surface equipment

According to the results shown in Table 3, cycle ***S6*** was chosen, having the best performance even at the low NCG average flow rate assumed and the highest flexibility to cope with variations of NCG content in the brine (difficult to accomodate with the adoption of a centrifugal compressor of very large size needed in cycle S4).

The net power output to the grid of around 26 MW could be increased by approximately 4 MW with the addition of binary units fed by the spent brine to be reinjected, for which a seasonal direct-heat utilization is also envisaged (Figure 4).

It is worth mentioning that the Latera power plant is the first application in the world of the reboiler concept on a commercial scale.

Following the cycle selection process, power plant design was carried out and the permitting process started, together with the execution of the environmental impact studies. In the meantime, ENEL, formerly the operator of a joint-venture with AGIP in the Latera area, took over the whole property of the field.

The drilling of the additional wells (Latera 2bis and 4bis, Gradoli Ibis) needed to make the design production and reinjection flow rates available was successfully completed in 1992. Due to unforecasted delays in obtaining the necessary authorizations, the construction activity started only in mid-1993 with the site preparation work. The power plant is expected to come on line in 1996.

4. CONCLUSIONS

EEC financing in the early stages of the development (both for the drilling of two wells and the construction of the 4.5 MW power plant which allowed a comprehensive field testing) proved to be a very helpful contribution to meet the final goal of the project.

Drilling and production-reinjection results were in fact used both to address further drilling and as inputs for the reservoir modelization. In their turn, model results were used to compare different exploitation cycles, among which the most efficient and flexible was chosen.

The Latera field development may be considered a significant example of the way a geothermal venture has progressed from the early exploration drilling to the power plant construction. The complexity of the reservoir structure and the time-consuming permitting process both contributed to the unusual length of the development process.

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