FIFTEEN YEARS OF REINJECTION IN THE LARDERELLO-VALLE SECOLO AREA: ANALYSIS OF THE PRODUCTION DATA

Guido Cappetti, Luigi Parisi, Angelo Ridolfi and Giancarlo Stefani

ENEL S.p.A. - DPT VDT/G, Via A. Pisano 120,56122 PISA - ITALY

Key* words: *Larderello, Reinjection, Secondary heat recovery.

ABSTRACT

Intensive exploitation of the Larderello-Valle Secolo area has gradually depleted the fluid inside the reservoir and caused the reservoir pressure to fall to about 0.5 MPa, although the reservoir temperature remains 240-250°C. Under these conditions a large fraction of themial energy remains stored in the reservoir rocks.
Water injection tests in this "superheated" area started in 1979 and demonstrated that an enhancement of heat recovery through the boiling of injected water is feasible.

Starting in 1984, reinjection **of** waters discharged from power plants became an important part of the exploitation strategy for this area. Analysis of the well production parameters confirms the positive effects of reinjection with a significant increase in steam flow-rate and reservoir pressure.

In light of the positive results, a supplementary injection program was planned and put into operation in 1994 in order to increase secondary heat recovery in the Valle Secolo area.

1. INTRODUCTION

Reinjection was begun in Larderello in the early 1970s to dispose **of** the steam condensate discharged from the power plants, in compliance with new environmental legislation.
The fear that lengthy injection of cold water might damage the field production characteristics led to the choice of wells located relatively far from the exploitation areas, in marginal zones which were already affected by the inflow of meteoric waters toward the geothermal field.
Later on, however, studies and field tests were begun in order to check the possibility of using reinjection to recover the thermal energy stored in the reservoir rocks, paying special attention to those areas characterized by high permeability and by a high degree of superheating of the steam inside the reservoir (Giovannoni et al., 1981).
Of several examined areas, Valle Secolo was the most promising.

2. CHARACTERISTICS OF THE VALLE SECOLO AREA

The Valle Secolo area, located a few kilometers west of the town of Larderello, extends over a surface of about 5 km^2 and is characterized by a structural high of the geothermal reservoir formations.
A high fracture-derived permeability exists at its top and the numerous wells drilled in this area (Figure 1) turned out to be highly productive.
The fluid produced by these wells was characterized by a high degree of superheating and by a homogeneous chemical and isotopic composition, allowing better assessment **of** the reinjection effects.

The geologic setting of the area is given in Figure 2 and is described as follows (from top to bottom):

1. the Flysch Facies Formation (shales, limestones and sandstones), which acts as the cap rock of the geothermal reservoir;
2. the Tectonic Wedges Complex (Pandeli et al., 1991), mainly constituted by anhydrites and dolomitic limestones in the upper part, and by quartzites and phyllites below;
3. a Polymetamorphic Complex made up by phyllites, micaschists and gneiss.

Formations 2 and 3 constitute the reservoir and the upper **part** of 2 **is** highly permeable.

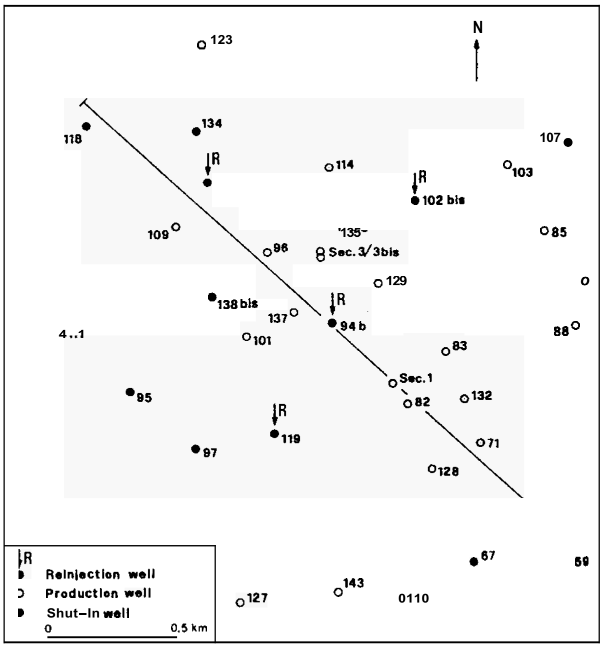

Figure 1. Valle **Secolo** area: location of the wells and line **of** geologic section.

Recently drilled deep wells discovered productive layers to a depth of 3000 m in the Polymetamorphic Complex (Barelli et al., 1995).
From the structural viewpoint, the geological edifice is made up of a series of nappes which had been thrust one on top of the other with a prevalently ENE vergence.

The exploitation of this area began in the early 1950s with the drilling of wells to depths of 400 to 600 m.
The first wells were highly productive (up to 80 kg/s) and a total steam flow-rate of about 300 kg/s was reached in early 1954. Unfortunately, these wells were characterized by a strong production decline. To compensate for this drop, additional wells were drilled in the same area, until the spacing became too close and the strong interference forced the drilling to be halted.

The intensive exploitation of this area caused a sharp decline in fluid production (from 300 kg/s to 110 kg/s in 20 years) and depleted the reservoir pressure from 3 MPa to 0.5 MPa. In the same period the reservoir temperature remained at 240-250°C and the degree of superheating increased progressively and reached about 100°C.
In spite of this intensive exploitation, a large amount of thermal energy was still stored in the reservoir rocks.

Water injection into this superheated zone might permit part of the thermal energy to be recovered and maintain, if not even increase, the steam production of the area.

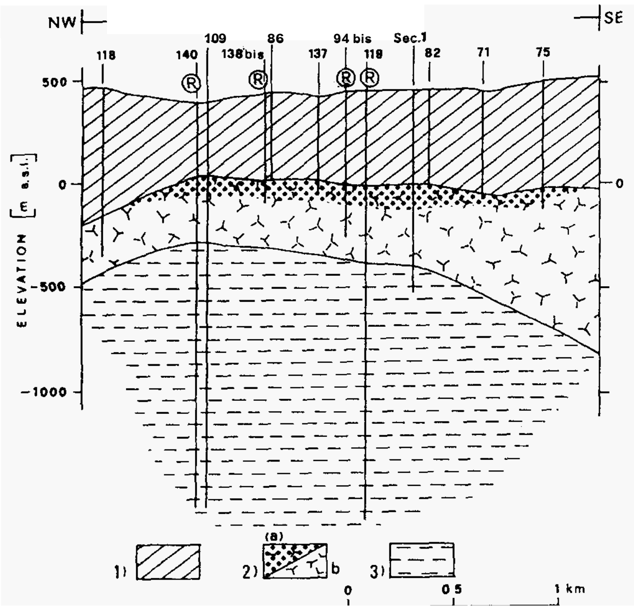

Figure 2. Geologic section
1) Flysch Formation
2) Tectonic Wedges Complex; (a) high permeable zone
3) Polymetamorphic Complex

3. REINJECTION TESTS

The first reinjection test in the Valle Secolo area was conducted in well N94 from Jan. 1979 to April 1982, with flow-rates ranging from 10 to 50 l/s.

The results were encouraging because practically all the injected water was recovered as steam by the surrounding production wells, with an increase in fluid production and reservoir pressure (Giovannoni et al., 1981; Cappetti et al., 1982).

Despite the vicinity of the reinjection well to the production wells, no thermal breakthrough was observed and the well-head temperature of the production wells remained practically constant, showing the presence of a vertical permeability that allowed water penetration at depth with efficient fluid-rock heat exchange.

The amount of injected water recovered as steam was estimated by applying tracing techniques based on differences in non condensable gas content and isotopic composition between the injected water and the fluid produced by the wells before the start of reinjection (primary steam), as shown in Table 1 (Bertrami et al., 1985; D'Amore et al., 1987; Scandiffio et al., 1992; Panichi et al., 1995). The injected water is a steam condensate which has practically no gas and is enriched in ^{18}O and Deuterium, as a result of the stripping process in the cooling towers.

Table 1.
Tracing methods applied in Valle Secolo for reinjection monitoring.

Tracer	Primary steam min - max	Injected water min - max
Gas	2-10 %w/w	0
$\delta^{18}O$	(-1) - (-3)	(+3) - (+5)
δD	(-40) - (-42)	(+3) - (+6)

The casing collapse caused the end of the reinjection experiment and a new reinjection well (N94bis) was drilled close to the first one.

Due to these positive results, further injection tests have been performed in other wells of the Valle Secolo area since 1983.
The following 7 wells were tested N138/N138bis, N102bis, N140, N119, N118, N134, N59. Well N138bis was drilled to replace N138, which collapsed during these tests. The location of these wells is given in Figure 1.
The tests were positive since breakthrough phenomena between injection and production wells did not occur here, contrary to what happened in another area of the Larderello field.

Wells N138/N138bis and N102bis responded in the same way as well N94: the injected water was vaporized in a short time inside the reservoir and was recovered by the surrounding production wells without appreciable temperature variations in the produced fluid.

The tests carried out on more peripheral, deeper wells gave less rapid responses to steam recovery and in some cases small accumulations of liquid phases might have formed locally. However, this liquid phase was vaporized later on, when the injection rate was reduced or interrupted.
Such tests confirmed that the best conditions for rapid vaporization of the injected water are those at the reservoir top (Figure 2), where both the permeability and the degree of superheating are higher.

4. REINJECTION OPERATION PHASE

Based on the positive test results and modeling studies (Calore et al., 1986), the Larderello - Castelnuovo power plants were connected to the tested reinjection wells by a network of pipelines. Since 1984, all the discharged condensed steam (about 65 l/s) has been reinjected into the central part of Valle Secolo area.

Thus the reinjection went from an experimental to an operational phase and from that moment on had to face field operation problems such as:

- changes in flow rate and well-head pressure of the production wells due to their progressive connection to the new gathering system operating at higher pressure;
- the reinjection rates of the individual wells were often modified due to operating problems in the pipeline network;
- workover operations in some production and reinjection wells;
- drilling of new wells, often in total loss of circulation

Such operations modified the water and steam flows inside the reservoir, so a detailed study of the effects of each reinjection well on the surrounding production wells was no longer possible.

The effects of reinjection in the Valle Secolo area have therefore been analyzed by monitoring the changes in the production characteristics of the area affected by reinjection (Figure 1) taken as a whole.
The flow-rate evolution of the area is given in Figure 3, while the weighted average gas content is plotted in Figure 4.

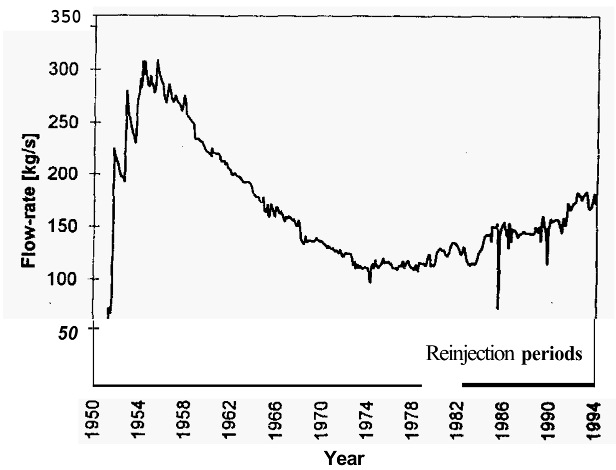

Figure 3. Flow-rate history of the wells in the Valle Secolo area.

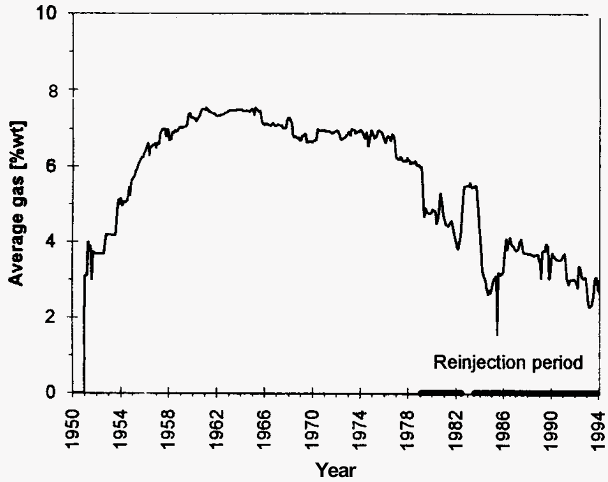

Figure 4. Non condensable gas content history of the Valle Secolo area.

It is worth noting the strong flow-rate decline during the first 25 years of exploitation and the subsequent increase caused by reinjection. The boiling of injected water produced additional steam devoid of gas which diluted the primary steam and therefore allowed a reduction of the weighted average gas content, with considerable energy savings for gas extraction from the power plant condensers.

From a mass balance on the weighted average gas content and the total flow-rate for the Valle Secolo wells, the amount of injected water recovered as steam (secondary steam) has been evaluated and is given in Figure **5** together with the reinjection rate.

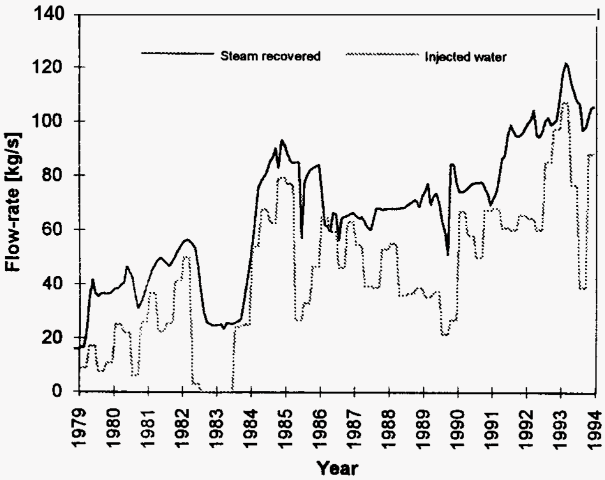

Figure 5. Flow rate **history of the secondary** *steam* and of the **injected** water.

In the period 1987-1990, part of the condensed steam discharged by the power plants was utilized for workover and drilling activities in the same area, often carried out in total loss of circulation. In practice, this fluid has been reinjected into the reservoir also, and thus the injection rate during this period can be considered to be about 65 l/s.

It is interesting to note that the flow-rate trend of the secondary steam is in line with the reinjection rate. The fact that the secondary steam is always higher than the injection rate is due to the conmbution of the inflow of meteoric waters through outcropping reservoir formations, which began in the second half of the 1970s (Celati et al., 1991; Panichi et al., 1995).

The reinjection also contributed to increasing the reservoir pressure to about 0.2 MPa, as can be observed from the trend of the shut-in pressure of well N111 (Figure 6).

This well, even though not located in the middle of the Valle Secolo area, is the best reservoir pressure gauge since it has been shut-in since the beginning of the field exploitation.

The long reinjection period has not substantially modified the temperature of the produced fluid, as can be seen in Figure **7,** where the well-head temperatures of five production wells close to the reinjection wells are given.

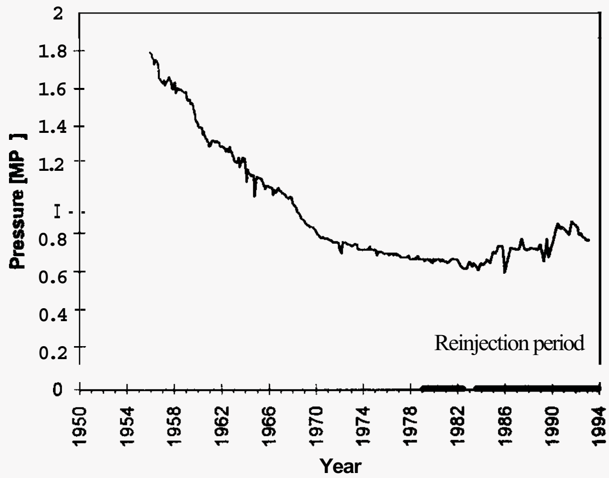

Figure 6. Shut-in pressure history of well N111.

Based on the positive results of some 10 years of reinjection operation, an increase in injection rate has been decided in order to increase secondary heat recovery.

Installations have therefore been constructed to transfer to **Valle** Secolo both the steam condensate discharged by the power plants in operation at the Travale-Radicondoli geothermal field (about **20** km away) and the water pumped from a well located in the aquifer bordering the Larderello field.

These installations increase the injection rate from 65 l/s to 130-140 l/s and were started at the beginning of 1993 for a short testing period. The operation of these installations was begun in 1994.

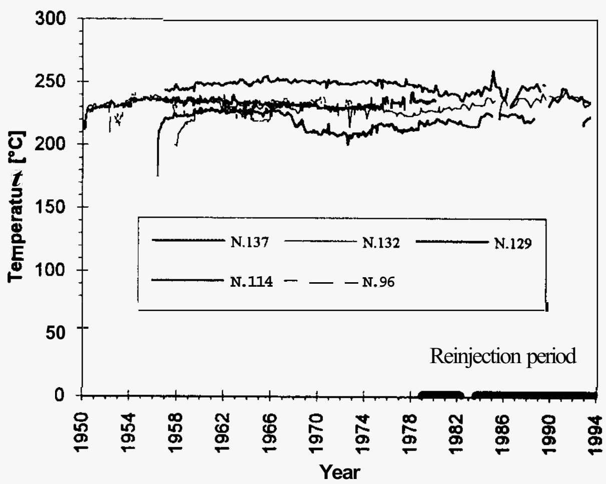

Figure 7. Well-head temperature **history** of **5** production **wells** located close to reinjection wells.

Thus the exploitation strategy for the Valle Secolo area has evolved from simple reinjection to artificial field recharge.

Problems may arise from possible build-up of liquid plumes inside the reservoir that reduce secondary heat recovery.

Should this happen, the reinjection pattern will be changed: the injection in the well responsible for the plume build-up must be reduced or halted and new wells must be activated to look for new superheated zones of the reservoir.

To monitor reinjection and particularly to locate the possible presence of liquid plume, some geophysical surveys have been begun.

Since 1985, microgravity surveys have been performed **periodically.** They showed a modest liquid accumulation below well N140 after an intense reinjection period in this well. This accumulation, however, disappeared shortly after reinjection in this well was reduced (Dini et al., 1995).

Geoelectric monitoring using the casing of the wells as electrodes is also in progress. The processing and interpretation of the first data is still underway.

An integration of the microseismic network, operating since 1979, has already been started: the installation of additional geophones inside some selected wells will allow improved hypocenter localization of seismic events.

5. CONCLUSIONS

The 15-year reinjection experience in Valle Secolo has proved that "secondary heat recovery" is feasible in those areas characterized by high permeability and a high degree of the superheating of the steam inside the reservoir.

A large part of the reinjected water has been recovered as superheated steam, with a significant increase in steam flow-rate and reservoir pressure.

No liquid water breakthrough was observed between the reinjection and production wells and the well-head temperatures of most production wells remained constant, demonstrating water penetration at depth with efficient fluid-rock heat exchange.
The reinjection at the reservoir top, where permeability is very high, gave faster steam recovery.

As the secondary steam contains no gas, the average gas content in the total produced fluid has decreased, with an improvement in power plant specific consumption due to the energy saving for gas extraction from condensers.

Based on the above results, a new exploitation strategy has been adopted for the Valle Secolo area. This geothermal system is now ragarded as a heat mine from which the heat is recovered by means of an artificial water flow.
The exploitation strategy is therefore progressively moving from a strategy typical of hydrothermal systems to one typical of Hot Dry Rock systems, according to the HDR definition:
"Any system where injection is necessary to extract the heat at a commercial rate for a prolonged period".

REFERENCES

Barelli, A., Cappetti, G. and Stefani, G. (1995 in press). Results of deep drilling in the Larderello - Travale/Radicondoli geothermal area. ***World Geothermal Congress, Florence, Italy, 1995.***

Bertrami, R., Calore, C., Cappetti, G., Celati, R. and D'Amore, F. (1985). A three-year recharge test by reinjection in the central area of Larderello field: analysis of production data. ***Geothermal Resources Council Trans.***, Vol. 9 (2), pp. 293-298.

Calore, C., Pruess, K. and Celati, R. (1986). Modeling studies of cold water injection into fluid-depleted, vapor-dominated geothermal reservoir. ***Proceedings, Eleventh Workshop on Geothermal Reservoir Engineering, Stanford University,*** pp. 161-168.

Cappetti, G., Giovannoni, A., Ruffilli, C., Calore, C. and Celati, R., (1982). Reinjection in the Larderello geothermal field. ***Proceedings. Inter. Conf. on Geothermal Energy, BHRA Fluid Engineering, Florence 11-14 May.*** Vol. 1 pp. 395-407.

Celati, R., Cappetti, G., Calore, C., Grassi, S. and D'Amore, F. (1991). Water recharge in Larderello geothermal field. ***Geothermics,*** Vol. 20 (3), pp. 119-133.

D'Amore, F., Fancelli, R. and Panichi, C. (1987). Stable isotope study of reinjection processes in the Larderello geothermal field ***Geochimica et Cosmochimica Acta,*** Vol. 51, pp. 857-867.

Dini, I., Marson, I., Palmieri, F. and Rossi, A. (1995, in press). Reinjection monitoring in the Larderello geothermal field using microgravity and topographic measurements. ***World Geothermal Congress, Florence, Italy, 1995.***

Giovannoni, A., Allegrini, G., Cappetti, G. and Celati, R. (1981) First results of a reinjection experiment at Larderello. ***Proceedings Seventh Workshop on Geothermal Reservoir Engineering, Stanford University,*** pp. 77-83.

Pandeli, E., Bertini, G. and Castellucci, P. (1991). The Tectonic Wedges Complex of the Larderello area (Southern Tuscany-Italy). *Boll. Soc. Geol. It.,* Vol. 110, pp. 621-629

Panichi, C., Scandiffio, G. and Baccarin, F. (1995, in press). Variation of the geochemical parameters induced by reinjection in the Larderello area. ***World Geothermal Congress, Florence, Italy. 1995.***

Scandiffio, G., Baccarin, F., Valenti, M., Panichi, C., Noto, P. and Bellucci, L.(1992). Secondary effects of reinjection on the Larderello, Italy geothermal system evaluated by the study of the isotopic and chemical composition of the gas mixtures. ***7th Int. Symp. on Water-Rock Interaction, Park City, Utah, USA,*** pp. 1349-1352.