NUMERICAL SIMULATION OF THE MONTEVERDI ZONE (WESTERN BORDER OF THE LARDERELLO GEOTHERMAL FIELD)

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ABSTRACT

ENEL is conducting a reservoir study of the Monteverdi geothermal zone. This paper describes the work done in 1994 using a three-dimensional numerical model (STAR: Pritchett, 1992).
The calibration of the Natural State Model **(NSM)** was carried out by adjusting the reservoir parameters until a reasonable match of the temperature and pressure spatial dismbution was obtained. Once an NSM had been developed, the expected production during field exploitation was evaluated.
Due to the high degree of superheating at reservoir conditions, adsorption phenomena are important for proper evaluation of field performance. **A** sensitivity study of the effects of adsorbed water on the main production parameters was made.
Different reinjection scenarios were also simulated in order to find the best locations for injection wells and to optimize the reinjection strategy.

1. INTRODUCTION

In 1980 a deep exploration program in the margins of the Larderello geothermal field was carried out in order to discover high temperature and pressure steam in deep formations (Metamorphic Substratum). In the Monteverdi zone, located to the south-west, promising results were obtained.
Seven exploration wells were drilled between 1980 and 1986, five of them productive: a reservoir was located between -2300 and -3500 m a.s.l., with a temperature of roughly 300°C and pressure of 7 MPa. Based on these results, a development project was designed. The drilling of an additional 23 wells was scheduled, together with the installation of two 20 MW generating units.
The number of productive wells was 16 (of a total of 26) as of December 1993, but drilling is still going on. All the wells produce superheated steam; the maximum reservoir temperature and pressure are 360°C and 7.5 MPa.
The geologic setting is referred to in a companion paper (Baldi, 1995); the area is a roughly rectangular shape of 4x8 km, and the reservoir elevation is from -1000 to -3500 m a.s.l.
Unfortunately, due to the presence of chloride in the geothermal steam, it has not been possible to perform long term production and interference tests because of corrosion problems. Well performances have been evaluated only on the basis of short (few days) production tests. **A** mathematical model of the field was developed in order to have a preliminary field evaluation.

2. MODEL CHARACTERISTICS

2.1 Grid geometry

The grid used for the simulation is rectangular, with all the cells 500x500 meters in each horizontal (XY) plane.

The number of cells **is** 8x15x12, covering a volume of 4000x7500x2500 m3. The vertical thickness of the reservoir is from -3500 to -1000 m a.s.l. The grid orientation is north-west-south-east, as shown in Figure 1.

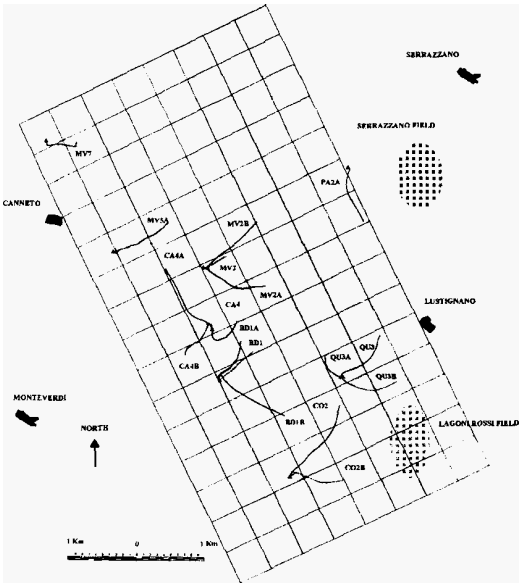

Figure 1. Monteverdi zone with the **grid** orientation.

The vertical (Z) cell distribution is irregular (see Figure 2), starting from 500 (at the bottom) to 100 meters (at the top).

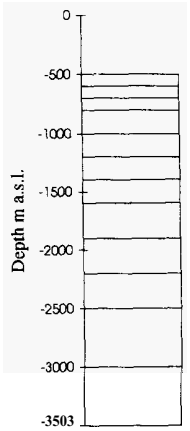

Figure 2. Vertical layer division

2.2 Boundary and initial conditions

During the Larderello exploitation, the total production from the wells close to the Monteverdi zone reached about 170 kg/s in the early 1970s and has been stable up to now, as shown in Figure 3.

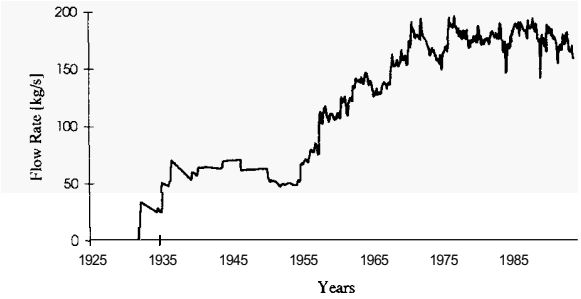

Figure 3. Flow rate history of the wells close to the Monteverdi zone.

These old shallow wells, with low pressure and temperature, under exploitation since 1926, are located outside the south-east side of the Monteverdi system. Because their production did not affect the pressure of the deep field, we conclude that there is no hydraulic communication from this south-east border. The same conclusion arises from analyses of data from wells located **inside the** study region, with depths less than -1000 m a.s.l. On the north-west side, no data are available; we therefore conservatively assumed that these boundaries are closed, even if meteoric water inflow from surrounding acquifers could be expected, because it has been observed in other areas under exploitation.

Temperature and pressure indicate superheated conditions; the maximum degree of superheat is 70°C (7.5 MPa and 360°C). The initial temperature distribution was based upon extrapolated values taken *ad hoc* during drilling; the temperature distribution at -2500 has a maximum to the south-east (360°C) and a minimum to the north-west (300°C), as shown in the contour plot given in Figure 4.

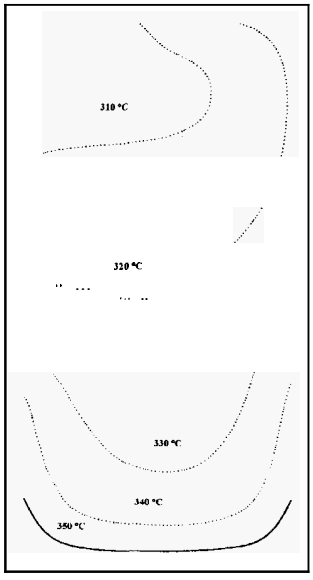

Figure 4. Isotherms at -2500 m a.s.l.

2.3 Rock properties

The geological structure of the area was analyzed in order to determine which lithofacies could be assigned to each cell element; the geological elements are listed in Table 1, where the spatial averages of the top and bottom elevations for each lithofacies are collected:

Lithofacies	Top elevation m a.s.l.	Bottom elevation m a.s.l.	Average thickness m	Total volume in the model m^3
Caprock	+500	-950	1450	1.1E+10
Phyllites	-950	-1600	650	8.1E+09
Micaschists	-1600	-2300	700	2.2E+10
Gneiss	-2300	-3500	1200	3.0E+10

The value of -3500 for the reservoir bottom was assumed arbitrarily in consideration of the maximum well depth the cap rock does not play a role in the steam production, but it is important for the thermal exchange. The phyllites formation was subdivided between "low" and "normal" permeability, in order to follow the real reservoir distribution: the reservoir lithofacies consists of Gneiss, Micaschists and Phyllites; the low permeability Phyllites were considered as a part of the impermeable cover.

The values of porosity, rock density, thermal conductivity, heat capacity and permeability were measured from cores, and are given in Table 2; we have made two groups with averaged properties: the cap rock and the reservoir rocks.

Table 2. Rock properties at 20°C

Rock name	Density kg/m3	Heat capacity J/kg°C	Thermal conductivity Watt/m°C	Permeability m^2	Porosity %
Caprock	2500	825	2	1E-19	0.5
Reservoir	2700	770	4	4E-15	1.5

2.4 Well data

The main well characteristics are summarized in Table 3.

Table 3. Well characteristics

Well name	Initial flow rate kg/sec	Fracture depth m a.s.l.	Lithofacies
BADIA 1 (BD1)	15.6	-2181	GNEISS
BADIA 1A (BDIA)	0.9	-2212	MICAS
BADIA 1B (BD1B)	4.2	-2383	MICAS.
CANNETO 4 (CA4)	9.2	-2690	GNEISS
CANNETO 4A (CA4A)	5.6	-1443	PHYLL.
COLLA 2 (CO2)	3.6	-2202	MICAS.
COLLA 2B (CO2B)	4.4	-2152	MICAS.
MONTEVERDI 2 (MV2)	6.9	-1939	MICAS.
MONTEVERDI 2A (MV2A)	4.2	-2088	MICAS.
MONTEVERDI 2B (MV2B)	5.6	-2216	GNEISS
MONTEVERDI5A (MV5A)	12.5	-2589	GNEISS
MONTEVERDI 7 (MV7)	7.2	-3281	GNEISS
PADULE 2A (PA2A)	2.5	-2856	GNEISS
QUERCENNE 3 (QU3)	3.6	-2916	GNEISS
QUERCENNE 3A (QU3A)	22.2	-1700	MICAS.
QUERCENNE3B (QU3B)	10	-1640	MICAS.
REINJECTION WELL			
CANNETO 4B (CA4B)	-	-1516	PHYLL.

The location of the wells in the grid is shown in Table 4.

Table 4. Well locations

X/Y	1	2	3	4	5	6	7	8	X/Y
15									15
14		MV7(1)							14
13									13
12									12
11			MV5A(2)						11
10					MV2B(3)			PA2A(2)	10
9									9
8			CA4A(6)	MV	MV2A(4)				8
7		CA4B(6)		CA					7
6			BD1A(3)	BD					6
5			BD1B(3)			QU3A(5)	QU3(2)		5
4						QU3B(5)			4
3				CO					3
2				CO					2
1									1
X/Y	1	2	3	4	5	6	7	8	X/Y

years with the current temperature and pressure values everywhere in the reservoir was found. It was a long trial-and-error procedure, **A** satisfactory agreement was found for a permeability value of 1.3 E-14 m^2.

3.3 Exploitation

The same procedure described above for the permeability evaluation was performed for each production well. Unfortunately, only data related to short term production tests were available for the fit because serious corrosion problems were experienced on the casings and well-heads due to the presence **of** chloride in the steam.
Exploitation for 20-year at a back pressure of 1 MPa with all the wells in operation was simulated, with the following conservative assumptions:

a) no adsorption;
b) absence of natural water recharge,
c) no reinjection in the field.

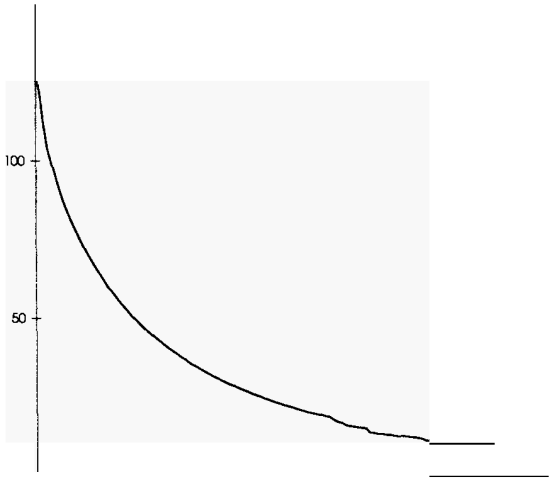

Figure 6. Simulated exploitation without adsorption.

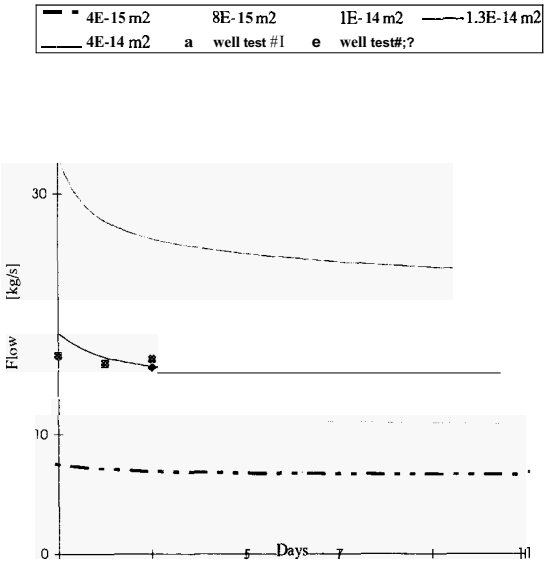

Figure 5. Badia 1 well test analysis.

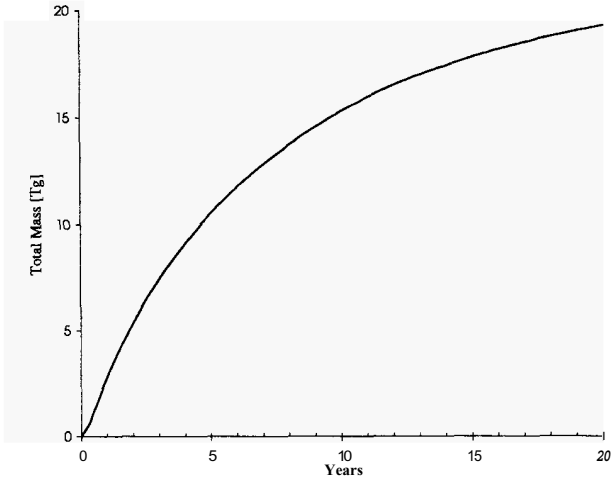

Figure 7. Cumulated extracted mass.

4. ADDING ADSORPTION TO THE MODEL

In a superheated system a particular - and not very well understood - phenomenon can play an important role during the exploitation: the adsorption of liquid water inside the pore volume, due to the molecular forces between rock surface and a contact layer **of** the fluid (Economides, 1985; Hornbrook, 1994). Water adsorption can be a possible storage mechanism for this high temperature reservoir. Available experimental data show that the amount of adsorbed water depends on the pressure, temperature and rock properties. Only a small fraction of the pore volume can be occupied by the adsorbed film, but the overall effect on the fluid density can be significant: for example, at 350°C and 7 MPa the steam density is 28 kg/m^3; we have, with 10% of the pore volume filled with liquid water, a change **of** the effective steam/water mixture density to 85 kg/m^3, with an increment of 200% in fluid storage.

The results of laboratory measurements performed on core samples collected from the Monteverdi wells (S. Shang and R. Home, private communication, 1994) are shown in Figure 8, which plots the values of the adsorbed (or desorbed) water in mg per gram of rock versus the relative pressure (i.e. the ratio between the pressure and the saturation pressure) at different temperatures.

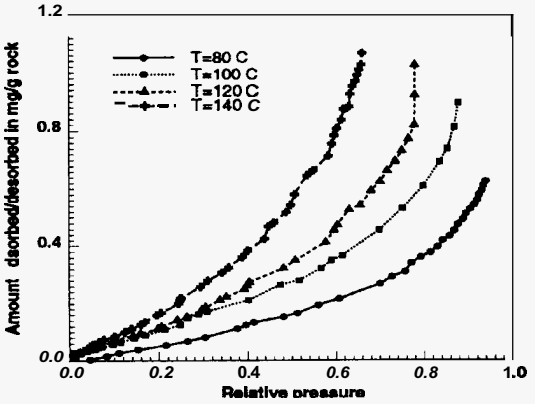

Figure 8. Measured mass of adsorbed water versus relative pressure at different temperatures.

We can define a global reservoir value of the amount of adsorbed liquid water per kg of rock (called ADS in the present paper). At a temperature of 330°C, we have a saturation pressure of 13 MPa; our relative pressure is ***-0.5, so*** ADS can exceed 1 gram of water per kg of rock.

We simulated the natural state with different values of ADS, with all the other rock parameters unchanged. The main characteristics of the two adsorption runs are summarized in Table 5.

ADS mg/g	Liquid water volume	Liquid water mass	Steam volume m^3	Steam mass kg	Reservoir rock mass kg	%volume adsorbed water/pore
NO			9.37E+8	2.72E+1	1.63E+14	-
0.42	1.08E+8	6.85E+10	8.31E+8	2.68E+1	1.63E+14	11%
0.79	2.02E+8	1.28E+11	7.36E+8	2.42E+1	1.63E+14	22 %

4.1 Exploitation

The results of the exploitation are illustrated in Figure 9. The average electrical power for 20 years roughly increases from 15 MW (ADS=0) to 35 MW in the two ADS runs.

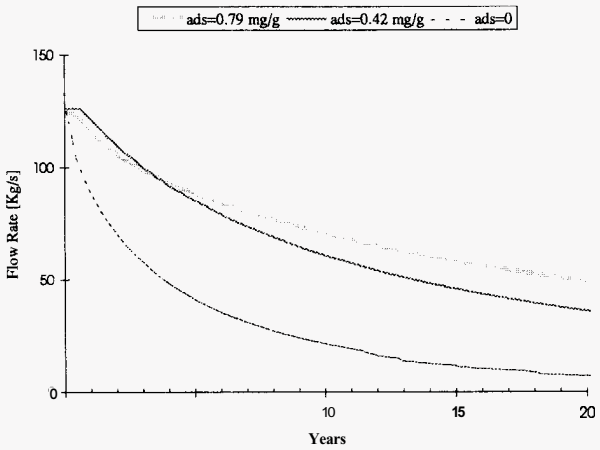

Figure 9. Simulated exploitation for different adsorption values.

The important effect **of** the value of ADS on the total electrical energy is evident. We are performing a series of measurements on other rock samples at higher temperature and pressure in order to get more reliable data on the adsorption phenomena. In any case, with the lowest value (ADS=0.42), we can exploit the reservoir for twenty years with adsorbed water still stored in the pore volume. For this reason, there is only a small difference between the two ADS values over practical industrial exploitation time scales.
On the other hand, in the two ADS cases, it is possible to exploit the reservoir with a different number **of** wells: it will give a greater difference of extracted mass in the same time.

4.2 Discussion

Are the above values reasonable for the amount of liquid water we can produce from a superheated reservoir? What is it possible to learn from analyses of similar thermodynamic conditions in other reservoirs?
In order to try to answer these questions, we selected three previously exploited zones: Lagoni Rossi, Gabbro and Travale-Radicondoli.

In the first zone we have 8 production wells, at a reservoir pressure of 0.7 MPa and temperature of 180°C (15°C of superheat). The ratio (called C_M in the following) between the extracted **mass** and the pressure drop is 100 Mg/Pa.

In the second zone, we have 9 production wells, located north of Larderello, at an average depth of 1000 m. The typical reservoir pressure is around 1.5 MPa, at a temperature of 230°C (30°C of superheat). In this case, the ratio C_M is 31 Mg/Pa for the 12-year period from 1965 to 1977. The data are presented in Figures 10 and 11.

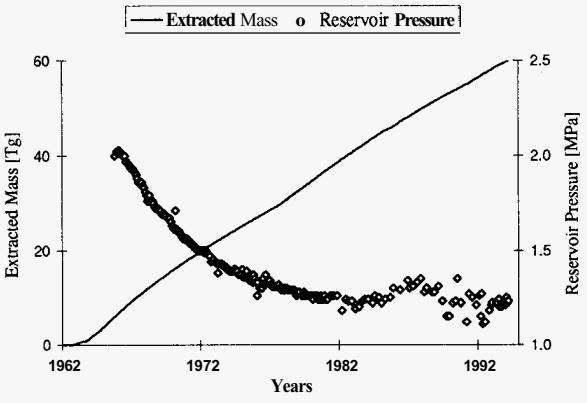

Figure 10. Extracted mass at Gabbro and reservoir pressure decline.

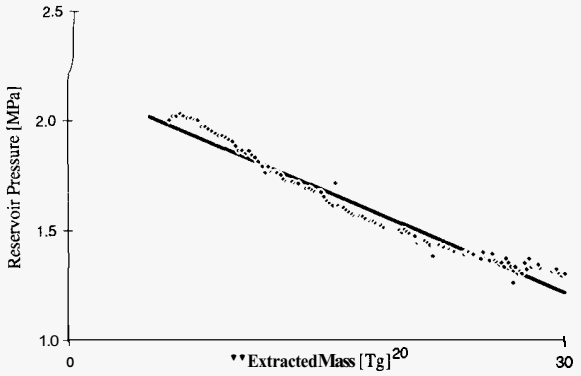

Figure 11. Reservoir pressure versus extracted mass at Gabbro.

In Figure 11 the best fit line is also represented: the ratio C_M can be easily calculated by the reciprocal of the measured slope.
In a companion paper (Barelli, 1995), the Travale-Radicondoli high temperature (but not superheated) reservoirs are analyzed: the C_M parameter ranges from 12.5 to 18.5 Mg/Pa.

In the adsorption simulations the same C_M ratios are 15 and 23 Mg/Pa for the two ADS values, 0.42 and 0.79 mg/g respectively. In the field cases the measured ratios are higher than those foreseen for Monteverdi. We cannot state that in Lagoni Rossi or in Gabbro we have such a large amount of adsorbed water, because a part of the water may be originating from natural recharge; however, we can say that the order of magnitude of the adsorption phenomenon is roughly the same as other real exploitation cases.

5. REINJECTION

Different reinjection strategies were tested in order to find the best reinjection well among those available. The best results were obtained from CA4B, where water is reinjected at the top of the reservoir (-1500 m a.s.l.). The reinjection program is linked to the operation of the power plants. According to the present schedule, a 20 MW plant will start at time zero, and a second unit will follow the first after 12 months.
We have studied the following cases:

a) no reinjection at all;
b) reinjection with a flow rate equivalent to 25% of the produced fluid.
c) reinjection with a flow rate equivalent to 50% of the produced fluid.

The influence of the quantity of reinjected water is shown in Figures 12 and 13, for ADS=0.79 and ADS=0, respectively.
In the presence of adsorption the reinjection effect is negligible because there is enough water stored inside the reservoir for the operation of two units.
In case of ADS=0, reinjection plays an important role: an early start of reinjection with a flow rate of 50% of produced fluid is recommended. The percentage of the reinjected water which is evaporated is about 85%.

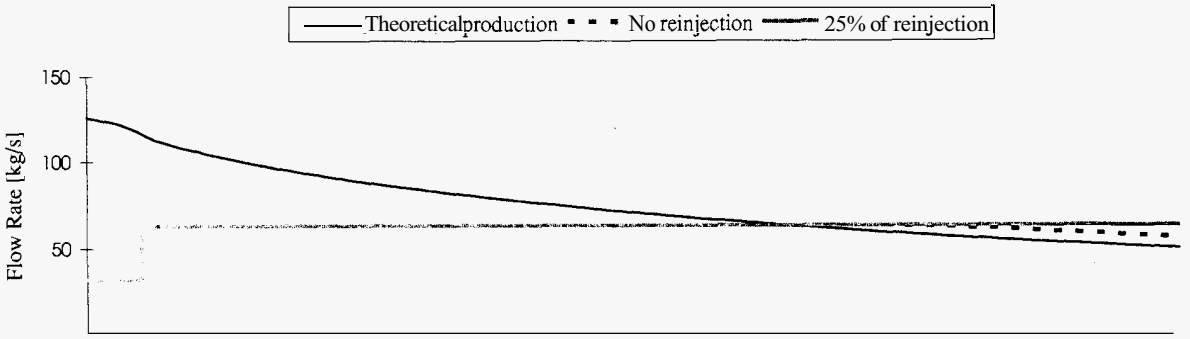

Figure 12: Effect of the reinjection with adsorption.

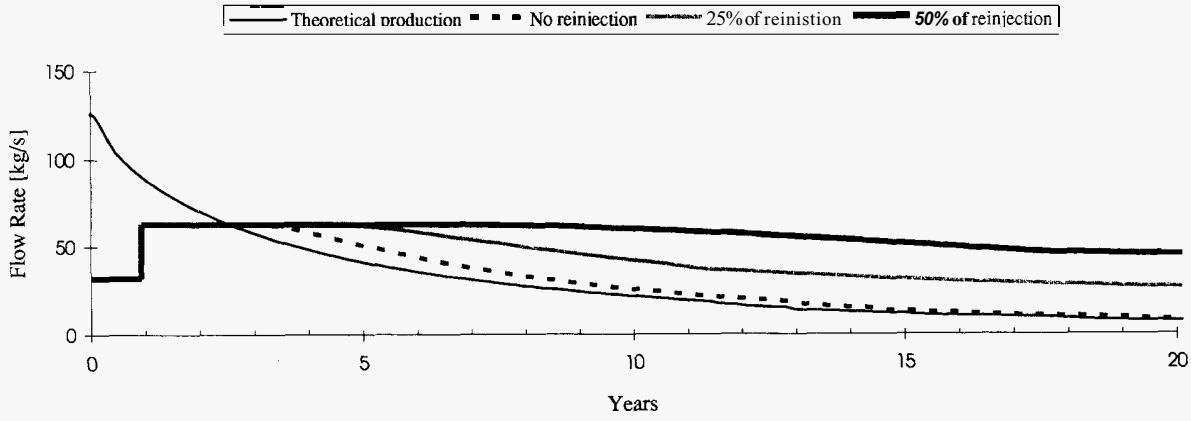

Figure 13: Effect of the reinjection without adsorption.

6. CONCLUSIONS

The present simulation results should be considered preliminary because the model was not calibrated with a production history, nor with sufficiently long production and interference tests, as is usually done.
The influence of adsorption, given the high degree of superheating, is fundamental, permitting the operation of two 20 MW units for twenty years. Reinjection can significantly increase the energy recovery from the field only if adsorption is negligible.
The fist power plant is planned to come on-line in 1996, and will permit the model to be adjusted, matching experimental data collected during the field exploitation. More precise and reliable quantitative assessment of the future production trends will therefore be obtained in future years.

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