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PRESENT STATUS AND FUTURE PROSPECTS OF GEOTHERMAL DEVELOPMENT IN ITALY

by
R. CATALDI and A. CALAMAI

WITH AN APPENDIX ON RESERVOIR ENGINEERING

by
G. NERI and G. MANETTI

ENEL/National Geothermal Unit - Pisa, Italy

ABSTRACT

This paper consists of two parts and an appendix.

In the first part a review is made of the geothermal activity in Italy from 1975 to 1982, including electrical and non-electrical applications. Remarks then follow on the trends that occurred and the operational criteria that were applied in the same period, which can be considered a transitional period of geothermal development in Italy.

Information on recent trends and development objectives up to 1990 are given in the second part of the paper, together with a summary on program activities in the various geothermal areas of Italy.

The appendix specifically reviews the main reservoir engineering activities carried out in the past years and the problems likely to be faced in the coming years in developing Italian fields.

In particular, production and injection well-testing in high and low enthalpy liquid-dominated reservoirs are illustrated, as well as:

- reinjection tests carried out in the Larderello field with the aim of enhancing heat extraction from the upper steam-dominated part of the reservoir;
- flow-rate transient tests in the Larderello and Travale fields.

1. INTRODUCTION

In Italy the utilization of geothermal resources for industrial purposes dates back to about 150 years ago. Exploitation of by-products associated with hot fluids and direct use of heat for chemical processing until 1913, combined electrical and chemical production between 1913 and 1965, and electric generation alone from 1965 to 1980 are the three main steps of geothermal development in Italy.

Where the direct use of geoheat is concerned, apart from balneotherapy, examples of agricultural applications and space heating are surely not lacking; but until the energy crisis exploded in the past decade little attention was paid to this problem.

Throughout the period of geothermal development in Italy, and particularly after 1960, hundreds of specific notes and general papers were published by Italian authors illustrating the various aspects of the research and the utilization of this energy source. Two progress reports, in particular, presented by CATALDI et al. (1970) and CERON et al. (1975) at the U.N. Geothermal Symposium in Pisa and the U.N. Geothermal Conference of San Francisco, respectively, outline the geothermal situation in Italy at the beginning and the middle of the 1970s. Both of these reports, however, confine themselves to illustrating the state of research and exploration for the purposes of geothermoelectric production, without making any mention of direct uses of geothermal heat.

The first part of this paper will start from the situation illustrated by the above-mentioned progress report of CERON et al. in order to give an organic, although general, account of the geothermal development in Italy after 1975, including electric production and direct applications of geoheat.

The second part of the paper illustrates the objectives and summarizes the program of activities scheduled up to 1990.

Appended to this paper is a note by G. MANETTI and G. NERI, dealing specifically with the main activities carried out in reservoir engineering during the past years, together with and overview of the problems likely to be faced in the future in this branch of geothermal activity.

In this way, the Authours of both the paper and the appendix hope to make a general as well as a specific contribution to the Ninth Stanford Workshop on Geothermal Reservoir Engineering.

PART I

2. SITUATION IN 1982 AS COMPARED TO THAT IN 1975

To facilitate comparison of the results obtained in the period in question, it seems appropriate to consider separately two groups of activities: those carried out or in progress having the main goal of producing electricity, and those conducted or still ongoing with the chief aim of directly using the terrestrial heat.

With respect to drilling, however, this distinction is not easy to make, and Table 1 summarizes all geothermal wells drilled in Italy up to the end of 1982.*

* Excluded from Table 1 are only the wells drilled in the 1940s in the Phlaegrean Fields, and a few other wells drilled in the 1950s in the island of Ischia, Sciacca and Viterbo.

With reference to the central section of Table 1, attention must be drawn to three points:

- wells have been considered productive only where they have encountered fluids with physicochemical characteristics permitting their utilization (at present or in the near future) for the production of electric power and/or for other uses. It is clear that this represents a limitation, since many wells that are now non-commercial, and are thus considered dry, due to insufficient temperatures or for other reasons (rapid scaling, for example), might, in a few years, fall within the category of productive wells;
- the flow-rate of the various productive wells is expressed in terms of the total output of fluid, which, from case to case, may be superheated steam, saturated steam, water/steam mixture or water only. In all cases, however, the gas flow-rate has been deducted;
- the delivery pressure to which the flow-rate figures refer generally ranges between 5 and 15 atm.

2.1 - First group: electrical uses

In Italy the production of electric energy from geothermal fluids is currently limited to the zones of Larderello, Travale, Radicondoli and Mt. Amiata. However, considering their perspectives, the new areas of Latera, Torre Alfina, Cesano and Phlaegrean Fields have been included in this first group as well. Indeed, the studies in the these areas indicate in some

Table 1 - WELLS DRILLED - MARCH 1975 AND DECEMBER 1982

ZONE	SITUATION AT JANUARY 1975			FROM JANUARY 1975 TO DECEMBER 1982				SITUATION AT DECEMBER 1982		
	WELLS DRILLED (no.)	AVERAGE DEPTH (m)	WELLS /km^2 (no.)	WELLS DRILLED (no.)	AVERAGE DEPTH (m)	PRODUCTIVE WELLS (no.)	FLOW-RATE t/h*	WELLS DRILLED (no.)	AVERAGE DEPTH (m)	WELLS /km^2 (no.)
LARDERELLO	539	656	3.08	34	1642	11	350	573	714	2.86
TRAVALE-RADICONDOLI	34	644	4.86	20	1703	9	810	54	1036	1.46
Mt. AMIATA	60	780	1.50	8	2882	4	270	68	1027	1.46
LATERA	-	-	-	8	2129	3	1200	8	2129	0.61
CAMPI FLEGREI	-	-	-	9	2226	4	520	9	2226	1.80
CESANO	-	-	-	11	2274	4	750	11	2274	0.59
TORRE ALFINA	5	742	1.67	4	1766	3	500	9	1197	1.38
OTHER ZONES	12	951	-	5	2210	2	300	17	1321	-
TOTAL	650	673	2.83	99	1951	40	4700	749	842	2.24

* STEAM AND/OR WATER (SEE TEXT)

cases (Latera and Phlaegrean Fields) that electric generation is already feasible, and in other cases (Torre Alfina and Cesano) that this generation might become feasible in the future.

The situation in the old and new zones (see Fig. 1 for the locations and Table 2 for the plants) can be summarized as follows.

- Larderello. Of a total of 573 wells existing in this zone (see Table 1), only 34 were drilled in the period in question. Since 1975 drilling has been carried out mainly in the peripheral areas with the aim of exploring the margins of the field and delimiting the size of the main reservoir, which is chiefly made up of carbonate rocks.

  During these years, moreover, the average depth was considerably increased (more than 1600 m), since exploration was directed at locating permeable horizons within the metamorphic basement down to approx. 4 km.

  The fluid produced in this zone is generally superheated steam.

  Aside from the exploration activities, the reinjection activity in this zone is worth mentioning. It was started a few years ago with the aim of gradually attaining (by 1985) a total subsurface disposal of approx. 600 t/h of condensing water. The results so far obtained with reinjection into the carbonate reservoir are encouraging both from the stand point of the increase in flow rate and the containment of the decline in pressure in the older producing wells.

  In addition, a modernization program has been initiated on the old generating units; the program also provides for a more rational location of some smaller plants. The recovery of efficient power achieved with this program from 1975 to the present is estimated at approx. 25-30 MW.

- Travale-Radicondoli. In this zone a small geothermal field was discovered in the 1950s which for a brief period supplied a 3 MW

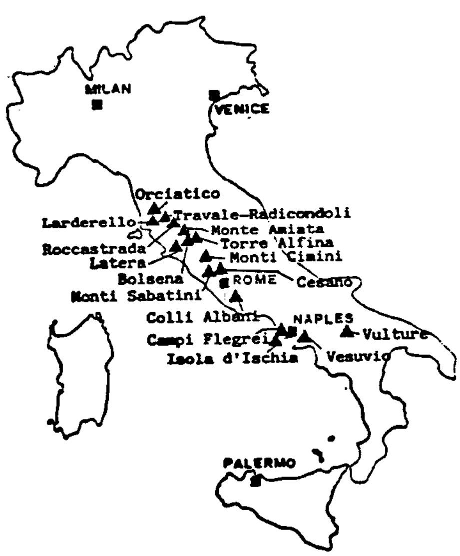

Fig. 1 - Location of high enthalpy zones

Table 2 - INSTALLED CAPACITY OF ITALIAN GEOTHERMOELECTRIC POWER PLANTS

REGION	POWER PLANT	JANUARY 1975			DECEMBER 1982		
		NO. OF UNITS	UNIT RATING (MW)	TOTAL INST.CAP. (MW)	NO. OF UNITS	UNIT RATING (MW)	TOTAL INST.CAP. (MW)
LARDERELLO	LARDERELLO 2	4	14.5	69	4	14.5	58
		1	11		-	-	
	LARDERELLO 3	3	26		3	26	
		1	24	120	1	24	111
		2	9		1	9	
	GABBRO	1	15	15	1	15	15
	CASTELNUOVO	2	11		2	11	
		1	26	50	1	26	50
		1	2		1	2	
	SERRAZZANO	2	12.5		2	12.5	
		2	3.5	47	2	3.5	47
		1	15		1	15	
	SASSO 2	1	12.5		1	12.5	
		1*	3.2	22.7	1*	3.2	22.7
		2	3.5		2*	3.5	
	LAGO 2	1	12.5		1	12.5	
		1	6.5	33.5	1	6.5	33.5
		1	14.5		1	14.5	
	MONTEROTONDO	1	12.5	12.5	1	12.5	12.5
	VALLOSORDO	1*	0.9	0.9	1*	0.9	0.9
	MOLINETTO	1*	3.5	3.5	1	8	8
	LAGONI ROSSI 1	1*	3.5	3.5	1*	3.5	3.5
	LAGONI ROSSI 2	1*	3	3	-	-	-
	LAGONI ROSSI 3	-	-	-	1	8	8
	S. MARTINO	-	-	-	1	9	9
Subtotal		33	-	380.6	32	-	379.1
TRAVALE RADICONDOLI	TRAVALE 2	1*	15	15	1	15	
		-	-	-	1	3	18
	RADICONDOLI	-	-	-	2	15	30
Subtotal		1		15	4	-	48
Mt. AMIATA	BAGNORE 1	1*	3.5	3.5	1*	3.5	3.5
	BAGNORE 2	1*	3.5	3.5	1*	3.5	3.5
	PIANCASTAGNAIO	1*	15	15	1*	15	15
Subtotal		3	-	22	3	-	22
TOTAL		37	-	417.6	39	-	449.1

* Discharging-to-atmosphere units

discharging-to-atmosphere power plant. But the shallow depth of the reservoir and the proximity of large outcrops of permeable rocks communicating with it rapidly led to the thermal degradation of the fluid produced and to the impossibility of continuing the electric power generation.

Subsequently, a new geothermal field having been located in the early 1970s a few km NE of the old production area,exploration and exploitation activities were concentrated in the new zone. As at Larderello, the main reservoir is made up of carbonate formations, but productive horizons are also present in the schistose-quartzitic formations below. Approximately 75% of the fluid produced in the new fields is constituted by superheated or saturated steam, while 25% is made up of water/steam mixture.

The installed capacity, which was 15 MW in 1975, reached 48 MW in 1982. Moreover, fluid is available for supplying some additional 30 MW.

- Mt. Amiata. The generating units installed in this region (at Bagnore and Piancastagnaio, for a total of 22 MW) are fed with generally saturated steam produced by a shallow reservoir (500-1000 m) made up of carbonate formations.

  In 1979, however, exploration of the schistose-quartzitic basement underlying the aforementioned reservoir was begun in order to individuate deep permeable horizons down to 3-4 km. This deep exploration, which explains the sizeable increase in the average depth of the wells (see Table 1), is giving very encouraging results at Piancastagnaio where the presence of permeable layers has been ascertained between 2500 and 3500 m.

  It is still too early to say whether these layers belong to a second reservoir which is completely separate from the first; what it is clear for the moment is the fact that the fluid produced is (at least initially) a water/steam mixture having pressures and temperature (300-350°C) greatly higher than those of the fluid yielded by the carbonate reservoir.

  The fluid produced by the deep horizons will therefore feed a new 15 MW geothermoelectric group which is already under construction.

- Latera. ENEL and AGIP, working in joint venture, discovered a new geothermal field of the water-dominated type in this zone in 1980.

  The top of the reservoir (600-1500 m deep) is made up of Mesozoic carbonate rocks whose structural attitude is controlled by a recumbent fold. The temperature of the fluid is of the order of 200-230°C, with TDS of 8-10 g/l. Although there are problems of carbonate scaling during both production and reinjection, the feasibility study (now approaching conclusion) indicates that the fluid can be utilized for generating electric power. It is thus planned to install a provisional 3.5 MW generating plant in the near future, to be followed by a first 15 MW power plant.

- Phlaegrean Fields (Mofete). Setting aside the activities carried out in the 1940s, it can be said that the systematic exploration of this zone was first begun by the AGIP-ENEL joint venture towards the end of the 1970s.

  The wells drilled thus far (of which nearly half are productive - see Table 1) indicate that in this volcanic area the production of fluids does not stem from a reservoir that can be unambiguously defined in lithological and geometrical terms. A certain fortuitousness of production is in fact found in correspondence with a few fracture systems which in some places are sealed and in others open. It would thus seem that there are various productive horizons, but actually, at least up to approx. 3 km down, it is a matter of discountinuities oriented almost vertically. The production of greatest interest has been found between 1300 and 1600 m, with wellbottom temperatures of around 250-300°C.

  The fluid produced is a water/steam mixture with a salinity of the order of 35-40 g/l or more, mainly controlled by sodium chloride.

  While the feasibility study is still in progress, the orientation is towards installing a 4-5 MW discharging-to atmosphere power unit in the near future, which would also serve for testing the field.

- Cesano. Here we have a field of the "hot brine" type, with a total salinity varying between a minimum of 70-80 and a maximum of 300-350 g/l. The highest salinity values (which is of the sulfate-alkalic type in all cases) are found in the central part of the field in correspondence to fractures connected with the explosion chimneys. Temperature in the reservoir ranges between 120-130°C on the periphery of the field and 220-230°C in its central part.

Given the marked scaling properties of the fluids (ALLEGRINI et al., 1982), various possibilities of utilization of the fluid are being experimented for separate sectors of the field.

As far as generating electricity is concerned, based on experimentation of various flash processes (and also tests made by using a helical screw expander), it has been concluded that the production of electricity alone in this field is not economically profitable. Therefore, the orientation is towards achieving an integrated utilization of the resource: electrical production, subordinate to the extraction of chemicals and/or the direct use of the geothermal heat (see also Cesano Project in section 2.2.1).

- Torre Alfina. In this zone about 1000 t/h of fluid can be drawn from a shallow carbonate reservoir (500-1000 m) in which the temperature is 140-160°C.

  It is a water-dominated field in which the fluid produced, although not having a very high salinity (TDS = 7000 ppm), but being saturated with CO_2, determines severe carbonate scaling phenomena.

  Mainly on account of this, but also because of other problems linked to disposal of the waste waters, it was decided to postpone for the time being the utilization of this kind of resource. Nevertheless, the Alfina zone will be brought back under consideration to explore the schistose-quartzitic basement and see whether it is possible (as in the Mt. Amiata zone) to achieve the production of fluid from deep layers with better chemical and physical characteristics than those mentioned above.

- Other regions. In addition to the zones described above, surface exploration activities have been carried out from 1975 to the present in a certain number of other zones considered of potential interest for finding high temperature fluids. These zones are: Orciatico-Montecatini and Roccastrada in Tuscany; Volsini Mountains, Cimini Mountains, Sabatini Mountains and Albani Hills in Latium; Vesuvius in Campania; Vulture in Basilicata.

  In one of these zones (Sabatini Mountains), deep exploration has already begun; but the first well drilled here, even though it encountered a temperature at the bottom (2500m) of over 280°C, turned out to be dry. This because of the lack of permeability, due to a marked self-sealing process of the fractures in the carbonate formations, which were expected to constitute the reservoir of the geothermal fluids.

  Naturally, the deep exploration in this zone will be continued and will soon be started in some of the other new zones mentioned above.

  A summary of the fluid found in recent years in the various zones examined in this section, not yet utilized but nonetheless already available for feeding new geothermoelectric groups, is given in Table 3 below.

Tab. 3 - Fluid available at Dec.'82 for the supply of new geothermoelectric units

REGION	FLUID AVAILABLE (t/h)	EXPECTED CAPACITY (MW)
- Larderello	200	20
- Travale-Radicondoli	300	30
- Mt. Amiata	180	18
- Latera	1200	10
- Cesano	750	5
- Phlaegrean Fields (Mofete)	520	9
TOTAL	3150	92

The total capacity corresponding to this fluid (∿92 MW), which will be installed gradually in the next few years, will constitute part of the increase is geothermoelectric capacity that is planned to install by 1990 in accordance with the objectives of the Italian National Energy Plan, as will be more fully reported in section 4.

2.2 - Second group: non-electrical and combined uses

2.2.1 - Projects already realized or in the course of realization (locations in Fig. 2)

- Abano. This town, located near Padua, is one of the best-known European spas with a very flourishing balneotherapeutic activity. The hot water (65-90°C) produced by some 120 wells (250-400 m deep) is utilized, through heat exchangers, firstly for space heating and hot sanitary water production and later for supplying spas. Some 75 hotels, each having its own well(s) and heating circuit, in addition to many homes, are heated in this way (BARBIER, 1977).

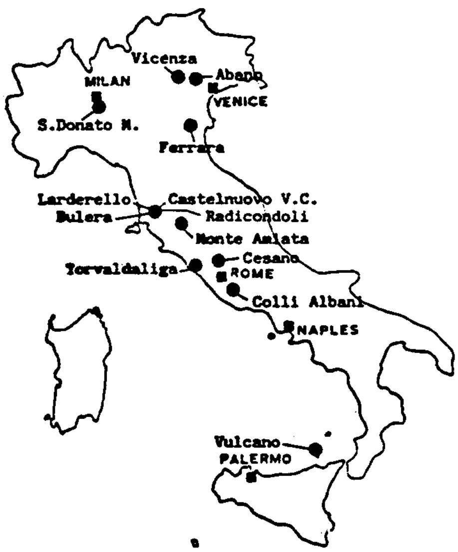

Fig. 2 - Location of low enthalpy zones

- Galzignano. This village is located in the same geological district as that of Abano. Near it some 20,000 m^2 of greenhouses have been in operation for about 25 years, producing mainly decorative plants and flowers. Low-salinity water at 65°C is yielded by a 300 m deep artesian well which supplies the greenhouses heating circuit 28 km long (BARBIER, 1977).
- Vicenza. A well drilled 15 km north of Vicenza for oil exploration yielded some 100 m^3/h of very low salinity water at 65-70°C. This is a very favorable circumstance in that, after its use as heat source, the water can be used for civil and/or agricultural purposes.

  Two district areas of the town, suitable for geothermal heating, were selected after the feasibility study (ELECTROCONSULT, 1982): the first one includes a group of private houses (about 656,000 m^3) having an expected energy consumption of nearly 20,000 Gcal per year and a required peak power of 8.6 Gcal/h. This group needs a distribution network 3500 m long.

  The second area, including military barracks and the prison being constructed nearby, requires no new distribution network, because both barracks and prison have their own heating systems. The volume to be heated in this second area is 561,600 m^3, with an estimated yearly consumption of 20,300 Gcal and a required peak power of 9.9 Gcal/h.

  The previously mentioned existing well will not be used, because it is too far from Vicenza; therefore, two new wells (one north and one southeast of the town) will be drilled near the utilization areas. Heat pumps will be used to increase the energy recovery.

  The water temperature in the distribution circuit will be 75°C at the inlet and 60°C at the outlet. Moreover, a network of pipes, parallel to heat-transport ones, will deliver hot water for sanitary uses.This water will be directly supplied by the production wells due to the fact that water in the whole sedimentary basin near Vicenza has a very low saline content.
- San Donato. This project is aimed at heating the SNAM's buildings (a company of the ENI group), located in the outskirts of Milan, for a total volume of 467,000 m^3.

  One producing well (100 m^3/h of water at 65°C) and one reinjection well, both 2000 m deep, will be used in this project. The maximum thermal power available from the geothermal fluid is expected to be 4.4 Gcal/h, supplying an annual geoheat content of 15,000 Gcal (CERON-SOMMARUGA, 1979). Due to the low fluid temperature, a heat pump will be employed to enhance heat extraction from geothermal water.
- Ferrara. Two wells located about 4 km outside this town spontaneously produce some 250 m^3/h of water at nearly 100°C; but the flow-rate can be increased by means of submerged pumps.

  A market survey of the potential users concluded that some 7,500 apartments can be heated by using the water of these wells. The district heating system envisages an overall yearly consumption of 110,000 Gcal, out of which about two thirds will be of geothermal origin whereas the remaining part should be provided by a backup liquid fuel heater. The heat distribution network will have a total length of approx. 20 km with operation temperatures of 90°C at the inlet and 53°C at the outlet (INVERNIZZI-SARTI, 1982).
- Larderello. Low-temperature fluids (70-130°C) have been used in this area since 1827 for several purposes: extraction of valuable chemicals (mainly boron compounds) and drying of saline solutions until 1950, greenhouses and space heating until now-a-day.

  At present, non-electrical applications concern district heating (office and residential buildings) and greenhouses only by using low-pressure/low-temperature steam produced by shallow, old wells. An indirect-cycle system is now adopted in both cases; steam is made to flow through shell-and-tube exchangers and heats fresh waters running in conventional circuits. A total volume of nearly 350,000 m^3 of district heating and some 15,000 m^3 of greenhouses (growing mainly vegetables) are heated in this way at Larderello and surrounding villages (ALLEGRINI, 1976).

- Castelnuovo V.C. Waste low-pressure/low-temperature steam available in this area from shallow, almost exhausted wells will be used for heating 154 buildings (approx. 200,000 m^3) in this village located near Larderello.

  The steam will be condensed in a mixture condenser and the hot water produced, at a temperature of about 95°C, will be conveyed to a plate heat exchanger, where it will heat the secondary water of a distribution circuit. The users will draw heat from the distribution through other plate heat exchangers, each serving a small group of consumers.

  The heat distribution system will be rated for a peak power of 7 Gcal/h, out of which 5 Gcal/h will be obtained by the geothermal heat recovery plant. The backup and the reserve will be supplied by liquid fuel heaters.

  The annual consumption of geoheat in this system (including sanitary water) is expected to be some 7800 Gcal.

- Bulera. This is a particular type of integrated project which is being implemented by ENEL for demonstration purposes. It is aimed at producing electric power and heat by using the geothermal fluid of the well Bulera 1, near Larderello. The fluid is made up of steam at 120°C with a very high uncondensable gas content (over 50%). Steam will be condensed and the resulting water at 85-90°C will be used in a binary cycle to evaporate a low-boiling fluid (freon) whose vapour will drive a 50 kW_e turbogenerator. After this heat exchange, the outflowing water (at about 70°C) will be used to heat several greenhouses, where ornamental plants and vegetables will be grown. Lastly, before being reinjected, the geothermal water will heat water for catfish breeding and water-hyacinth growing.

  The project will involve the exploitation of geothermal heat for a total of 1.35 Gcal/h, out of which 0.6 will be required by the binary cycle plant. Moreover, the unconsensable gas, made up almost entirely of CO_2, will be recovered and used in the greenhouses to improve the plant growing.

- Amiata. This is a typical example of multi-purpose utilization projects, recently implemented in an area characterized by underemployment and other socioeconomic problems.

  In this area two back-pressure power plants were installed by ENEL, one at Bagnore and the other at Piancastagnaio (see section 2.1), discharging steam into the atmosphere at nearly 100°C.

  To exploit the heat of this (previously wasted) steam at Piancastagnaio, an agricultural development project was set up for a nearby area (approx. 42 hectares) some years ago and has recently (1983) come into operation. More than half of the project area is used for growing ornamental plants and flowers in glass-covered greenhouses heated by a secondary circuit. Moreover, a drying plant is connected with these greenhouses, which also serves other nearby greenhouses where vegetables are grown.

  Modifications of the power station were necessary to allow the recovery of waste heat. The geoheat utilization scheme, described in detail by FRANCIA et al. (1982), basically consists of:
  - a heat recovery circuit (including a mixture condenser and a 50 m high gas escape chimney) and a reinjection circuit;
  - a heat transport circuit supplied by clean water and including surface heat exchangers at both ends of the circuit, as well as a pumping system;
  - a distribution circuit, including the pipe network and the circulating pumps.

  The estimated yearly heat consumption is 150,000 Gcal for the greenhouses and 200,000 Gcal for the drying plants.

- Cesano. As mentionned in section 2.1, the central part of this hot brine field features temperatures of the order of 230°C and salinity of 300-350 g/l, whereas the peripheral part of the reservoir has temperatures of 120-170°C and salinity of 80 to 150 g/l (BALDI et al.,1982; ALLEGRINI et al., 1982).

  Due to these peculiar characteristics, a feasibility study is under way concerning the integrated utilization of the resource: electric energy production, chemicals recovery (mainly glaserite and subordinately bromide and iodine), and geoheat for district heating.

As regards the latter utilization in particular, a project is being set up for the central heating of the military buildings and facilities pertaining to the Cesano Infantry School, totalling a volume of about 350,000 m^3 space heating (ENEL, 1982). The estimated yearly energy consumption is 8600 Gcal, with a peak power of 6.7 Gcal/hr (out of which 5.6 are for space heating and 1.1 for sanitary water heating).

The distribution network (5.7 km long, made of a preinsulated double pipe buried under the ground level) will enable circulation of pressurized water having a maximum pressure of 17 bar, inlet temperature of 120°C and outlet temperature of 60°C.

Table 4 summarized dimensions and heat data of the projects summarized above, while Fig. 2 shows their location.

Tab. 4 - Geoheat of Italian district heating and greenhouse projects under development in Dec. 1982

PROJECT	DISTRICT HEATING VOLUME (m^3)	GREENHOUSE AREA (m^2)	ANNUAL GEOHEAT (Gcal)	ANNUAL OIL SAVING (PET)
Abano and Galzignano	100,000	20,000	150,000	20,000
Vicenza	1,118,000	-	23,000	4,200
San Donato	467,000	-	15,000	2,100
Ferrara	2,100,000	-	75,000	9,000
Larderello	350,000	15,000	90,000	14,000
Castelnuovo V.C.	20,000	-	7,800	1,100
Bulera	-	5,500	2,200	300
Amiata	-	220,000	350,000	54,000
Cesano	350,000	-	8,600	1,300
TOTAL	4,505,000	260,500	721,600	106,000

2.2.2 - Projects under preliminary study

In addition to the projects above, many prefeasibility studies are being carried out in other areas, aimed at exploiting geothermal fluids for direct or combined uses. Among them, it is worth mentioning the following.

- Radicondoli. This project envisages heating 24,000 m^2 of greenhouses for flower and vegetable growing. The forecasted heat consumption is some 23,000 Gcal per year, with a peak of 7.5 Gcal/h. The geothermal fluid will be used in an indirect cycle, heating (through a heat exchanger) the water of a secondary circuit.
- Torvaldaliga. In this area, near Civitavecchia, a large low-temperature (50-60°C) reservoir exists at relatively shallow depth (500-600 m). Wells drilled in this area are of the artesian type and water has a low salinity.

  A project is under study to use hot water for pre-heating fuel oil supplying a large thermoelectric power plant operated by ENEL in that locality.
- Colli Albani. A preliminary market survey carried out in this region has individuated a number of high consumption areas where geothermal energy might profitably be used for non-electrical applications. Based on this survey and on the geological situation of this region, a series of possibilities are being considered to provide mainly industries and, to a lesser extent, district heating systems and agricultural activities with geothermal heat. Should the market conditions prove to be attractive, geothermal heat for direct uses could be available within a few years for an energetic content corresponding to 5000 PET/y.
- Vulcano. On this island of the Aeolian archipelago a project is being implemented aimed at producing electricity and fresh water by means of high-temperature fluids likely to exist within 1500-2000 m depth. The objective is to install a 5 MW_e power plant and to use geoheat to obtain approx. 1.1 million cubic meters of fresh water per year from the sea water or from steam condensate or residual geothermal water. Production of both electricity and fresh water should suffice for meeting energy and hydric demand of the three main Aeolian isalnds, i.e. Vulcano, Lipari and Salina.

2.3 - Remarks on the development between 1975 and 1982

As can be inferred from the summary presented in the preceding sections, and by comparing the information given in this paper with that contained in the progress report of CERON et al. (1975), the geothermal situation in Italy in the period considered here has changed remarkably with respect to the preceding years.

Indeed, up to beginning of the 1970s, the production of electric energy being the sole industrial objective to pursue, the interest in the development of Italian geothermal resources was concentrated chiefly in the areas of Larderello, Travale and Mt. Amiata, and secondarly in a few other zones of the pre-Apennine belt in Tuscany, Latium and Campania where it was thought that the geological conditions could be favorable for finding steam or, at least, fluids at temperatures over 180°C. In the subsequent period, however, and particularly towards the end of the 1970s, boosted by the energy and economic crises following the events of 1973, exploration was gradually expanded to numerous other zones with the objective not only of producing electric power, but of utilizing geothermal resources for direct and combined applications to the greatest extend possible. For this reason fluids with temperatures of 100°C or even less have been considered of possible industrial interest.

A prominent aspect of the period in question is that of "deep exploration". By this is meant the fact that, whereas up to the first years of the past decade the extraction of geothermal fluids was limited in the areas of Larderello, Travale and Mt. Amiata to the reservoir made up of Mesozoic carbonate formations and to the upper part of the positive structures of the metamorphic basement, after 1975 a program was launched (called, as a matter of fact, "deep exploration") directed at verifying two hypotheses: the first concerning the existence within the metamorphic complex (at depths between 2500 and 5000 m) of permeable horizons capable of forming a deeper reservoir; the second regarding the possibility of extracting, from deep layers, fluids of higher temperature and pressure than those contained in the part of the reservoir exploited so far.

As mentioned in section 2.1, this programme has already begun to produce very encouraging results both in the Larderello area and, in particular, at Piancastagnaio.

In the new areas, on the other hand, the objectives of "deep exploration" seemed premature in the period from 1975 to present-day, since it was firstly necessary to verify the existence of a first reservoir. However, with the increased competitivity of geothermal energy, the average depth limit in drilling has now been fixed at 3000 m, as opposed to the earlier limit of 1500-2000 m.

Another important program in the period considered is reinjection, which was launched in the mid 70s as a means of: i) discharging the waste condensate from the Larderello power-plant back into the underground; ii) attempting a partial recharge of the field (which has a strong deficit in the mass balance between water inflow and fluid out-flow); and iii) slowing down pressure drawdown in the more intensely exploited area.

Reinjection tests were initially carried out in the more marginal areas of the field, and were later extended gradually to the central areas affected by a more intense and prolonged exploitation. The results are very satisfactory in all instances.

Further aspects of geothermal activity in the 1975-1982 period include: improving of certain exploration methodologies, study and experimentation of utilization of hot brine resources, study and application of reservoir engineering techniques, various injection and production tests on certain wells in the water dominated fields, application of various stimulation and fracturing tecniques, design and construction of new instrumentation for high temperature and pressures, modernization and rationalization of the steam pipelines, modernization of some old generating units, resiting of some small power-plant, extension of the remote control system in the power-plant, design of new types of generating units.

This is clearly a very wide spectrum of activity that reflects a profound shift on the Italian geothermal scene. The results of these activities were already gratifying, but hopefully will become even more fruitful in the future, thus contributing to attain the geothermal objectives of the National Energy Plan for 1990. These objectives and the future activities are outlined in the second part of this paper.

PART II

3. TYPE OF RESOURCES AND GEOTHERMAL POTENTIAL OF ITALY

High (> 150°C), intermediate (100-150°C) and low temperature (< 100°C) resources are known to exist in Italy. If reference is made to 3 km depth, the thermal situation of Italy can be schematically illustrates as in Fig. 3.

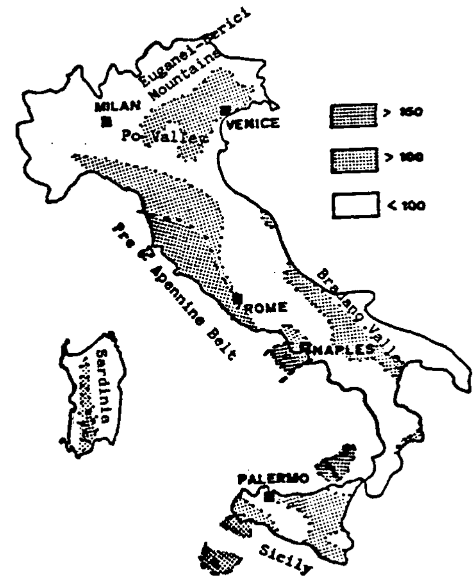

Fig. 3 - Sketch map of the temperature (°C) at a depth of 3000 m b.g.l. (from Fanelli et al. - 1979 modified)

Where the type of geothermal systems are concerned the following can be said: hydrothermal convection systems predominate in the pre-Apennine belt (western Tuscany, Latium and Campania) and occur also in a few other geologic provinces of the peninsula (Euganei-Berici Mts., Bradano Valley and Vulture) and of the islands (Ischia, Aeolian archipelago, eastern and southwestern Sicily, and southern Sardinia); magmatic systems are likely to exist below 2.5-3 km in some active or recent volcanic areas (Vesuvius, Phlaegrean Fields, Pantelleria); geopressurized systems are known to exist below 3 km in the central sector of the Po Valley and near the shore of Northern Adriatic Sea, but their existence at great depth cannot be ruled out in other sedimentary basins of Italy; conduction-dominated systems (due to insufficient permeability rather than lack of water) have been documented in an area of the Northern Sabatini region and are likely to exist also in some geologic structures of the Alps, in some zones of Tuscany (Apuan Alps, and other areas) and in central Sardinia; normal gradient systems feature the remaining part of Italy, i.e. most of the Alpine chain, western and central Po Valley, the whole Apennine range, the southeastern belt of the peninsula, southern and northeastern Sicily and eastern Sardinia.

Assessment of geothermal potential for part of the Italian territory or for the whole country has been made on several occasions during the past decade (BARELLI et al., 1975a and 1975b; CATALDI et al. 1978); CATALDI-SQUARCI, 1978); but the methodologies and the results of these studies are being reviewed at present, also on the basis of the criticism made by CATALDI-CELATI (1983). However, the most recent data available are those published by CATALDI et al. (1978) for central and southern Tuscany and by CATALDI-SQUARCI (1978) for the whole country. Both studies are based on the terminology and methodology proposed by MUFFLER-CATALDI (1978). These data refer to a depth of 3 km and can be summarized here as follows:*

- accessible resource base (ARB) ..... 3x10 GW_y (thermal)
- resources (RSS) $5x10^4$ GW_y (thermal)
- reserves (RSV) $12x10^3$ " "

With reference to the last figure it is estimated that nearly 30% (∿3500 GWy_t) are characterized by temperatures sufficiently high to be used for electric generation, some 50% (∿6000 GWy_t) could be suitable for non-electrical applications and some 20% (∿2500 GWy_t) have temperatures insufficient (at least for the moment) for any kind of use.

Where geothermoelectric generation is concerned, it is estimated that some 110 GWy (electric) could be obtained from the reserves. Duly taken into account the part of reserves already exploited thus far at Larderello, Travale and Mt. Amiata (∿10 GWy_e), the remaining 100 GWy_e would correspond to 2000 MW_e for 50 years. However, when formulating industrial scale programs, the geothermoelectric potential of Italy, to be on the safe side, should be kept at 1000 MW_e for 50 years (PACCHIAROTTI-PARIS, 1979).

More than 90% of the high-temperature reserves, related to hydrothermal convection systems, are expected to come from the pre-Apennine belt of Italy (western Tuscany, Latium and Campania), with the remaining 10% attributable mainly to the islands. The intermediate and low-temperature reserves, on the contrary, are to be found not only in the abovesaid areas but also in many other regions of Italy.

* The temperature limits considered in this assessment are:
  - mean annual temperature (reference temperature) .... 15°C
  - minimum reservoir temp. for non-electrical uses ....60°C
  - minimum reservoir temp. for electrical generation .... 130°C

4. RECENT TRENDS, DEVELOPMENT OBJECTIVES AND EFFORT UNTIL 1990

In one of the preceding sections it was said that the five year period 1975-1980 can be considered a transitional period as far as geothermal development in Italy is concerned. The re-examination of previous experience carried out during these five years in light of the profound changes that had occured on the world market of energy sources has led to the identification of the following main areas of activities for the future geothermal development in Italy:

- intensification of study, research and experimental activities in all sectors of exploration and utilization technologies;
- expanding prospecting and drilling zones to include not only areas with strong and moderate thermal anomalies, but in some cases also areas with normal temperature gradients, with the aim of taking in the whole spectrum of the possible uses of geothermal resources: electrical, non electrical and combined;
- deepening drilling in the old fields up to a maximum of 5000 m, and increasing the average depth of wells in new fields up to a mean value of approximately 3000 m, with the objective of exploring deep levels and recovering fluids at higher pressures and temperatures;
- modernization of power stations and/or replacement of old generating units with the aim of improving by 20-25% the mean efficiency of the present geothermoelectric plants;
- reducing the time elapsing between the discovery and utilization of the fluids,either by more widespread use of small, mobile, discharging-to-atmosphere plants in the initial production stage in new fields or for decentralized wells, or by ordering the condensation units in advance;
- designing new types of turbines with greater flexibility (in terms of pressure, temperature, gas content, etc.) than the ones used in the past, and thus adaptable to various production characteristics;
- normalization of the sizes of the individual units according to three basic values (4-5 MW for those discharging to atmosphere, 20 MW and 55-60 MW for the condensation ones) in order to standardize the constructional and operational components of the plants.

On the basis of these working lines, the geothermal objectives of Italy by the end of the current decade in the framework of the National Energy Plan established by the Italian government can be summarized as follows.

As far as electric production is concerned, bearing in mind that the 450 MW presently installed permitted generating 2.7 billion kWh on 1982 (a figure corresponding to approx. 1.5% of the total electric energy produced and 0.4% of the overall energy consumption in Italy in the past year) , it is envisaged to attain an increase of about 250 MW for the year 1990, therefore, the net geothermoelectric capacity installed is expected to reach some 700 MW with a production of 4.2 billion kWh in 1990. The last figure correspond to 1.7% of the total electricity likely to be produced in Italy by the end of this decade.

Where the direct applications are concerned, in addition to the projects mentioned in one of the preceding sections, a number of other initiatives are planned for the coming years, with the goal of achieving in 1990 the utilization of low-to-moderate enthalpy fluids for an energetic content corresponing to 300,000 PET/year.

The aggregate energy contribution of electrical and non-electrical uses of geothermal resources is thus expected to increase from the present 0.4% to 0.6% of the overall Italian energy consumption in the year 1990.

To reach this objective, a total capital investement of 1000* billion Italian liras has been allocated for the decade 1981-90, accounting for exploitation of known and new geothermal areas, as well as for the modernization of old power stations and the construction of new plants. This is therefore a great effort, that involves, among other things, drilling wells for a total of about 400,000 m.

However, as regards the type of fluid necessary to attain the abovesaid objectives, the situation differs greatly with respect to direct and indirect applications. Indeed, for indirect utilization (i.e. for electric energy generation), there is no problem of end-product consumption, and the only limitation derives from the relative scarcity of high-enthalpy resources; on the contrary, for direct heat uses one can count on a huge amount of low-enthalpy resources in Italy, but so far a strong demand has been lacking. Hence, from the latter point of view, the problem of creating a demand for low-to-moderate temperature

* Figure refered to constant money value 1980. At the rate change of that year this figure corresponds to 1.2 billion US $.

heat and the location of its utilization poles will have to be faced.

To solve this problem two lines of action are being pursued: the first, provided for by a specific law, is to stimulate the demand by supplying incentives (grants, soft loans, free-of-charge consulting and other subsidiary means) for the direct applications of geothermal energy wherever it is technically possible and economically convenient to use geoheat in place of fuel oil and/or electric energy; the second is a market survey aimed at individuating any a significant users (industries, farms, district heating systems, etc.) of low-to-moderate enthalpy fluids with the objective of "addressing" as much as possible the exploration of geothermal resources towards the most important consumption areas.

If these actions bear fruit as hoped, the direct uses of geothermal heat at low or moderate temperature could, by 1990, reach values even considerably higher than those corresponding to the 300,000 PET foreseen by the National Energy Plan.

Furthermore, in order to give a continuing and more significant boost to direct uses of geothermal heat, in the spirit of the actions aimed at stimulating demand, ENEL is soon to organize a "Demonstration Center" in Larderello which will be provided with test facilities, plant schemes, models and informational material that will be put at the disposal of any users interested in knowing and/or developing non-electrical applications of terrestrial heat.

5. PROSPECT AREAS AND IMPLEMENTATION OF PROGRAMS

In order to achieve the objectives described in sect.4. highest priority has been given to the development of hydrothermal systems, whereas all the other systems mentioned in section 3 will be the subject of studies or, at the most, experimental activities until the end of the present decade.

Particular attention will be paid to the high enthalpy systems that are now being exploited, or have recently been discovered. With regard to the reservoir already being exploited at Larderello, effort will continue on reinjection of waste condensate and the modernization and optimization of the utilization plants, in order to increase the generating capacity by about 50 MW.

Exploitation of the shallow reservoir will continue in Travale-Radicondoli, Latera, Cesano and Phlaegrean Fields (Mofete) with the objective of installing an aggregate capacity of 100-110 MW by the end of 1990. Moreover, in the other prospect areas discovered in Tuscany, Latium, Campania and Basilicata, all the pre-feasibility studies are expected to be completed by 1990 and deep exploration begun in some.

Where the deep reservoir is concerned, exploitation will continue at Larderello and Piancastagnaio and exploration will begin at Travale-Radicondoli and Bagnore, with the objective of increasing generating capacity by an estimated 100 MW.

With regard to the implementation of the activities mentioned above, ENEL will be the sole operator at Larderello, Travale-Radicondoli, Mt. Amiata, Alfina and Cesano, whereas ENEL and AGIP will operate as a joint-venture in the remaining areas. In particular situations, such as the Vulcano Project (Aeolian islands, Sicily), the joint venture is extented to other operators. ENEL will thus be responsible of about 80% of the activities directed at the production of high temperature fluids.

With regard to the implementation of projects for the direct use of terrestrial heat, ENEL and AGIP have so far operated as a joint venture in most cases; however, in future other public or private organizations might be involved in low-enthalpy projects.

As far as base and applied research is concerned, in addition to ENEL and AGIP, other organizations (Universities, Laboratories, Enterprises, etc.) are involved in developing the geothermal activities. Particularly worth of mention, for its contribution to the background development of geothermal energy, is the National Research Council of Italy, whose effort is achieved either through the International Institute for Geothermal Research or in the frame of the "Energetics" Finalized Project.

Finally, mention should be made of the fact that some R. and D. activities, as well as a certain number of demonstration projects, are partly financed by the European Economic Community, as part of the programmes launched by the EEC in 1975 to promote the development of new and renewable sources of energy.

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APPENDIX

OVERVIEW OF RESERVOIR ENGINEERING IN THE ITALIAN GEOTHERMAL FIELDS

FOREWORD

The reservoir engineering studies conducted during the last few years by ENEL as part of the testing, development and management of its geothermal fields can be ascribed to the following four main sectors: reinjection, well and field tests, stimulation and instrumentation.

A description is given below of the programs of the above sectors, the results obtained, future programs and the objective set by ENEL.

1. REINJECTION

I.A - Criteria

ENEL has reinjected spent geothermal fluids since the mid-70s, with the objective of increasing energy production from particular reservoirs and avoiding with the minimum economic outlay, eventual adverse effects on the environment caused by discharging these fluids into the sea or rivers. The first reinjection project involved various known reservoirs in the Larderello and Mt. Amiata* zones, which are vapour-dominated high enthalpy and lower enthalpy (corresponding to satured steam) systems respectively.

Recently reinjection has also been extended to the liquid dominated reservoir of the recently discovered Latera field.

The criteria followed in planning reinjection are tied to the objective of these projects, and can be summarized as follows.

Objective: Recovery of energy from the rocks in vapour-dominated systems

- Reinjection into the top of the "dry" volume of the reservoir, in wells with a low hydraulic resistance and intersecting vertical fractures. Injection pressure in the reservoir is lower than the saturated vapour pressure corresponding to rock temperature (∿250°C).
- Reinjection into deep layers of the dry reservoir (2000-2500 m below the top of the reservoir) where temperature is around 300°C.

Objective: Discharge waste into the underground

- Reinjection into the aquifers next to the vapour-dominated reservoir, preferably where there is a small hydraulic gradient in the direction of the reservoir. Restrictive legislation prohibits any discharge into the underground beyond the geothermal reservoir.
- Reinjection into the liquid-dominated reservoir at safe distances from the productive wells.

The safe distance is evaluated theoretically on the basis of various conceptual schemes of the flow regime between the reinjection well and productive well.
Preliminary tests tracers are contemplated in order to verify the compatibility between the theoretical results and the effective flow regime in the reservoir.

I.B - Experiments and projects

Heat recovery from a geothermal reservoir is undoubtely the most attractive objective of every reinjection project. It seems particularly propitious for vapour-dominated reservoir such as that at Larderello, where large volumes of rock (many km^3) at temperatures of about 250°C are saturated in superheated steam at pressures of a few bars.

Extraction of a small fraction of the thermal energy of the dry rock would theoretically allow to stabilize the decline in production for many years or, if necessary, to increase steam production and reservoir pressure for a more limited period of time. This objective cannot be set for areas of the Larderello field in which the steam reservoir interfere naturally with relatively cold aquifers; nor is it viable in the Mt. Amiata reservoir where the steam is, in the best of circumstances, dry saturated steam and the recent meteoric waters flowing through the volcanic chimneys, that out crop on the surface, contribute to the natural recharge of the reservoir.

The first reinjection tests were accompanied by preliminary theoretical studies to evaluate, at least approximately, the effects of reinjection on vapour- and liquid-dominated and two-phase fluid reservoirs.

The first reinjection test into the dry volume of the Larderello system began in 1979, using an old shallow well that was no longer producing at a significant level. The criteria used in choosing this well were as described above. The test was performed in two phases: at first 30-40 m^3/h of water were injected for a few months and, after a short interval, ∿140 m^3/h of fluid were again injected; the test continued in this way for 30 months. The same qualitative results were obtained in both phases: almost total vaporization of the injected water, no decrease in the temperature of the fluid produced by the wells known to interfere with the reinjection well.

Further tests were carried out in the various wells of the reservoir, not always producing as satisfactory results as these described

* In this section we refer to the shallow reservoir of Mt. Amiata region. A second productive level of the reservoir also exists in this region at a depth of about 3000 m; it is under exploration at present.

earlier.

The main conclusion to be drawn from these reinjection tests at Larderello is that energy could be recovered from the dry rocks of the system. The success of such an operation depends mainly on permeability distribution around the reinjection well, so that, in practical terms, it is essentially a question of selecting the reinjection wells.

The program of activity for the Larderello system for the next few years includes reinjection of vast quantities of water in order to try to maintain the present production rates and increase wellhead pressure to 10 bar.

The quantity of reinjected water should gradually be increased over 400 m^3/h, which is far higher than the amount available as discharge from the power-plants.

The problems raised by this program are: selection of reinjection wells, reinjection flow-rates for each of the latter, methods and techniques for monitoring the effects of these tests on the thermodynamic state of the reservoir, monitoring of induced seismicity and recovery of the quantities of water required in the tests.

II. WELL AND FIELD TESTS

During the last few years well tests, which are a routine operation after completing a well, have been conducted in the wells of the new geothermal fields still under exploration; i.e., at Latera and the deep reservoir at Mt. Amiata.

The field tests have involved part of the Larderello reservoir and all of the Travale field.

II.A - Well tests

A few deep wells (2600-3500 m) drilled into the deep reservoir at Mt. Amiata have revealed the existence of a reservoir containing pressurized water in the 300-340°C temperature range. Four wells have been put into production - PC 26, PC 27, PC 29 and PC 30 - and the reservoir is estimated to cover such a wide area that 50 production wells are programmed for the next ten years.

The low permeability of the rocks limits the productive capacity of the single wells. The flow-rates of the productive wells vary from 25 to 40 t/h of steam and uncondensable gas (0.04-0.09 by weight) at a wellhead pressure of 11 bar, together with a few t/h of water in the liquid phase.

During production liquid flashing begins first in the well, and then spreads to the surrounding formation, thus producing a temporal increase in fluid enthalpy at well-head, which stabilizes after 20-30 hours of production.

This corresponds to the "stabilization"* of the vaporization front around the wellbore. The position of this front, and the specific enthalpy of the fluid produced, depend on wellhead pressure.

Let us take as an example some results of a well test in Piancastagnaio 27 well (PC 27).

Pressure and temperature logs obtained along the bore-hole in static and dynamic conditions, show a marked decrease in pressure at well-bottom in flow conditions caused by the low permeability of the rocks. This phenomenon affects the back-pressure curve, which is almost flat in the well utilization pressure range.

The pressure build-up occuring after shut-in shows the trend typical of fractures media. The instability regime occuring 17 hours after shut-in is caused by in-hole fluid condensation. After the condensation phase pressure starts to rise again, returning to its static value before the well was opened.

The behaviour of the wells at Latera is quite different, because of the different nature of the reservoir. Although it is a liquid-dominated reservoir, it is characterized by a gas cap lying between the cover rocks and the liquid surface, at depths between 500 and 1600 m. The reservoir fluid contains sodium chloride, alkaline sulphates and boric acid, at temperature between 210°C and 232°C.

Three productive wells, L2, L3D and L4, produce a two-phase mixture of water, gas and steam, with a specific enthalpy of 215-240 Kcal/kg; the flow-rates of the first two wells have been estimated at 500-600 t/h.

Based on the results of the preliminary tests, the CO_2 content in the reservoir fluid has been evaluated at 0.025-0.06 of the water. The carbonate rocks of the reservoir, along with the CO_2 in the fluid, produce large-scale calcium carbonate precipitations during production, and consequent scaling in the casing. Scaling inhibitors have proved very successful in some tests, even in small doses, and it does seem

* The vaporization front continually moves away from the wellbore, but at an ever decreasing rate.

possible to combat this phenomenon.

In this exploitation program for the Latera reservoir, well L3D and L2 will be used as production and reinjection well, respectively. The distance between the well (∿1800 m) and formation permeability should theoretically guarantee that the warm front of the production well will not be broken until after 30 years of exploitation.

II.B - Field tests

The development programme for the Larderello reservoir envisages an increase in steam pressure by means of reinjection, concentrating production during daytime in order to preserve the reservoir.

With these programs in mind and considering past policy, some tests have been conducted in the Larderello field to evaluate reservoir volume where the steam phase is continuous and the hydraulic resistance between the reservoir and the steam manifolds in the utilization plants.

The field tests involved a 10% reduction in the flow-rate of the production wells, which was achieved by temporarily shutting off a turboalternator unit. The consequent increase in production pressure, measured at the manifolds of the production plants, was analysed using a conceptual scheme of the reservoir with concentrated parameters.

This model assumes that the reservoir is intensely fractured, and that a variation in pressure is propagated much faster than usually occurs in a porous medium, from one end of the reservoir to the other.

The empty volume is thus evaluated at $\sim 10^9$ m^3, which is compatible with the values attainable using other methods.

The tests in the Travale field entailed total shut-in of the wells producing superheated steam for 10 days; after re-opening the wells flow-rate was reduced to 60% of the pre-test value.

The objective of the test was to evaluate pressure recovery in the reservoir to verify the results obtained with a mathematical model of the field, and to obtain the necessary information for optimizing management of the Travale reservoir, which is affected by meteoric waters that infiltrate the nearby outcrops of reservoir rocks and which may impair fluid quality.

Although these tests are still under way, the results so far corroborate qualitatively the reservoir scheme based on past experience and studies, and are also quantitatively comparable with the results of the mathematical model.

The pressure build-up in the wells that were specifically shut-in for the tests reveals the typical trend of flow in fractures and some short term storage effects in well R8.

Field development at Travale will in future be directed at exploiting the deepest layers of the reservoir where the liquid and steam phases coexist. At the same time production will be limited in the uppermost layers of the reservoir so as to facilitate recovery of steam pressure and reduce the flow of meteoric waters.

Instrumentation

One of the main activities in reservoir engineering is the development of measuring tecniques for use in the bore and on the surface during well and field tests.

Among the characteristics required of this instrumentation, in geothermal wells in particular, is the ability to operate in high temperatures, to record data in real time and to provide accurate and immediate readings.

Because of the well-known drawbacks in adopting mechanical instrumentation, we have chosen electrical ones. Development has automatically been hampered by the temperature limitations in electronic components (125-130°C) and in plastic materials (FEP, PTFE, PFA: 260-280°C).

Our temperature and pressure probes have non built-in electronic sensors, are run on direct current, and transmit the data analogically from the probe to the surface using multi-conductor cables.

-: The modular design of the instruments includes:
  - a 7 conductor cable
  - truck with hoist
  - data acquisition system comprising computer and peripherals, magnetic tape unit, printer and plotter for direct log recording.

-: These instruments are the results of several years experience in the development of equipment for well-logging applications.

The equipment from the CISE geothermal line are at present adopted regularly by ENEL at Larderello during intense geothermal exploitation and have proved to be reliable, sturdy and versatile.

The main characteristics of the various instruments already in use or in the experimental phase are:

1) Probe for temperature and pressure measurements (TP probe)
   The probe, is 52 mm in diameter, 0.5 m in length and 4.5 kg in weight.
   - maximum temperature 300°C
   - maximum pressure 50 MPa (500 bars) (in dependence on the transducer mounted in the probe)
   - maximum depth 4000 m
   - temperature accuracy ± 0.2°C
   - temperature resolution 0.01°C
   - time constant 6 s
   - pressure accuracy ± 0.3% of the transducer capacity
   - pressure resolution 0.004% of the transducer capacity.

2) Caliper
   The caliper, is 120 mm in diameter, 3 m in length and 160 kg in weight.
   It performs the simultaneous measurements of two orthogonal diameters of a borehole cross-section and of the velocity drift of the fluid emitted (during production tests) or injected (during injection tests).
   - maximum temperature 250°C
   - maximum pressure 35 MPa (350 bars)
   - maximum depth 4000 m
   - diameter measurements from 120 to 650 mm
   - diameter measurements accuracy ± 5 mm
   - fluid velocity accuracy ± 10%

3) Bottom sampler
   The tool, collects fluid samples in the well at the wanted depth. It consists of a bottle and two valves, and is sent down the well with the two valves closed: when it reaches the wanted depth, an electric motor opens the two valves in order to let the fluid enter into the bottle and the air come out of it. When the bottle is filled, the same electric motor closes the two valves and the tool is lifted with the sample. The tool can be used at:
   - maximum temperature 250°C
   - maximum pressure 25 MPa (250 bars).

4) Fluid level gauge
   Slow variation of fluid level in deep wells measurements, no electric signal; useful in presence of evaporating fluid. Housed in a valise (weight 40 kg; max. detectable variation 10 m; accuracy ± 1 cm; max. depth 800 m).

5) Heat conductivity gauge
   Thermal conductivity measurements for hard rocks; direct reading; computerized data analysis (specific linear power-T vs time-thermal conductivity); Von Hertzen-Maxwell needles (O.D.: 0.8 to 15 mm; lenght: few centimeters to 1 m; range: 0.003 to 0.3 W cm^{-1} $°C^{-1}$; accuracy: better than 3%).

6) Electric clinometer
   The clinometer is provided with a magnetic compass and carries out the measurement of borehole drift angles and their direction with reference to the geographic coordinates. Owing to the compass, it cannot be used in cased holes and is affected by the possible formation magnetism. A second version with a gyro-compass is begin planned. The instrument is 4.4 m long and can be extended to 6.9 m, its weight is 65 Kg. It is provided with three different interchangeable measurement equipments. Its characteristics are:
   - maximum temperature 300°C
   - maximum pressure 50 MPa (500 bars)
   - maximum depth 4000 m
   - borehole diameters from 120 to 400 mm
   - drift angle measurements:
     0÷15° with accuracy better than ± 1°
     0÷30° " " of ± 1°
     0÷60° " " of ± 2°
   - direction error ± 3°40'.

7) Recovery electromagnets
   These tools are used to pick up small steel objects fallen into the boreholes. In order to identify the objects, the electromagnets are provided with a specially designed load cell that can measure the object weight directly at the well bottom with consequent better accuracy.
   Four tools have been constructed having the following characteristics:
   - diameter 116 mm - maximum liftable weight 600 N
   - diameter 175 mm - maximum liftable weight 900 N
   - diameter 250 mm - maximum liftable 1400 N
   - diameter 400 mm - maximum liftable 2000 N.

A study is now being made of a tool for measuring scaling in casings in geothermal bores.

The use of probes with no built-in electronic parts means that the temperature limit of the cable must be increased to a least 400°C. Consequently experiments are now being conducted on developing a multi-conductor cable capable of operating in temperature conditions of at least 400°C; this cable is now being constructed.

As the same time we have also developed thick film ceramic transducers to obtain a more intense starting signal.

Another innovative concept, aimed at overcoming the limitations of electric insulators, is the development of an optical temperature probe, together with optical cable and surface electronics. This instrument can be adopted in temperature conditions up to 500°C and to depths of 3500 m.

Stimulation

Another important activity of the last few years and which is expected to be of considerable interest in future is the development of pratical methods for stimulating wells that are no longer commercial but could at least be used as reinjection wells.

The poor local permeability encountered by these wells is normally responsible for their decreased productivity and/or injectivity.

For some time now ENEL has been conducting hydraulic stimulation tests, sometimes using chloric acid, as the formations are usually carbonates.

The results of these experiments have been analyzed by a theoretical model (numerical simulation), as well as by well test analyses, in order to achieve a greater under-standing of the phenomenology involved in stimulation operations.

Two types of stimulation have been tested:
- removal of skin effects with a high matrix permeability
- creation and/or propagation of fracture systems connected with the wells.

In the first case, removal of skin effect generally succeeds in vastly improving injection properties.

The test results obtained so far in the second type of operation are encouraging, but cannot be considered totally adeguate for practical purposes.

In this cases stimulation by pressurized injection until hydraulic fracturing is achieved results in:
- the creation or propagation of a fractured zone
- a gradual shift in skin from positive to negative values
- a reduction in the initial over-pressure limit
- an improvement in injectivity for increasingly longer injection times
- a hydraulic behaviour typical of fractured media.

These results are interpreted as follows:
- the fractures remain partly open as injection pressure ends
- thermal stress, by reducing effective stress in the fracture zone, explains the permeability increase on the fracture surface;
- because of the low heat conductivity of the rocks, this increase in permeability is maintained with time.

However, as the effects are confined to a small part of the medium and increase in its average permeability not expected, more satisfactory results can only be achieved when the artificial fractured surface reaches a high permeability zone.

Tests will be held in future in wells sited in particular conditions.

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