FIFTEEN YEARS OF DEVELOPMENT OF LOS AZUFRES GEOTHERMAL FIELD, MEXICO

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ABSTRACT

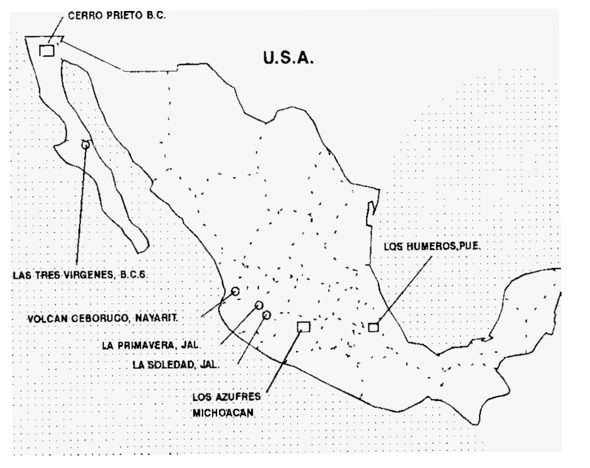
At the Los Azufres, Mexico geothermal field, jluid and energy have been extracted since 1980, although its intense exploitation began by 1982. Today, it has an installed capacity of 98 MWe, which make this reservoir the second in importance in Mexico, and the first in generating electricity from fluids located in volcanic fractured rock. This hydrothermal system was thoroughly studied since the beginning of its exploitation. Technical and scientific information generated by the continuous observation of the field, is numerous. Geochemical, geophysical and geological traditional studies, are supplemented by mineralogy of hydrothermal alteration, jluid inclusions, core analysis, pressure tests, aeromagnetic surveys and Landsat image studies. The waste liquid is continuously injected at Los Azufres. The reinjection is accompanied by some incidental admission of atmospheric air. This has resulted in an improvement on heat recovery and in the development of a simple and cheap method to estimate three-dimensional distribution of permeability. The pressure decrement at field's sectors subject to intense exploitation, has an average value of 1.02 bar/year. Decrement of produced vapour, obtained comparing representative jluid rates at the beginning of exploitation to present values, is in average, equal to 1.0 T/h of stem every year for those sectors.

INTRODUCTION

In 1954 the first geothermal producer well in Mexico was drilled at Pathé, Hidalgo. At the same place, in 1959 started to operate the first geothermal power plant in Latin America with 3,5 MW_e. Since that year the Mexican geothermal development has notably grown. Today, there are in operation three geothermal fields (Fig. 1) having a total installed capacity of 753 MW_e. This figure represents 2,6% of the 29.204 MW, of country's total electric capacity. In 1994 geothermic produced 5880 GWh contributing with 5% to the total generated energy. Cerro Prieto in Baja California, with more than 20 years of generation has an installed capacity of 620 MW_e, Los Azufres in Michoacán, 98 MW_e and Los Humeros in Puebla, 35 MW_e. The average plant factor in these fields is around 90%.

At the Los Azufres field is located the second largest geothermal reservoir; its existence is known since pre-Hispanic times. The ancient inhabitants (purhépechas) left oral testimonies about practical uses they made with the fluid in different forms. In this century, the reservoir was studied somewhat in the 50's and then given up. In 1972 the investigations were renewed, culminating in 1977 with the completion of the first producer well. To date 63 wells have been drilled at depths ranging between 627 and 3544 meters. Among them, there are 28 producers, 11 injectors, 13 are under study, 7 have low permeability and 4 have not been completed. The field generates about 650 GWh per year with 12 generating units; it feeds electricity to Morelia City and part of the El Bajío region. The installed capacity is distributed into nine 5 MWe non-condensing plants, a 50 MWe condensation unit constructed in 1988, and two binary cycle units of 1,5 MWe each. The first 5 plants were installed in 1982 with the double objective of generation and to study the reservoir subject to continuous exploitation. In this field at least 200 additional MWe could be installed.

Fig.1 LOCATION OF THE LOS AZUFRES FIELD AND OTHER GEOTHERMAL AREAS IN MEXICO



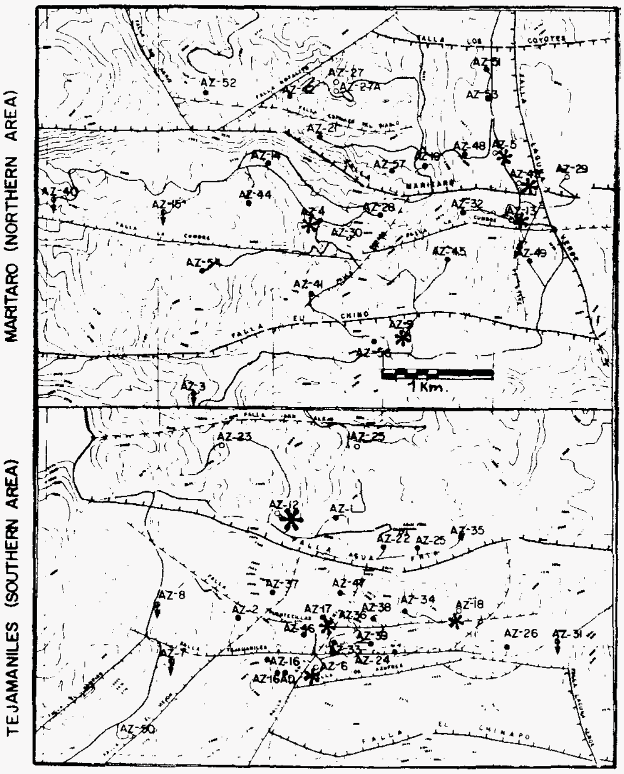
igures 2, 3 and 4 show the evolution of electric power installed, generation per year and total energy produced by this field in the period 1982-1994.

CHARACTERISTICS OF THE RESERVOIR

Los Azufres, at 2800 masl, is one of several high temperature reservoirs located in the so called neo-Volcanic Mexican Belt. Its explored area by geological, geophysical and geochemical techniques covers an extension of about 60 km^2. Regional (high altitude) and detailed (low altitude) aeromagnetic surveys were completed in past years (Ross et al, 1989); the regional survey covered an area of 1500 km^2, the second covered approximately 96 km^2. A study of a LANDSAT-5 image was also done on this geothermal area, providing or corroborating structural information (Wright et al, 1989). Compared to other geothermal systems in the same belt such as Los Humeros and La Primavera both related to calderas, Los Azufres reservoir is associated with young silicic domes emplaced into a geological system formed by andesites of tertiary age, presenting several faults and intense fracturing. Several important faults exist in both sectors; some of them are intersected by wells at different depths (Fig. 1.1).

The reservoir's sedimentary basement is covered by a thick andesitic series of tuffs, breccia and flows. The volcanic activity at this system changed from dominantly andesitic to dominantly silicic approximately one million years ago. Silicic volcanism began with the eruption of Tejamaniles dacites and Agua Fria rhyolites in the south, and rhyodacites in the center of the geothermal field. The actual reservoir was developed in fractured lava flows of andesites that are overlain by rhyolites. These last rocks typically range from ten to three hundred meters thick, nevertheless, the wells drilled into the vent areas encountered silicic rocks down to 1100 meters (Razo et al, 1989). The known reservoir consists of complex series of andesitic layers with different textures, and rhyolite in the upper levels.

FIG. 1.1 - MAP OF THE LOS AZUFRES GEOTHERMAL FIELD SHOWING MAIN FAULTS, PRODUCTION AND INJECTION WELLS



LEGEND: nn Main Fault — ✳ 5 MWe Wellhead Generator

● Production Well — ✷ 50 MWe Unit at the Tejamaniles Sector

Injection Well

Locally, the field is affected by several structural systems, the most important are oriented E-W, controlling the ascent of fluids and related to intensely fractured zones that might be the main responsible for fluid's conduit through this direction. Distribution of hydrothermal alteration minerals suggests a possible field's geometry that corresponds to a main reservoir at depth, discharging ascending fluids through fractured subsystems, defining two probably connected geothermal zones: Maritaro in the north and Tejamaniles in the south.

A high electric resistivity central zone separates both portions of the field. At shallow layers hydrothermal alteration is very low but at 1800 m depth, an alteration continuity binding both zones suggests a deep common aquifer existence. In Tejamaniles the circulation zone is narrow and brings out fumaroles, steam plumes, hot springs, mud lakes and steaming ground. There is no isotopic evidence of mixture of meteoric water or shallow groundwater with geothermal fluid.

Enthalpy and chemical data show that boiling occurs in the reservoir (Nieva et al, 1983). Chemical fluid composition is different in several wells, suggesting the existence of different production sections. The CO_2 mass fraction in vapour discharged at 10 bar, varies between 0.2% at well Az-4 (north) and 8.5% at well Az-34 (south). The highest CO, content is found in shallow wells with high steam fraction. In the southern sector around Puentecillas fault, there is a non-condensible gas concentration gradient: the amount of CO_2 dissolved in fluid appears higher in the Eastern portion of the reservoir than in the Western section. Chemical data show that concentration of volatile components in fluid decreases with depth, while concentration of non-volatile components, such as chloride, increases (Nieva et al 1987).

Fig. 2.- ELECTRIC POWER INSTALLED AT THE LOS AZUFRES FIELD 1982-1994

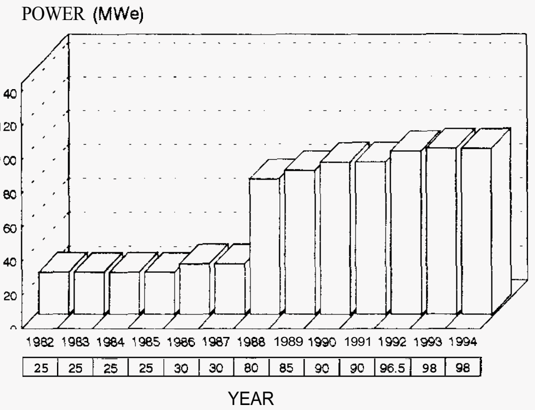


Fig. 3 GENERATION AT LOS AZUFRES GEOTHERMAL FIELD 1982-1994

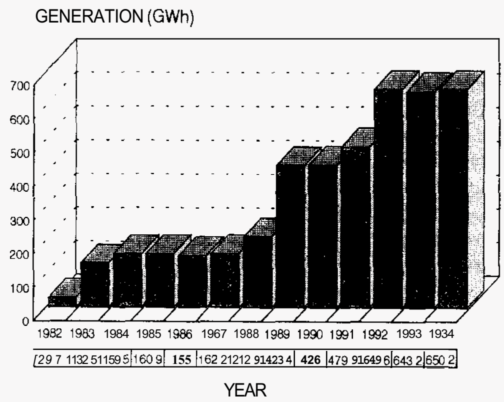
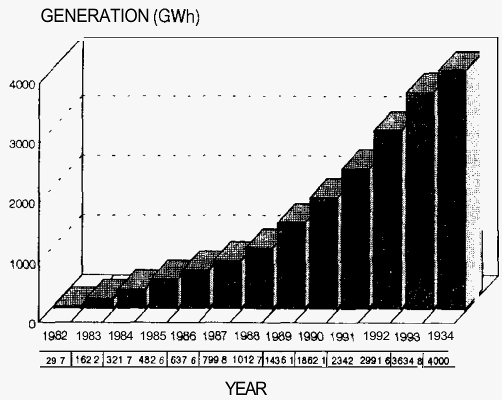


Fig. 4 TOTAL ENERGY GENERATED BY LOS AZUFRES RESERVOIR Electricity 1982- 1994



CONCEPTUAL RESERVOIR'S MODEL

Petrographic studies were carried out on cuttings and core samples from 52 deep wells, during ten years. Fluid inclusions' analyses were also performed in some wells (Viggiano, 1987). Such studies helped to figure out the flow regime, the reservoir's geometry and to better characterize the production strata. A synthesis of petrophysical measurements done in 24 drilling cores of 17 wells is presented in Table 1 (Contreras et al 1988).

The reported properties are: total dry rock density, effective porosity, absolute matrix permeability (k_{Abs} in microdarcy), permeability estimated by pressure tests (k_{Pres} in md), specific heat,

Table 1.- LOS AZUFRES RESERVOIR ROCK PARAMETERS

Well	Z (masl)	Rock Density (g/cm³)	Porosity (%)	k_{Abs} (μD)	k_{Pres} (mD)	K_{Ter} W/m/C
Az-01	1029.2	2.72	2.6	1.0	?	-
Az-03	2185.7	2.30	14.8	3.5	?	1.68
Az-03	911.5	2.56	13.2	177.3	14.3	1.84
Az-03	670.2	2.74	2.1	1.3	?	1.99
Az-04	1865.0	2.43	12.6	1.8		
Az-05	2300.0	2.08	23.2	1.7		
Az-05	1737.5	2.38	11.9	151.3	?	
Az-08	1995.0	2.59	7.8	123.5	42.3	2.34
Az-09	1233.5	2.66	2.6	2224.0	?	-
Az-10*	1649.5	2.66	4.7	1.3	?	-
Az-19	1837.0	2.29	15.5	15.0	?	1.97
Az-20'	1847.8	2.26	13.1	1.8	?	1.58
Az-20'	898.5	2.66	4.7	1.5	?	1.71
Az-22	2053.5	2.45	9.9	1.7	56.0	2.17
Az-25	2215.0	2.30	14.5	1.8		
Az-26	2310.5	2.61	2.6	2.0		
Az-26	1904.5	2.41	10.4	401.0	167.3	1.55
Az-29	2503.0	2.07	20.1	41.0		
Az-29	408.0	2.81	0.7	0.0	?	-
Az-41	2402.0	2.36	16.3	1.3	?	-
Az-46	2005.0	2.51	7.4	0.0	140.0	-
Az-47	-79.2	2.76	2.1	2.0	?	1.89
Az-48	239.7	2.84	1.0	0.0	?	-
Az-50*	1595.5	2.47	8.9	10.0	?	1.52
Rock Specific Heat (!)	1165 J/kg/C (0.278 cal/g/C)					
Thermal Diffusion (!)	6.6 10^{-3} cm²/s					

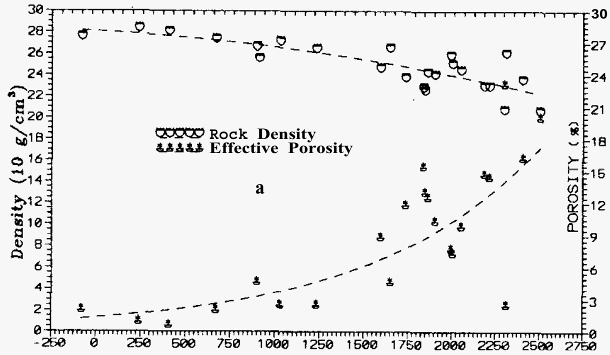
* *Out of the Reservoir* (!) *measured ut 250 °C and 80 bar.*

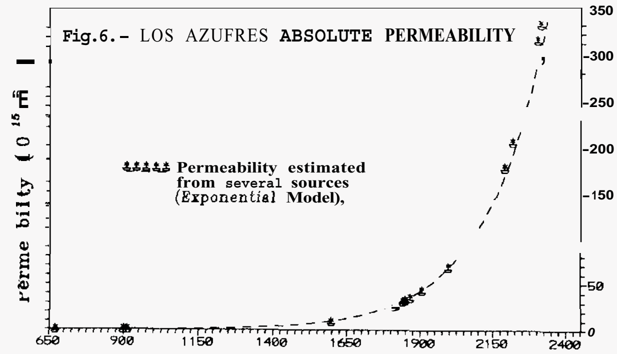
thermal conductivity and difussivity. Vertical distribution of these properties shows that porosity and probably permeability, decrease exponentially with depth, while rock density and thermal conductivity increase quadratically. On horizontal planes the same rock properties appear randomly distributed. This experimental evidence shows close dependence with depth of several key reservoir parameters (Figs. 5,6 & 7) suggesting that the amount of extractable heat and fluid stored into the reservoir and the recoverable energy fraction must be also functions of depth (Suárez, 1992). This information correlated to pressure test analysis and production data lead up to define several vertical layers in the southern sector; each stratum having different mineralogical and thermodynamical characteristics (Geotermia, 1991). The described strata are as follows:

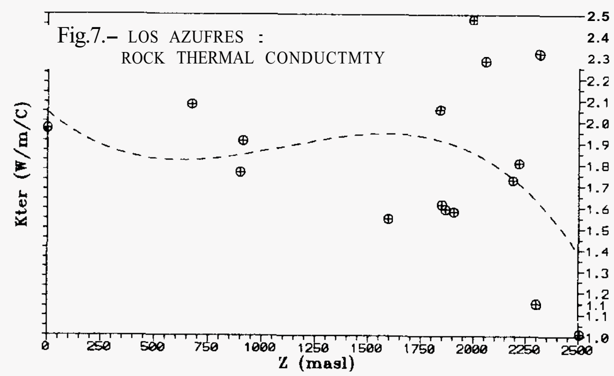
(A).- The caprock located between 2300 - 2950 masl, is formed mainly by rhyolite, containing clays as hydrothermal minerals. It includes the small shallow zones of superficial discharges.

(B).-The shallowest reservoir's portion is located between 2000 and 2300 masl; it contains two-phase, vapor dominated fluid; steam saturation reaches 0.67 as maximum value (Suárez et al, 1989). Clays, chlorite and quartz were found, average porosity and permeability are very high.

Fig. 5.- LOS AZUFRES ROCK PARAMETERS: POROSITY and DENSITY VERTICAL DISTRIBUTION







(C).- A thicker two-phase, liquid dominated zone is located between 1600 and 2000 masl. The first occurrence of both epidote and wairakite characterizes this portion which also contains chlorite, quartz and clays. Porosity and permeability are high. Most production wells have been completed in this layer, which is the highest production stratum.

(D).- The next zone located between 1200 and 1600 masl, is liquid dominated with small steam amounts; contains same hydrothermal minerals as before; porosity and permeability are low.

(E).- The deepest zone of the reservoir contains only compressed liquid and is located between 400 and 1200 masl. It could be the main source for vertical recharge. Hydrothermal minerals are the same as in layer *C;* porosity and permeability have the lowest reservoir's values.

(F).- An acquitard forming the reservoir's base, is located between 0 - 400 masl. It is composed by andesites having very low porosity and negligible permeability. Hydrothermal minerals are anhydrous (amphibole, biotite, K-mica, garnet, diopside). Compressed liquid attains here the highest pressure and temperature values.

(G).- A hypothetical region, assumed as a Hornfels, is placed below the acquitard and supplies thermal recharge to the reservoir; its thickness is unknown. At this, depth secondary minerals must be totally anhydrous, may be of contact metamorphism. Permeability and porosity are negligible. The thermal energy contained is very big but irrecoverable using current technology.

PRODUCTION AND INJECTION DATA

The field has been in continuous commercial exploitation since 1982 subjecting the reservoir to mass and heat extraction gradually incremented. In Tejamaniles, fluid extraction takes place at field's center, while reinjection is carried out at the extreme sides of production zones. Actually, in this sector, exploitation is concentrated in Puentecillas faults' system (Fig. 1.1), where 75% of total steam is extracted. In Maritaro, the northern sector, extraction of fluid is scattered over all the reservoir assigned area. Production characteristics of some wells are shown in table 2.

'able 2. Characteristics of Production Wells in Los Azufres

Wells in Maritaro (northern sector)				
WELL	WHP(bar_g)	STEAM@	LIQUID@	GAS ($\%_w$)
Az-04	12	50	89	1.4
Az-05	10	83	56	1.4
Az-09	7	31	36	0.5
Az-13	11	64	15	1.9
Az-28	10	24	37	0.3
Az-32	10	52	2	2.0
Az-41	10	36		-
Az-42	10	126	203	0.5
Az-43	12	50	35	1.0
Az-48	10	38	43	0.3
Az-51	10	47	105	0.4
Az-56	9	20	15	0.5
TOTAL		621	636	
WELL	WHP(bar_g)	STEAM@	LIQUID"	GAS ($\%_w$)
Az-02	20	73	211	0.7
Az-06	11	27	0	4.2
Az-16	10	32	92	0.9
Az-16D	12	20	11	4.0
Az-17	9	52	0	2.2
Az-18	11	71	35	9.0
Az-22	20	85	104	0.8
Az-26	10	88	180	4.5
Az-33	12	40	70	2.5
Az-34	10	50	0	7.0
Az-35	15	37	0	3.0
Az-36	11	36	27	2.4
Az-37	12	49	0	2.0
Az-38	11	105	0	2.8
Az-46	11	52	109	1.4
Az-55	10	38	48	0.8
TOTAL		855	1007	

Fluid feeding most wells is two-phase in natural state. Pressure and temperature vertical profiles are shown in figures 8 and 9. These profiles show that in the southern sector between 1800 and 2500 masl, pressure and temperature gradients are small, showing nearly vaporstatic conditions, they can be approximately represented by a boiling-point-for-depth curve. Between 0 and 1550 masl, the thermodynamic profiles correspond to hydrostatic conditions in both

Fig. 8.- PRESSURE VERTICAL PROFILE IN TEJAMANILES

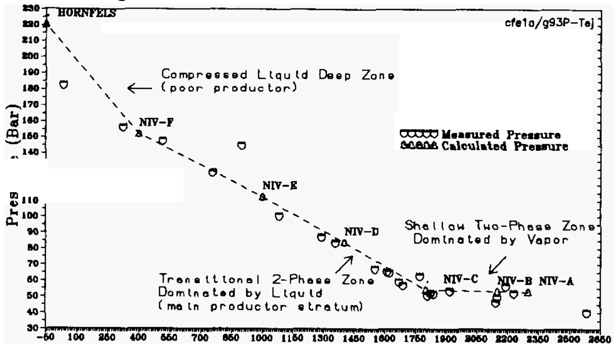
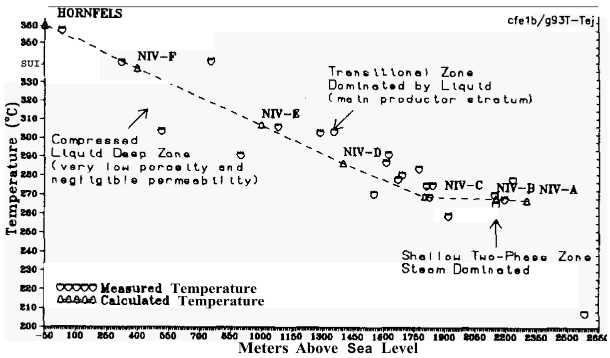


Fig. 9.- TEMPERATURE VERTICAL PROFILE IN TEJAMANILES



sectors. Various types of numerical simulations have been carried out with different purposes: to estimate the longevity and global evaluation of the resource; to the detailed study of faults and fractures and to know the influence of non condensible gases on wells' production.

Since August 1982, five wellhead non-condensing units, generating 5 MW, each, were installed. In November 1988 a 50 MW_e condensing unit was constructed at Tejamaniles. The installed capacity distribution is shown in Table 3. The total amount of primary steam available at field's surface is 1550 T/h; from this quantity, 950 T/h are used to feed nine power plants. Eight deep wells are being used to reinject 600 T/h of separated and condensed liquid coming from the power plants. The maximum amount of fluid accepted by some wells is about 350 T/h. The temperature of injection varies between 40 and 50 °C at an atmospheric pressure of 0.73 bar. Data coming from two-phase wells, show that concentration of chlorides and other salts (calcium, cesium, potassium, rubidium, sodium, etc.) dissolved in separated liquid, have been growing since June 1986 (Fig. 10). This effect extends to wells Az-16D, Az-33, Az-37 and Az-46 and could have a close relationship with liquid reinjected into the reservoir by inducing successive salts concentration due to the same injected water arrival into production zones.

The horizontal distance from injection wells to nearest productors ranges from 1000 to 2000 meters, injection wells being 500 to 1000 m. deeper. The total vectorial distance between production and injection zones is a critical parameter because reinjection too close to the producing zone would induce, inevitably, a temperature drop on produced fluid. Until 1994, average enthalpy data show that liquid is reinjected at adequate depth and distance from production zones. But locally, since 1991, the behaviour of some wells indicates important influence of injection on two-phase fluid composition (Fig. 12). Diminishing or incrementing the amount of reinjected water, the producers diminish or increment the separated liquid, but maintaining the same steam quality, although their enthalpy grows a little when the liquid decreases. Other undesirable aspects of reinjection such as serious lower enthalpy interference at producing wells, or decreasing formation permeability by chemical deposition, or contamination of groundwater have never been noticed at this field.

UNIT	manufacturer	Capacity (MWe)	On Line	Load (%) Dec - 94
U-1	Mitsubishi	5	07130182	94.6
U-2	Mitsubishi	5	08104182	99.7
U-3	Mitsubishi	5	08/10/82	93.7
U-4	Mitsubishi	5	08/17/82	100.7
U-5	Mitsubishi	5	08/26/82	97.7
U-6	Toshiba	5	12/23/86	98.4
U-7	General Electric	50	11/12/88	63.9
U-8	Ansaldo	5	12/01/89	98.9
U-9	Ansaldo	5	04/24/90	98.6
U-10	Ansaldo	5	15/06/93	83.7
U-11	Ormat	1.5	15/06/93	-
U-12	Ormat	1.5	15/06/93	-
TOTAL CAPACITY = **98.0**				

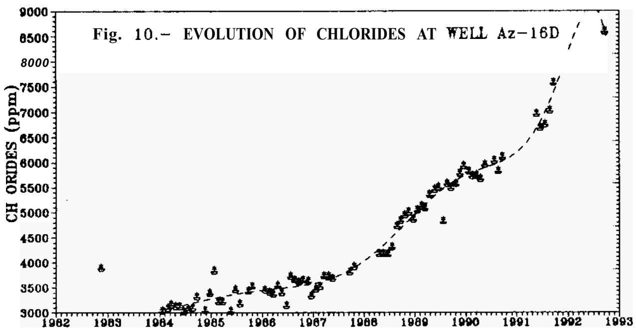
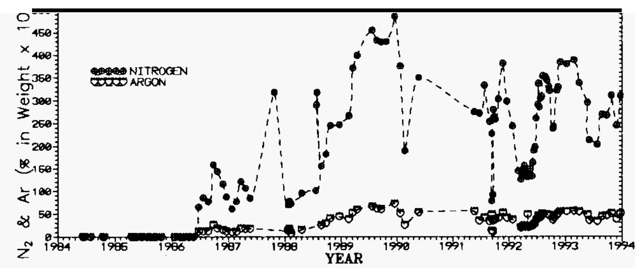


Fig. 10.– EVOLUTION OF CHLORIDES AT WELL Az-16D

Fig. 11.– NITROGEN and ARGON EVOLUTION IN WELL Az-16D



THE AIR INJECTION EFFECT

Simultaneously with geothermal water reinjection, an important amount of air has been continuously inflowing to the reservoir through open injection wellheads. Atmospheric air is also 'dragged' from the open surface of collection boxes. Several facts suggest that air injection into intensely fractured systems could be considered as a long term natural tracer test. Natural N_2 solubility in fluid at the Los Azufres reservoir represents about **0.2** % in weight. Figure 11 shows N_2 and Ar behavior as function of time at well Az-16D. It is inferred that nitrogen, separated from air mixture, is transported by hydrodynamic dispersion gradient through high permeability conduits, from reinjection zones to producing wells. In previous numerical studies concerning the mechanism of this phenomenon, it was possible to estimate that nitrogen takes between one month and 50 days to arrive at production zones. These times correspond to an average velocity between 46 mlday to 22 mlday. Distribution of permeability, calculated by trial and error matching the production/injection history, allows to deduce some preferential dispersion paths followed by N, during its rapid migration from reinjection to extraction zones. Oxygen coming together with nitrogen, enters into the reservoir, but is consumed by reducing agents present in the fluid/rock system, probably in the neighbourhood of injection wells. Except for Argon, the influence of other gases forming the air mixture is negligible.

RESERVOIR'S EVOLUTION

Figure 13 illustrates the behavior of one of the oldest wells in Los Azufres. Variation of temperature is very low. Pressure variation is assumed to represent depression at the vicinity of production zones. From 1982 to 1993, pressure decrement in Puentecillas system, the most exploited field's section, has an average value of 11.2 bar. This means a net fall of 1.02 bar/year in this sector. Pressure decline reaches a maximal value at well Az-16D (12.9 bar), and is minimal at well Az-22 (0.31 bar). The decrement of produced vapor, is obtained comparing representative steam rates at the beginning of the exploitation with present values. In average, steam loss is equal to 1.0 T Ih of vapor every year for the whole sector. A comparison between wellhead pressure, bottomhole flowing pressure and reservoir observed pressures are also shown.

Fig. 12.– ENTHALPY & PRODUCED LIQUID RATE, WELL Az-16D

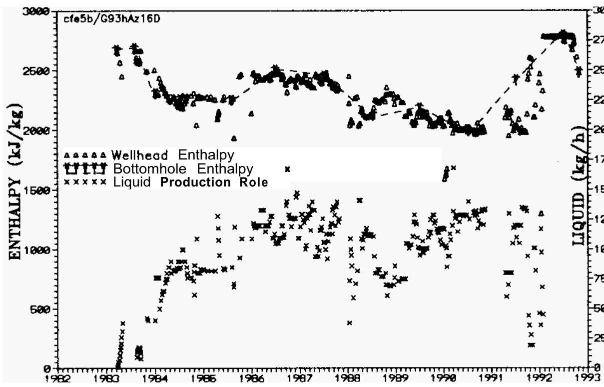
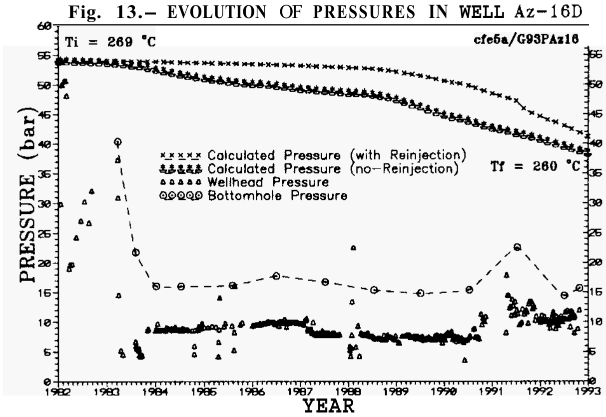


Fig. 13.– EVOLUTION OF PRESSURES IN WELL Az-16D



DIRECT USES OF GEOTHERMAL ENERGY

As an integral action for geothermal energy use, CFE has developed at Los Azufres diverse pilot projects for new applications development of this natural resource. Among them are: Industrial wood drying; space heating (offices); bulbs' germination and accelerated production of flowers; residual heat usage in a greenhouse, supporting reforestation works. On areas affected during the process of geothermal field construction, ecological restoration actions are carried out. This includes reforestation works and installation of compost wood boxes and soil. A tree nursery provides enough quantity of plants and *seed* for reforestation and pasture. Up to date it has been planting more than half million trees in an extension of 340 hectares and has covered 14 more hectares with grass and *seed.* New designs of mufflers have developed to lower noise from 115 to 75 decibels. Daily mensurations are carried out to keep permitted levels of noise and gases' concentration.

CONCLUSIONS

We present in condensed form, the most outstanding facts and knowledges proportionated by this hydrothermal system. Los Azufres can be conceptually simplified as a discontinuous volume of fractured andesites, intersected by several high permeability faults, having very low permeability in the block matrix and extremely high permeability in fractured meshes around faults. The permeability is also very low at the top and bottom of the reservoir, but the system allows the communication to the surface by small open conduits (cracks) through the caprock.

The initial response of the field to exploitation is primarily reflected by geochemical changes. Both sectors of the field show some important local alterations. From a thermodynamical point of view, Tejamaniles, the southern zone, presents three different vertical zones distinguishable by their vapor saturation. Maritaro, the northern sector, presents only one.

Fluid extraction from the reservoir occurs simultaneously with reinjection of cold liquid and air. The thermodynamical effect of this parallel process has been beneficial for the energy production and longevity of this reservoir. Injection of liquid involved since the beginning of exploitation, avoided the environmental impact of wastewater disposal and improves heat recovery.

Air mixed with injected water, is decomposed into its primary components. Nitrogen and argon propagate very fast through fractures network and arrive at producing regions with negligible thermal interference. This has resulted in the development of a simple and cheap method to estimate three-dimensional permeability tensor.

The response of the field to exploitation is heterogeneous and will require incorporating more realistic details, such as complex fractured meshes, into future reservoir simulations.

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