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RESPONSE OF THE LOS AZUFRES GEOTHERMAL FIELD TO FOUR YEARS OF 25 MW WELLHEAD GENERATION

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ABSTRACT

Production and chemical data have been compiled and analyzed on a six-month averaged basis for the first four years of electric energy generation with five 5-MW wellhead generators at the Los Azufres geothermal field. The data were evaluated with respect to the extent of observable thermal drawdown of the reservoir from 25 MW of generation in relation to the estimated capacity of the field of several hundred megawatts of power. The analysis updates the previous one compiled after the first two years of continuous production, at which time the results indicated that differences in reservoir temperature estimated from geochemical thermometers and wellhead production data were not statistically significant based on the number of data and the standard deviations. Analysis of the data after four years of operation were made for the larger number of data and smaller standard deviations. The results review the adequacy of the sampling frequency and the reliability of the measurements from statistical t-Test of the means of the first and second two-year periods.

INTRODUCTION

An important aspect of the development of geothermal resources is the observation of the effects on the reservoir from early sustained production with small generating units used to initiate potentially large fields. Such observations have been a continuous objective of the electric power production program started at the Los Azufres geothermal field in the summer of 1982 with five 5-MW wellhead units. Since production startup, a large database of production and chemical data has been compiled to characterize the well and reservoir conditions during the startup period and to establish the initial conditions of the reservoir near the production wells. The latter objective is of importance for observing changes in reservoir characteristics with production prior to installation of additional generating capacity planned for the near future.

The Los Azufres geothermal field is located in the State of Michoacan, about 200 km northwest of Mexico City. It is part of the Transmexico Neovolcanic Axis across central Mexico (Mooser, 1972). The geothermal reservoir is a complex structural and thermodynamic system, containing several major parallel faults. Sustained production in the field started with three 5-MW wellhead generator units in the northern (Maritaro) zone producing two-phase fluid and two 5-MW units in the southern (Tejamaniles) zone producing essentially all-steam or large steam fraction fluid. A review of the operating characteristics of the 5-MW turbine-generator units was given by Hiriart (1983).

A significant body of information on the Los Azufres field has been compiled since the early reports by de Anda (1951) on the geologic, geophysical, and geochemical characteristics. Geologic maps, first prepared by Camacho (1976), are continuously updated. The structural and volcanic features were described by de la Cruz (1982) and more recently by Dobson and Mahood (1985). Data for brine chemistry and noncondensable gases were reported by Templos and Lopez (1980) and Templos and Laredo (1980). An overview of the distribution of chemical and isotopic composition of Los Azufres geothermal fluids prior to startup was reported by Nieva et al (1983). Their data showed much heterogeneity of the liquid phase in the reservoir. The chemical data showed phase separation around the wells without evidence of recharge by infiltrating groundwater. From several chemical geothermometers, the temperature range in the northern (Maritaro) zone was estimated in the range of 248 to 315 °C, and in the southern (Tejamaniles) zone in the range of 248 to 328 C. Iglesias et al. (1983) investigated reservoir pressure as a function of depth in the Tejamaniles zone wells. They concluded that a continuous steam phase did not exist in the reservoir, but that isolated pockets of steam were developing by boiling of nearby immobile liquid water.

Two earlier evaluations of the startup effects of the 5-MW wellhead units have been reported. The first of these (Kruger, et al, 1985a) examined the initial chemical and reservoir conditions during the first two-year startup period with data compiled as six-month average values for each of the

Table 1

Six-Monthly Averaged Production Data

Well No.	Period	P(wh) (MPa)	P(sep) (MPa)	Q(wh) (kg/s)	X(v)	H(wh) (kJ/kg)
I. Tejamaniles Zone						
Az-6	2-82	0.84	—	12.4	1.00	2771
	1-83	0.80	—	11.7	1.00	2769
	2-83	0.82	—	11.7	1.00	2770
	1-84	0.81	—	11.7	1.00	2770
	2-84	0.85	—	10.4	1.00	2772
	1-85	0.85	—	10.8	1.00	2772
	2-85	0.91	—	10.5	1.00	2774
	1-86	0.95	—	10.7	1.00	2776
Az-16AD	2-83	0.94	0.93	8.4	0.89	2549
	1-84	0.92	0.92	9.0	0.77	2304
	2-84	0.93	0.92	9.1	0.74	2246
	1-85	0.91	0.90	8.9	0.73	2234
	2-85	0.96	0.94	9.0	0.72	2213
	1-86	0.95	0.92	9.6	0.65	2064
Az-17	2-82	2.16	0.88	17.4	1.00	2769
	1-83	2.02	0.90	17.2	1.00	2770
	2-83	1.98	0.93	17.2	1.00	2771
	1-84	1.88	0.96	16.7	1.00	2773
	2-84	1.88	0.86	15.4	1.00	2770
	1-85	1.82	0.83	15.8	1.00	2771
	2-85	2.00	0.84	15.8	1.00	2771
	1-86	1.89	0.91	15.2	1.00	2778
II. Maritaro Zone						
Az-5	2-82	3.10	0.90	26.5	0.63	2023
	1-83	2.77	0.92	26.5	0.62	2001
	2-83	2.68	0.94	26.8	0.60	1963
	1-84	2.72	0.96	26.4	0.62	2011
	2-84	2.55	1.01	28.6	0.60	1977
	1-85	2.46	0.93	30.0	0.61	1991
	2-85	2.29	0.94	29.3	0.61	2044
	1-86	2.13	0.86	29.1	0.60	1971
Az-13	2-82	1.07	0.85	27.8	0.60	1954
	1-83	0.88	0.86	28.2	0.60	1960
	2-83	1.01	0.85	27.9	0.59	1936
	1-84	0.84	0.83	29.7	0.57	1889
	2-84	0.84	0.81	32.6	0.52	1795
	1-85	0.76	0.74	31.9	0.55	1847
	2-85	0.77	0.75	31.9	0.54	1830
	1-86	0.79	0.78	30.6	0.55	1855
Az-19	2-82	0.83	0.83	17.0	0.44	1626
	1-83	0.89	0.87	15.6	0.32	1387
	2-83	0.76	0.74	15.9	0.28	1282
	1-84	1.19	*	*	*	*
	2-84	1.83	0.78	15.5	0.26	1245
	1-85	1.66	0.80*	10.4*	0.41*	1560
	2-85	1.44	0.71	11.3	0.36	1447
	1-86	1.34	0.63	11.3	0.30	1300
Az-28	1-84	1.10	—	27.8	0.48	1451
	2-84	1.26	0.78	25.4	0.37	1474
	1-85	1.14	0.80*	22.8*	0.34*	1425
	2-85	1.04	0.71	20.6	0.38	1488
	1-86	0.90	0.63	20.0	0.39	1491

*well shut-in part or all of semester.

Table 2

Aqueous Chemistry Data

Well No.	Period	pH	[Cl] (g/kg)	[Na] (mg/kg)	[K] (mg/kg)	[Ca] (mg/kg)	[SiO_2] (mg/kg)
Az-5	2-82	7.2	2.85	1654	399	7.4	1064
	1-83	7.0	3.07	1691	425	10.1	1168
	2-83	7.1	3.15	1741	429	3.6	1108
	1-84	7.1	3.03	1680	451	10.0	1081
	2-84	-	2.92	1607	446	7.2	907
	1-85	7.0	3.22	1680	472	7.5	1025
	2-85	7.2	2.98	1678	461	6.8	1069
	1-86	7.0	3.09	1723	468	7.5	1114
Az-13	2-82	7.6	3.00	1765	406	13.4	747
	1-83	7.7	2.77	1507	355	12.0	865
	2-83	7.8	2.94	1661	366	9.3	645
	1-84	7.7	2.84	1572	394	12.8	918
	2-84	7.6	2.73	1517	399	9.9	805
	1-85	7.6	2.88	1498	392	10.9	805
	2-85	7.8	2.87	1645	412	9.8	799
	1-86	7.6	2.84	1634	411	10.0	892
Az-16AD	1-84	7.6	3.11	1816	370	32.8	419
	2-84	7.5	3.25	1870	386	26.4	576
	1-85	7.6	3.37	1751	390	36.7	660
	2-85	7.6	3.38	1937	402	32.9	683
	1-86	7.4	3.40	1977	425	38.9	695
Az-19	2-82	7.4	2.88	1633	387	7.4	1034
	1-83	7.4	2.61	1445	343	8.1	910
	2-83	7.5	2.80	1580	357	5.3	961
	1-84	7.2	2.71	1537	412	8.1	1058
	2-84	6.9	2.82	1571	422	15.6	1015
	1-85	7.9	2.81	1462	372	7.3	900
	2-85	7.5	2.42	1355	365	6.9	889
	1-86	6.5	2.40	1305	343	5.9	856
Az-28	1-84	6.8	3.41	1972	508	12.1	1170
	2-84	6.3	2.66	1532	412	10.9	797
	1-85	6.9	3.44	1625	463	6.6	938
	2-85	7.1	2.70	1510	412	5.3	904
	1-86	6.7	2.68	1457	415	5.7	808

unit wells. From these data, initial reservoir and bottom-hole temperatures were estimated. It was noted that the data were obtained under a variety of objectives and analytical techniques with consequent uncertainties in the mean values larger than desirable for use as indicators of change with production. The second report (Kruger et al., 1985b) was based on a quality analysis of the sampling and chemistry data to reduce the uncertainty in the averaged values, and with the addition of an additional half-year of data, the initial thermodynamic and chemical characteristics of the reservoir were re-evaluated. The components of the chemical data included aqueous chemistry of the brines for the two-phase wells, noncondensable gases including radon for all of the wells, and geothermometer reservoir temperatures from the aqueous chemistry data.

The results of these two evaluations showed the clear delineation of the two major zones of the field, the vapor-dominated Tejamaniles (southern) zone with an initial temperature of about 260 ± 5 °C consistent with the observations of Iglesias et al. (1983) for the depth of these wells and an initial temperature of about 300 ± 10 °C for the two-phase Maritaro (northern) zone. Based on the two-year averaged reservoir temperature data, an isoenthalpic progression of steam fractions and temperatures from the reservoir to the wellhead were noted from the Fournier and Truesdell (1973) Na-K-Ca geothermometer and the Fournier and Potter (1982) silica geothermometer. The lower silica temperatures were in accord with the views of Truesdell et al. (1984) and Grant et al. (1984) that the silica based geothermometer indicates reservoir conditions closer to the wellbore as boiling increases the steam fraction and silica precipitates before fluid production. Over the first two years of production, no discernable changes were noted by statistical t-Test analysis of the first vs second year's data due primarily to the small number of samples and the relatively large standard deviations of the means. These data have now been updated with production and chemical data for the first four years of operation of the 5-MW generator units. At this time, a larger number of samples and reduced uncertainty in the means have allowed more reliable t-Tests of the data grouped into two 2-year periods.

ACCUMULATED DATA

Production data have been compiled for the original wells used for the five 5-MW wellhead units: Az-6 and Az-17 in the Tejamaniles zone and Az-5, Az-13, and Az-19 in the Maritaro zone. Two of the units have since required additional steam supply; in 1983 flow from well Az-16AD was added to the flow from Az-6 in the Tejamaniles zone and in 1984, flow from Az-28 was added to the flow from Az-19 in the Maritaro zone. Due to a heavy influx of cold water, well Az-19 has been shutin on occasion since then.

Table 1 summarizes the mean six-monthly production data for the five generator units over the four year period. Table 2 summarizes the mean six-monthly chemical data for the five wells in the Maritaro two-phase zone. Table 3 shows the mean six-monthly reservoir temperatures calculated by the Na-K-Ca geothermometer of Fournier and Truesdell (1973) and the SiO_2 geothermometer of Fournier and Potter (1982). Also given in Table 3 are the mean wellhead enthalpies obtained from production data and the reservoir enthalpies corresponding to the silica geothermometer relationships from Fournier and Potter (1982).

The production data in Table 1 reflect the continuous steam production in wells Az-6 and Az-17 in the Tejamaniles zone. The small and declining production rate in well Az-6 has been augmented with flow from well Az-16AD. For the northern Maritaro zone, the data show the steady operation of wells Az-5 and Az-13 with slowly increasing flowrates as steam fraction declines. The data for well Az-19 reflect the continued cold-water influx with production augmented by the somewhat better quality flow from well Az-28. The separator pressure has been maintained at the minimum inlet pressure required for the 5-MW wellhead unit turbines.

The aqueous chemistry data are monitored by the chloride concentration, which shows no discernable change for wells Az-5 and Az-13. The chloride concentration seems to increase in well Az-16AD and decrease in the fourth year at well Az-19 and more rapidly in well Az-28. The sodium, potassium, and silica concentrations appear to follow these trends. The geothermometer temperature data in Table 3 indicate an increase in the Na-K-Ca temperature in several of the wells and a decrease in SiO_2 temperature in others. Figure 1 shows the data and trend line of the 33 individual Na-K-Ca temperatures for well Az-5 in comparison to the observed wellhead fluid enthalpy. The slope of the Na-K-Ca temperature trend line is +3.5 °C/yr and the slope of the wellhead enthalpy trend line is +2.6 kJ/kg-yr. Figure 2 shows these data for well Az-13. For this well the rate of increase of the Na-K-Ca temperature is +3.9 °C/yr and the rate of change of the wellhead enthalpy is essentially zero. Figure 3 shows the data and trend lines for the two reservoir temperature geothermometers for well Az-19, where cold-water intrusion from a casing break above is known to be occuring. The slopes of the trend lines are +0.25 °C/yr for the Na-K-Ca and -0.38 °C/yr for the SiO_2 geothermometers.

Table 3

Mean Semi-Annual Temperature - Enthalpy Data for the Maritaro Wells

Well No.	Period	Num Obs	T(Na-K-Ca) (°C)	T(SiO_2) (°C)	H(wh) (kJ/kg)	H(SiO_2) (kJ/kg)
Az-5	2-82	3	308 ± 2	293 ± 15	2023	1303 ± 74
	1-83	5	309 ± 12	302 ± 17	2001	1355 ± 99
	2-83	1	320	298	1963	1325
	1-84	6	311 ± 5	295 ± 13	2011	1311 ± 63
	2-84	5	318 ± 5	277 ± 13	1977	1223 ± 63
	1-85	5	320 ± 6	289 ± 5	1991	1284 ± 26
	2-85	4	319 ± 2	294 ± 8	2044	1305 ± 40
	1-86	4	317 ± 3	298 ± 5	1971	1328 ± 26
Az-13	2-82	6	292 ± 8	268 ± 21	1954	1180 ± 06
	1-83	6	295 ± 12	272 ± 17	1960	1200 ± 87
	2-83	1	294	248	1936	1080
	1-84	5	300 ± 4	283 ± 5	1889	1252 ± 26
	2-84	6	306 ± 4	267 ± 10	1795	1174 ± 50
	1-85	6	304 ± 4	266 ± 5	1847	1170 ± 26
	2-85	5	305 ± 2	266 ± 8	1830	1178 ± 42
	1-86	5	304 ± 2	276 ± 11	1855	1215 ± 53
Az-16AD	1-84	6	274 ± 7	216 ± 18	2304	923 ± 83
	2-84	3	280 ± 3	239 ± 10	2246	1036 ± 48
	1-85	6	278 ± 2	249 ± 3	2234	1085 ± 15
	2-85	4	276 ± 2	252 ± 10	2213	1101 ± 48
	1-86	6	278 ± 3	254 ± 7	2064	1109 ± 33
Az-19	2-82	4	304 ± 3	292 ± 7	1626	1298 ± 37
	1-83	3	299 ± 9	278 ± 8	1387	1225 ± 38
	2-83	1	303	283	1282	1251
	1-84	2	312 ± 7	293 ± 1	—	1300 ± 10
	2-84	4	315 ± 15	288 ± 7	1245	1279 ± 36
	1-85	2	297 ± 13	277 ± 2	1560	1221 ± 11
	2-85	4	310 ± 2	275 ± 9	1447	1214 ± 43
	1-86	6	310 ± 2	272 ± 10	1300	1197 ± 49
Az-28	1-84	4	311 ± 2	305 ± 3	1451	1365 ± 15
	2-84	4	310 ± 11	263 ± 32	1474	1156 ± 158
	1-85	6	322 ± 3	280 ± 12	1425	1239 ± 60
	2-85	5	319 ± 2	277 ± 9	1488	1222 ± 46
	1-86	6	321 ± 9	266 ± 15	1491	1170 ± 76

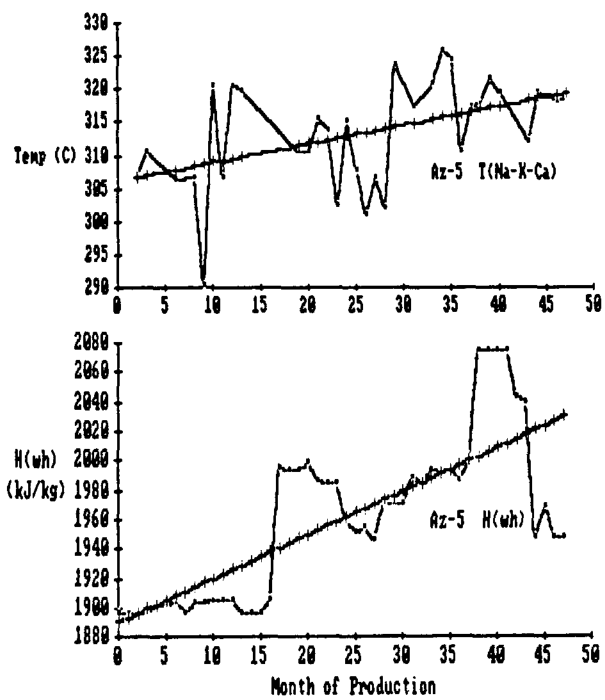

Fig. 1. Reservoir temperatures calculated by the Na-K-Ca geothermometer and wellhead enthalpies observed for well Az-5.

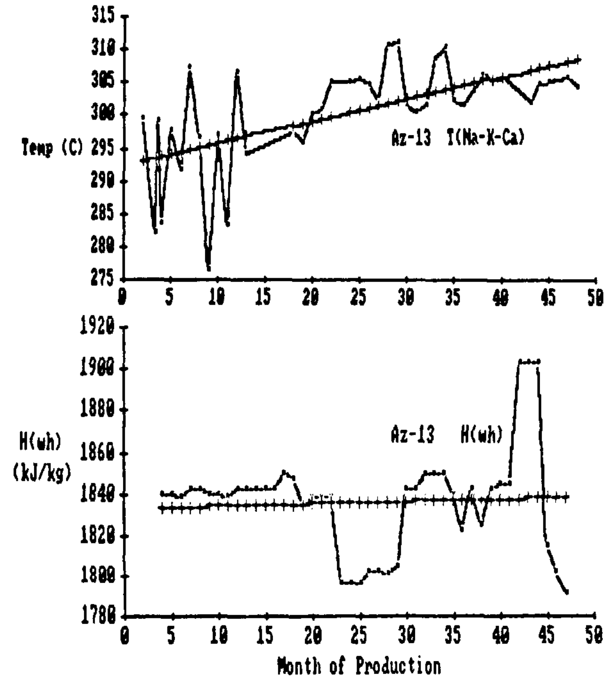

Fig. 2. Reservoir temperatures calculated by the Na-K-Ca geothermometer and wellhead enthalpies observed for well Az-13.

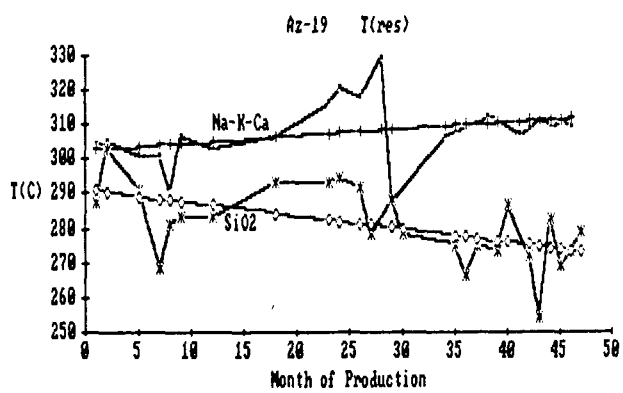

Fig. 3. Reservoir temperatures calculated by the Na-K-Ca and SiO_2 geothermometers for well Az-19.

t-TEST ANALYSIS OF THE GEOCHEMICAL DATA

To obtain a more systematic estimate of the changes that have occured in the Maritaro zone wells with four years of sustained production, the Student t-Test was applied to the data combined as two sets of two-year data samples. The standard t-Test, (see e.g., Volk, 1958) is used to determine the confidence level with which two sets of data belong to the same distribution, based on their means, standard deviations, and number of observations. It is especially useful for small data sets of a few to about 30 total observations. The t statistic is defined as

$$t = \frac{\left|\overline{x}_1 - \overline{x}_2\right|}{\overline{S(x)}\,[1/n_1 - 1/n_2]^{1/2}}$$

where $\overline{x}$ = means of the two data sets
n = number of obseravations in each data set
$\overline{S(x)}$ = pooled estimate of standard deviations from both data sets.

The t statistic for a given pair of data sets with the corresponding number of degrees of freedom, defined as $\nu = n_1+n_2-2$, determines in a standard table of t distributions, the value of α, the probability of a larger absolute value of t. Where a change in means can be either + or −, the two-sided t-Test is used, for which the $\alpha/2$ significance level allows for exceedence on either side of the distribution.

Table 4 shows the results of the t-Test applied to the data for the Maritaro zone wells calculated from a microcomputer program which incorporates the standard t-Test table values for confidence levels of α = 0.8, 0.9, 0.95, 0.98, and 0.99. Two means are generally accepted as belonging to the same distribution for $\alpha/2 < 0.975$. Table 4 shows the large confidence levels for the increase in mean Na-K-Ca geothermometer temperature and wellhead enthalpy for well Az-5. The decrease in SiO_2 geothermometer temperature and corresponding reservoir enthalpy is marginally signifcant due to the larger standard deviations of the silica measurements. The results for well Az-13 show only a significant increase in Na-K-Ca geothermometer temperature without a corresponding significant increase in wellhead enthalpy. The change would have been significant at the 95 % confidence level if the standard deviation of the mean for years 1+2 had been the same as that for years 3+4. For well Az-19, the 5 % increase in mean Na-K-Ca temperature does not exceed the 95 % confidence level, but the 4 % decrease in mean SiO_2 temperature does.

Table 4

t-Test Results of Maritaro Zone Well Data

Well No.	Parameter	Year (1+2) No.	Mean ± SD	Years (3+4) No.	Mean ± SD	t-stat Value	Confid Level(%)
Az-5							
	[Cl] (g/kg)	16	3.02 ± 0.17	17	3.06 ± 0.22	−0.59	< 80
	T(Na-K) (C)	15	310 ± 8	18	318 ± 4	−3.70	> 99
	T(SiO_2) (C)	15	297 ± 14	18	289 ± 11	1.95	~ 95
	H(Si)(kJ/kg)	15	1325 ± 75	18	1281 ± 56	1.92	~ 95
	H(wh)(kJ/kg)	23	1928 ± 43	24	1994 ± 45	−5.14	> 99
Az-13							
	[Cl] (g/kg)	18	2.84 ± 0.17	22	2.83 ± 0.19	0.30	< 80
	T(Na-K) (C)	18	295 ± 9	22	305 ± 3	−4.84	> 99
	T(SiO_2) (C)	18	273 ± 17	22	269 ± 9	0.99	< 80
	H(Si)(kJ/kg)	18	1201 ± 86	22	1180 ± 44	0.99	< 80
	H(wh)(kJ/kg)	20	1806 ± 147	24	1834 ± 33	−0.91	< 80
Az-19							
	[Cl] (g/kg)	10	2.76 ± 0.14	15	2.65 ± 0.39	0.85	< 80
	T(Na-K) (C)	10	304 ± 7	16	310 ± 10	−1.60	~ 85
	T(SiO_2) (C)	10	287 ± 9	16	277 ± 10	2.42	> 95
	H(Si)(kJ/kg)	10	1272 ± 45	16	1225 ± 50	2.42	> 95
	H(wh)(kJ/kg)		n/a	14	1400 ± 127	—	—

DISCUSSION

Four years of data accumulated for the wells providing steam to the five 5-Mw wellhead unit turbines show an interesting array of results with respect to near-well reservoir characteristics. The two units in the southern Tejamaniles zone do not provide sufficient aqueous chemistry data and the possibly most useful in-situ gas component, radon, has not been measured sufficiently often to afford a means to evaluate the extent of changes in reservoir thermal properties. The mean six-monthly production data do show a steady flow of fluid for well Az-6, with steadily declining steam fraction and enthalpy since the two-phase well Az-16AD was added to elevate the steam supply. Flowrates in well Az-17 have declined slowly as the system is operated at constant separator pressure, possibly indicating an increase in boiling in the formation around the well. Kruger et al. (1985b) have noted from the wellbore simulator developed by Ortiz (1983) based on the Orkiszewski (1967) method of estimating pressure drop in vertical pipes that the bottom-hole steam fraction in wells Az-6 and Az-17 was 100 percent. The data for these wells imply the need for careful reservoir management when the next step in field development occurs in 1987/88 with sustained production from 15 wells for the first 55-MW central power plant in the Tejamaniles zone.

The three units in the northern Maritaro zone, with the growing database of 30 or more chemical samples at each well, can be evaluated in terms of both production and chemical data. The decline in wellhead pressure at these units are noted as the separator steam quality changes, slowly at well Az-5 and more rapidly at wells Az-13 and Az-19+Az-28. The chemical data in Table 2 do not reflect these thermal declines, where except for wells Az-19+Az-28 in which cold water is known to be inflowing, the major component concentrations have remained essentially the same within the large standard deviations. The implication is that the replacement water from further out in the formation has essentially the same gross chemical composition. However, the thermal properties of the fluid seem to be changing over the four years of production. The trends, supported by t-Test statistics, show for well Az-5 a 3.5 °C/yr increase in the Na-K-Ca temperature, a mean annual increase of 2.6 kJ/kg in fluid enthalpy, but no significant change in SiO_2 temperature. On the other hand, with a larger rate of increase of 4 °C/yr in the Na-K-Ca temperature, the change in both fluid enthalpy and SiO_2 temperature for the 40 total number of samples is not significant. Even for well Az-19, where cold water is entering, the chemical composition of the produced fluid does not appear to have changed, but there is an almost significant increase in the Na-K-Ca temperature and a significant decrease in the SiO_2 temperature and associated reservoir fluid enthalpy.

These observations may be considered to be in accord with the views of Truesdell et al. (1984) and Grant et al. (1984) about the silica based temperatures noted earlier. It may be possible to examine the thermodynamic changes in the reservoir in a simple way by considering the reservoir around each well as a hydrologic system with a just-penetrating well. Under this assumption the annual integrated flow for each well can be considered as a series of concentric hemispheric shells. Muskat (1937) noted that for a well which just taps the production zone in a porous medium, the flow regime can be expressed as a hemispherical flow system in which the Laplace equation for the potential function, $\Phi = -k/\mu(p-\rho gz)$, has as its solution

$$Q = 2\pi\ (\Phi_e - \Phi_w)/(1/r_w - 1/r_e)$$

where k = permeability, μ = viscosity, p = pressure, ρ = density, g = gravitational constant, and the subscripts w and e refer to the well location and the effective external boundary where pressure is unchanged by drawdown. For just-penetrating wells, the annual production volumes can be calculated by

$$V_i = 3.16\times10^7 * Q_i/\rho\phi$$

and the outer effective radius by

$$R_o = (3V_i/2\pi + R_i^{\,3})^{1/3}$$

To obtain an idea of the dimensions of the reservoir size supporting the two 5-MW units at wells Az-5 and Az-13, the successive radii were calculated based on a fluid density of 920 kg/m^3 at formation temperature and a mean porosity estimated by the Los Azufres staff as 8 percent. The calculations are given in Table 5.

The results show that for the essentially equal mean annual flowrates for both wells, the dimensions of the reservoir extraction

Table 5

Annual Reservoir Depletions from Az-5 and Az-13 as Just-Penetrating Wells

Well No.	Year	Mean Annual Flow Rate (kg/s)	Depletion Volume ($10^7 m$)	Outer Shell Radius (m)	Shell Thickness (m)
Az-5	1	26.5	1.13	175	175
	2	26.6	1.14	221	46
	3	29.3	1.25	256	35
	4	29.2	1.25	283	27
Az-13	1	28.0	1.20	179	179
	2	28.0	1.23	226	47
	3	32.3	1.39	263	37
	4	31.2	1.33	291	28

over the four years are of the order of 300 m, without accounting for either fluid recharge or boiling. The implication of these values is that small generator units on potentially large geothermal fields indicate effects on the field only within the zone of drawdown influence.

In using a model of just-penetrating wells, it is noted that r_e is almost always very large with respect to r_w, and thus the flow from a hemispherical system varies linearly with r_w compared to the much slower logarithmic dependence of r_w on flow from a radial system. With the further assumptions that gravity is not important in the reservoir and that the well just penetrates into a sufficiently fractured system to resemble porous media, the flowrate should be linearly related to the pressure drawdown and the wellbore radius. Studies on the ability to examine these relationships are underway.

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REFERENCES

Camacho, P., Mapa Preliminar del Area Geotermica de Los Azufres, Mich., CFE Technical Report, 1976.

de Anda, L. F., Primer Estudio para el Aprovechamiento de la Energia Geothermica para la Generacion de Energia Electrica en Mexico, International Geological Congress, (1951).

de la Cruz, V., Estudio Geologico Estructural a Detaile del Campo Geothermico de Los Azufres, Mich., CFE Technical Report, 1982.

Dobson, P. F. and G. A. Mahood, Volcanic Stratigraphy of the Los Azufres Geothermal Area, Mexico, J. Volc. and Geoth. Res. 25, 273-287 (1985).

Fournier, R. O. and R. W. Potter, A Revised and Expanded Silica (Quartz) Geothermometer, Bulletin GRC 11, 3-12 (November, 1982).

Fournier, R. O. and A. H. Truesdell, An Empirical Na-Ka-CA Geothermometer for Natural Waters, Geochim. et Cosmochim. Acta 37, 1255-1275 (1973).

Grant, M., A. Truesdell, and A. Mañon, Production Induced Boiling and Cold Water Entry in the Cerro Prieto Geothermal Reservoir Indicated by Chemical and Physical Measurements, Geothermics 13, 117-140, 1984.

Hiriart, G., One Year Experience with Portable Back-Pressure Turbines in Los Azufres, Proceedings, Ninth Workshop on Geothermal Reservoir Engineering, Stanford University Report SGP-TR-74, December, 1983.

Iglesias, E., V. Arellano, A. Garfias, C. Miranda, J. Hernández, and J. Gonzalez, A Method to Recover Useful Geothermal Reservoir Parameters from Production Characteristic Curves (1) Steam Reservoir, Proceedings, Ninth Workshop on Geothermal Reservoir Engineering, Stanford University Report SGP-TR-74, December, 1983.

Kruger, P., L. Semprini, S. Verma, R. Barragán. R. Molinar,A. Aragón, J. Ortiz, C. Miranda, A. Garfias, and M. Gallardo, Initial Chemical and Reservoir Conditions at Los Azufres Wellhead Power Plant Startup, Proceedings, Tenth Workshop on Geothermal Reservoir Engineering, Stanford University Report SGP-TR-84, January, 1985a.

Kruger, P., Proceedings, 1985 International Symposium on Geothermal Energy, Geothermal Resources Council, August, 1985b.

Mooser, F., El Eje Neovolcanico Mexican, Debilidad Cortical Prepaleozoica Reactivada, Part 3, Proceedings, Second National Convention Sociedad Geologica Mexicana, 1972.

Muskat,, M., The Flow of Homogeneous Fluids Through Porous Media, (McGraw-Hill, NY, 1937).

Nieva, D., L., Quijano, A. Garfias, R. Barragán, and F. Laredo, Heterogeneity of the Liquid Phase, and Vapor Separation in Los Azufres (Mexico) Geothermal Reservoir, Proceedings, Ninth Workshop on Geothermal Reservoir Engineering, Stanford University Report SGP-TR-74, December, 1983.

Orkiszewski, J., Predicting Two-Phase Pressure Drops in Vertical Pipes, J. Petrol. Engr., June, 1967.

Ortiz, J., Two-Phase Flow in Geothermal Wells: Development and Uses of A Computer Code, Stanford University Report SGP-TR-66, June, 1983.

Templos, L. A. and F. Laredo, Geoquimica de los Gases Incondensables del Campo Geotermico de los Azufres, Michoacan, Mexico, Third National Symposium on Geothermy and Geology, Mexico, DF, September, 1980.

Templos, L. A. and J. M. Lopez, Estudios Quimicos del Agua Separeda de los Pozos Productores del Campo Geotermico de los Azufres, Michoacan, Mexico, Third National Symposium on Geothermy and Geology, Mexico DF, September 1980.

Truesdell, A., N. Nehring, J. Thompson, C. Janik, and T. Coplen, A Review of Progress in Understanding the Fluid Geochemistry of the Cerro Prieto Geothermal System, Geothermics 13, 65-74, 1984.

Volk, Applied Statistics for Engineers (McGraw-Hill, NY, 1958).