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THERMAL EXTRACTION ANALYSIS OF FIVE LOS AZUFRES PRODUCTION WELLS

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ABSTRACT

Thermal energy extraction from five wells supplying 5-MWe wellhead generators in three zones of the Los Azufres geothermal field has been examined from production and chemical data compiled over 14-years of operation. The data, as annual means, are useful in observing small-scale changes in reservoir performance with continuous production. The chemical components are chloride for quality control and the geothermometer elements for reservoir temperatures. The flowrate and fluid enthalpy data are used to calculate the thermal extraction rates. Integration of these data provides an estimate of the total energy extracted from the zone surrounding the well. The combined production and chemical geothermometer data are used to model the produced fluid as coming from just-penetrating wells for which the annual produced mass originates from a series of concentric hemispheric shells moving out into the reservoir. Estimates are made of the drawdown distance into the reservoir and the far-field conditions.

INTRODUCTION

The Los Azufres geothermal field, located 100 miles west of Mexico City, has produced electricity since August, 1982 with the installation of five 5-MWe backpressure wellhead units. The capacity of the field has since grown to 98 MWe (Quijano and Sanchez, 1993) which includes another four 5-MWe units. The field is characterized by a series of east-west faults with two areas of intense fracturing: (1) Tejamaniles-Agua Fria to the south and (2) El Chino-Maritaro to the north. The location of the five study wells with respect to the faulting system is shown in Figure 1.

With the initiation of operations in 1982, an extensive database has been compiled by CFE to monitor the properties of the total Los Azufres geothermal field. One aspect of the overall program has been a joint project between CFE and the Stanford Geothermal Program to evaluate the extent of changes observable by operation of small (5-MWe) generating units in a potentially large (> 200 MWe) geothermal field. The joint project consisted of three study phases:

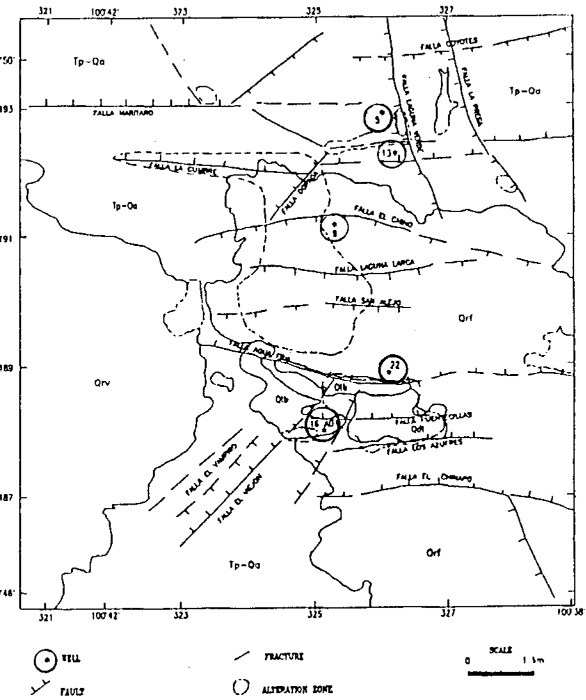

Fig.1. The Los Azufres geothermal field showing the location of the five study wells in relation to the main faulting system.

(1) data reduction and trend analysis of the production and chemical data for selected wells in the major production zones of the field; (2) evaluation of the combined data in relation to reservoir thermodynamic conditions: and (3) analysis of thermal extraction with respect to deliverability, longevity, and reservoir volume.

In the initial study, the wells selected were the wells supplying steam to the original five generating units. The results of the study after 2 and 2.5 years of operation of these wells were reported by Kruger, et al (1985a,b) and after 4 years by Kruger, et al (1987). Results after 5 years of operation with changes in the well-generator couplings were reported by Kruger, Sanchez, and Ortiz (1989). Analysis of the compiled

Table 1
Well Production History

Zone	Well No.	Startup Year Well	Startup Year Unit	Years Prodn
Maritaro	Az-5	1979	1982	14
	Az-13	1980	1982	14
El Chino	Az-9	1987	1988	7
Tejamaniles	Az-16AD	1983	1984	11
	Az-22	1981	1987	13

data for 5 wells covering three major production zones continued by Kruger and Gutierrez (unpublished) until 1991 when it was determined that the production and chemical data for these wells prior to generation of electricity had not been included in the joint study. Reanalysis of the database for the five wells is examined in this report.

Table 1 lists the five Los Azufres wells in the Maritaro, El Chino, and Tejamaniles production zones and the startup dates for the wells and generators. Since an important part of the well production history occurs in the early years of its life, attempt was made to obtain all available pre-generation data. The production data for the wells consisted of semester and annual means of the wellhead and separator pressures, the liquid- and steam-phase flowrates, and wellhead enthalpy. The chemical data consisted of chloride concentration for quality control, sodium-potassium-calcium concentrations for far-field temperatures (Fournier and Truesdell, 1973), and silica concentration for near-field temperature (Fournier and Potter, 1982). The individual data were evaluated for short-term by the Student t-test and for long-term small changes in reservoir characteristics by trend analysis. The combined data were used to estimate the thermal extraction rate and cumulative thermal energy extraction. The volummetric behavior of the reservoir was examined as "just-penetrating" wells in a large well-fractured medium by the method of Muskat (1937).

MODEL OF "JUST-PENETRATING" WELLS

The wells drilled into the Los Azufres geothermal reservoir may be visualized (as shown in Figure 2) as "just-penetrating" wells, in which drilling stops when a zone of well-fractured, fluid-bearing, permeable rock is encountered. The "just-penetrating" well was described by Muskat (1937) for porous media in which production over time is given as concentric hemispherical volumes moving out into the reservoir. Since the Los Azufres geothermal field consists of a dense network of fracturing between major E-W faults, the application of the model for porous media should be sufficiently sensitive for examining drawdown around the well-fractured wellbore zones.

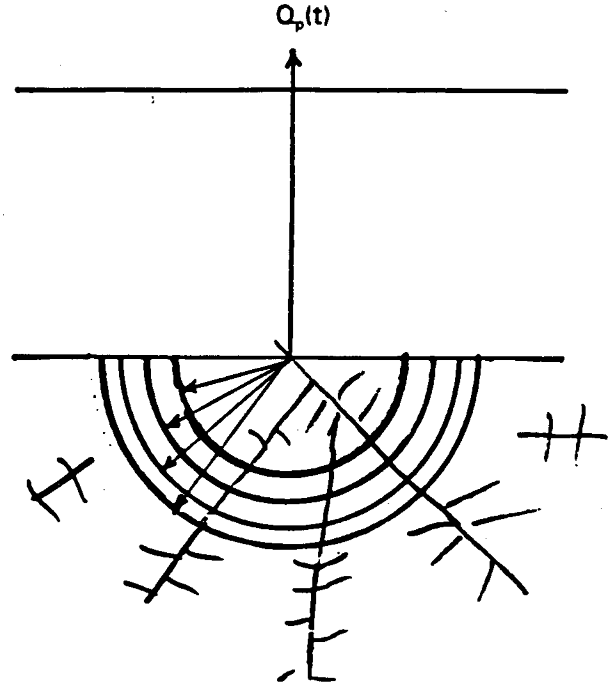

Fig. 2. Schematic of a "just-penetrating" well with concentric hemispherical zones over well-fractured media around the wellbore.

Muskat (1937) noted that the potential, Φ, for a "just-penetrating" well is given by

$$\Phi = - k/\mu \, (p - \rho gz) \qquad (1)$$

where k = permeability
μ = viscosity
p = pressure
ρgz = hydrostatic head

The "just-penetrating" well differs from the line-source well in that the relationship between flowrate and potential is linear rather than logarithmic and is given by

$$Q = 2\pi(\phi_e - \phi_w) / (1/r_w - 1/r_e) \qquad (2)$$

where ϕ_e = far-field potential
r_e = far-field radius
ϕ_w = well-bottom potential
r_w = well radius

To examine the extent of the Los Azufres wells as "just-penetrating" into a well-fractured reservoir, it was assumed that the reservoir pressure is much greater than the hydrostatic pressure ($p \gg \rho gz$) and that the pressure in the i^{th} concentric hemisphere is approximated by the far-field pressure ($p_o \approx p_e$). Thus,

Table 2
Annual Averaged Production Data
Well: Az-5 1979-93

Year No.	P(wh) (MPa)	T(wh) (C)	P(sp) (MPa)	Q(v) (kg/s)	X(v) (%)	Q(t) (kg/s)	Mass (Mt)	H(wh) (kJ/kg	TER (MJ/s)	FT (%)	HE (PJ)
1'79	2.62	219	0.07	14.2	61.6	23.0	0.598	1739	40.0	91.7	1.160
2'80	2.64	221	0.07	13.9	64.8	21.5	0.620	1820	39.0	100.0	1.234
3'81	3.21	237	0.07	9.3	61.5	15.1	0.447	1711	25.8	100.0	0.814
4'82	2.70	228	0.85	17.5	65.3	26.8	0.799	2008	53.7	91.7	1.556
5'83	2.81	230	0.94	16.6	62.0	26.8	0.850	2005	53.8	100.0	1.699
6'84	2.49	224	1.01	17.8	61.5	29.0	0.902	1988	57.6	100.0	1.821
7'85	2.58	225	0.99	18.0	61.5	29.2	0.797	1987	58.1	83.3	1.530
8'86	2.42	222	0.98	18.0	63.1	28.5	0.872	2039	58.2	100.0	1.838
9'87	2.37	221	0.92	17.5	63.1	27.8	0.845	2009	55.8	91.7	1.615
10'88	2.12	214	0.92	17.8	59.1	30.1	0.962	1926	58.0	100.0	1.834
11'89	2.17	217	0.98	17.5	57.5	30.4	0.941	1919	58.3	100.0	1.843
12'90	2.08	215	1.00	18.2	56.2	32.3	1.018	1893	61.2	100.0	1.933
13'91	1.70	204	0.81	18.3	59.9	30.6	0.810	1960	60.0	100.0	1.895
14'92	1.34	193	1.00	18.9	66.4	28.5	0.884	2100	59.8	100.0	1.890
Total							11.35				22.66
Avg.	2.38	219		16.7	61.7	27.1		1936	52.8		

the mean pressure in hemispherical shell i is given by

$$\overline{p}_o = \mu\overline{Q}/2\pi k\ (1/r_w - 1/R_e) + \overline{p}_w \qquad (3)$$

where R_o is the radius of shell i. If it is further assumed that parameters μ, k, r_w, Q, and p_w do not change appreciably with production time, the hemispherical shell pressure is given by the linear relationship

$$p_o = a + b/R_o \qquad (4)$$

in which a and b are given by the quasi-constant parameters:

$$a = \mu\overline{Q}/2\pi k r_w + \overline{p}_w \qquad b = \mu\overline{Q}/2\pi k \qquad (5)$$

The value for pressure in shell i is obtained as the saturation temperature for that shell, estimated from the Na-K-Ca geothermometer described by Fournier and Truesdell (1973).

DATA ANALYSIS

Preparation of the data for analysis consisted of converting each measurement in the CFE database to a consistent set of S.I. units, pressure adjusted to MPa-absolute, flowrate to kg/s, enthalpy to kJ/kg, and thermal extraction rate to MJ/s. To maintain an even distribution of measurements by time, individual measurements were averaged over each month. Thus some months with 6 or 7 measurements were given the same weight in the semester or annual average as months with only 1 or 2 measurements, although the latter had larger standard deviations. The smoothing by longer-period averages provides more readily observable small changes over long periods.

An example of the resulting averaged production data (for well Az-5) is given in Table 2. The cumulative mass for the three plus years of flow before generation is about 18 percent of the 14-year total of 11.35 Mt. The cumulative heat extracted is also about 18 percent of the total. The data were corrected for shut-in times, estimated in weeks, in the fractional time (FT) column. An overview summary of the thermal production data for the five selected wells in the three production zones is given in Table 3.

An example of the trends of the chemical data (for well Az-5) is given in Table 4. with the resulting geothermometer temperatures. A summary of the mean chloride concentration for the total production period for each of the five wells is given in Table 5. The uncertainty in chloride measurements derived from sampling and analytical procedures is estimated by the Los Azufres staff as less than ±5 %. Therefore, the

Table 3
Summary of Thermal Production

	Production Zone				
	Maritaro		El Chino	Tejamaniles	
Well Number Az:	5	13	9	16AD	22
Years of Production	14	14	7	11	13
Mean T(wh) (°C)	219	189	171	179	225
Mean Enthalpy(kJ/kg)	1936	1909	1703	224	1633
Mean TER (MJ/s)	52.8	47.5	34.3	19.6	61.4
Mass Extracted (Mt)	11.4	9.49	3.91	2.69	12.7
Heat Extracted (PJ)	22.7	17.4	6.68	6.21	22.7

Table 4
Annual Averaged Chemical Data
Well: Az-5 1979-93

Year No.	Dates	[Na] (mg/l)	[K] (mg/l)	[Ca] (mg/l)	[Cl] (mg/l)	[SiO2] (mg/l)	T(Na/K) (C)	T(Si) (C)	H(Si) (kJ/kg)
1	79-80	1775	469.1	12.0	3163	1247	309.9	307	1375
2	80-81	1740	485.3	8.6	3163	1303	318.0	315	1422
3	81-82	1656	420.1	7.8	3044	1159	308.6	302	1350
4	82-83	1677	421.8	9.1	2997	1129	308.6	297	1325
5	83-84	1689	447.4	9.1	3044	1085	312.5	293	1304
6	84-85	1644	459.1	7.3	3073	966	318.7	281	1245
7	85-86	1701	464.3	7.1	3044	1091	318.0	294	1307
8	86-87	1632	453.4	7.5	3006	1126	317.4	297	1324
9	87-88	1672	438.1	8.4	3037	1041	311.3	291	1291
10	88-89	1717	452.2	9.5	3141	1037	310.5	291	1289
11	89-90	1588	414.5	9.6	3107	1047	308.4	291	1293
12	90-91	1597	423.2	9.4	3029	1096	309.1	296	1319
13	91-92	1641	435.6	10.0	3059	1268	309.1	311	1405
14	92-93	1634	439.8	9.9	--	1098	310.4	296	1320

changes in chloride concentration seen in Figure 3 for wells Az-9, 16AD, and 22 are due to processes in the reservoir. The marked increase in chloride concentration exhibited by well 16AD is caused by local boiling and recycling of reinjected brine. The data for well Az-9, where the chloride concentration shows a continuous decrease, is more difficult to explain. The data suggest that there is an inflow of less saline water, but with similar geochemical temperature as noted by the constant temperature given by the Na-K-Ca geothermometer.

Table 6 lists the data for the hemispherical drawdown for well Az-5. The Na-K-Ca geotemperature is a key parameter in estimating the reservoir pressure in the hemisphere and the fluid density in the annual production shell. The weakest link in the analysis is the mean reservoir porosity. Available data for a few wells at Los Azufres consist of laboratory measurements of core porosity, which range from 4 to 10 percent. Based on discussions with several Los Azufres staff over the years, an average value of 8 percent is used in this analysis.

An example of a drawdown history (for well Az-5) is shown in Figure 4. Evaluation of the drawdown trend is conveniently made by type-curve matching of the infinite radius of the regression line and its slope by the matching parameters in Equ.(5). Figure 5 shows a set of curves for intercept p = 10 MPa. A summary of the hemispherical drawdown analysis is given in Table 7. The essentially zero regression coefficients for the three two-phase wells in the northern zones indicate that the reservoir pressure has been essentially independent of the fluid and thermal extraction over the first decade of production. The regression coefficients of 50 percent for the two wells in the steam-dominant Tejamaniles zone indicate significant dependence of reservoir pressure on fluid extraction. It is noted that the extent of pressure drawdown exhibited in the model agrees well with the observed pressure drawdown of about 1 to 1.5 MPa for these wells (Quijano and Sanchez, 1994). Efforts are currently underway to obtain estimated values for the quasi-constant parameters in the intercept and slope type-match parameters a and b, and to evaluate the extent of the model to predict longer-term behavior of continued production. One result of the model output is the estimate of drawdown radius of about 300-500 m into the fractured reservoir, which for a hemisphere is the minimum horizontal distance. It sets a reasonable minimum-distance value for drilling additional wells to avoid interference problems.

Table 5
Mean Chloride Concentration

Well	t (yrs)	[Cl] ± σ (mg/kg)	σ (%)
Az-5	14	3070 ± 56	± 1.8
Az-13	14	2839 ± 146	± 5.1
Az-9	7	3542 ± 412	± 11.6
Az-16AD	11	4970 ± 1494	± 30.0
Az-22	13	3828 ± 310	± 8.1

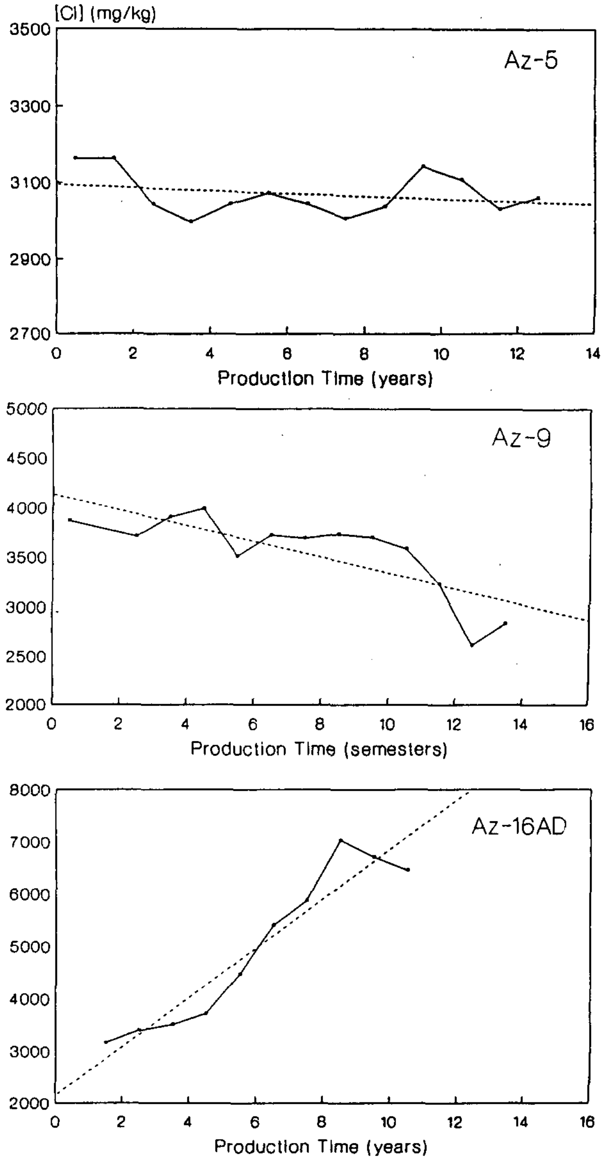

Fig. 3. Change of chloride concentration with production time for three wells: (a) Az-5; (b) Az-9; and (c) Az-16AD.

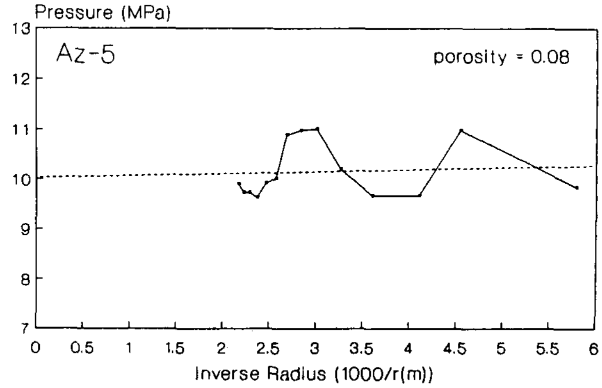

Fig. 4. Hemispherical drawdown history for well Az-5.

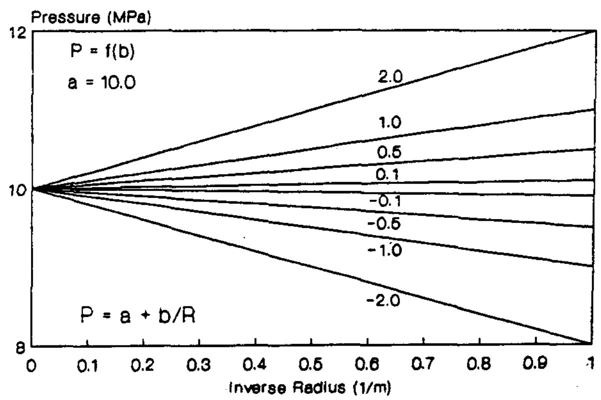

Fig. 5. Drawdown type curves for the slope of the outer-shell pressure as a function of the outer-shell inverse radius for pressure intercept of 10 MPa.

Table 7
Hemispherical Drawdown Analysis

Well	t (yrs)	R(t) (m)	P(o) (MPa)	Slope (MPa.m)	Regr. Coeff.
Az-5	14	462	10.04	0.038	0.005
Az-13	14	430	8.73	-0.057	0.027
Az-9	7	328	11.46	-0.011	0.001
Az-16AD	11	277	3.58	0.457	0.519
Az-22	13	479	8.97	0.352	0.542

Table 6
Hemispherical Drawdown
Well Az-5

Yr (t)	Year	Mass (Gg)	T(r) (C)	ρ(T) (kg/m3)	V(t) (Mm3)	V(Tot) (Mm3))	r(t) (m)	P(T) (MPa)	1000/r (1/m)
1	'79-80	598.0	309.9	691.1	10.82	10.82	172.9	9.84	5.785
2	'80-81	620.0	318.0	672.1	11.53	22.35	220.2	10.98	4.542
3	'81-82	447.0	308.6	694.0	8.05	30.40	243.9	9.67	4.100
4	'82-83	799.0	308.6	694.0	14.39	44.79	277.6	9.67	3.603
5	'83-84	850.0	312.5	685.2	15.51	60.30	306.5	10.20	3.263
6	'84-85	902.0	318.7	670.4	16.82	77.11	332.7	11.01	3.006
7	'85-86	797.0	318.0	672.1	14.82	91.94	352.8	10.98	2.835
8	'86-87	872.0	317.4	673.6	16.18	108.12	372.3	10.89	2.686
9	'87-88	845.0	311.3	687.9	15.35	123.47	389.2	10.03	2.569
10	'88-89	962.0	310.5	689.8	17.43	140.91	406.7	9.92	2.459
11	'89-90	941.0	308.4	694.5	16.94	157.84	422.4	9.64	2.367
12	'90-91	1018.0	309.1	692.9	18.36	176.21	438.2	9.74	2.282
13	'91-92	810.0	309.1	692.9	14.61	190.82	450.0	9.74	2.222
14	'92-93	884.0	310.4	690.0	16.01	206.83	462.2	9.91	2.163

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