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STARTUP ANALYSIS OF WELLHEAD UNIT PRODUCTION WELLS

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ABSTRACT

Wells Az-5 and Az-13 have been in constant production as steam supply for two 5-MW portable wellhead units in the two-phase Maritaro zone of the Los Azufres geothermal field. Production and chemical data for these two wells have been compiled over the initial five years of operation and analyzed at frequent intervals. Wellhead production data, obtained weekly, are summarized as semi-annual means. Aqueous chemical data for the brine samples collected about monthly and analyzed on-site, are summarized as individual data and as semi-annual and annual means. The data were evaluated statistically to detect the extent of observable changes in the Na, K, Ca, SiO_2 , and Cl chemical attributes of the reservoir over the five-year production period. The Na-K-Ca and SiO_2 geothermometer data were used to estimate reservoir temperatures, calculate reservoir specific volumes, and model the flow of reservoir fluid to the wellbore over the initial five-year production period. The data show the extent of observable changes in the reservoir resulting from early operation of a small wellhead unit in a potentially large geothermal resource.

INTRODUCTION

Early installation of small generating units at potentially large geothermal resources provides an opportunity to observe the effects of sustained production on the reservoir. The concern for long-term electric power generation is not only the longevity of the steam supply, but also the potential for changes in thermodynamic properties of the resource that effect the conversion efficiency of future power plant units. Development of the Los Azufres geothermal field accelerated in August, 1982 with the initiation of electric power production at five 5-MW wellhead units. Two of the units were installed at the Tejamaniles zone of the field at wells producing essentially all-steam fluid, and three were installed at the Maritaro zone at wells producing two-phase fluid with steam fractions ranging from 40 to 60 percent.

A large body of information has been compiled on the Los Azufres field, including geologic, geophysical, and geochemical characteristics (e.g., Palma and Bigurra, 1986; Conteras, et al, 1988; Venegas and Huitron, 1988). Studies of the reservoir include the distribution of chemical and isotopic composition (e.g., Nieva, et al, 1983; Quijano, et al, 1987), the distribution of reservoir pressure as a function of depth (e.g., Iglesias, et al, 1983), and the operating characteristics of the five 5-MW portable units (e.g. Hiriart, 1983,1988).

Three reports have been prepared which describe the startup effects based on the production and chemical data compiled during the operation of the 5-MW portable units in the two zones of the field. The first of these (Kruger, et. al., 1985a) summarized the initial chemical and reservoir conditions during the first two-year period with data compiled as six-month average values for each of the unit wells. Reservoir and bottom-hole temperatures were estimated from the mean data. Large standard deviations of the values, even for the means, precluded extensive evaluation of changes in production characteristics. The second report (Kruger, et. al., 1985b) covered the first two and a half years of operation. A description was given of the quality analysis of the sampling and chemistry data to reduce uncertainty in the mean chemical concentration values. The initial thermodynamic characteristics of the reservoir were re-evaluated. The components of the chemical data included aqueous chemistry of the separator brine for the two-pnase wells, non-condensable gases, including radon, for all of the wells, and geothermometer reservoir temperatures from the aqueous chemistry data.

A more detailed evaluation of the startup response was given by Kruger, Ortiz, Miranda, and Gallardo (1987) for the initial four years of sustained production at the five wellhead units. Two additional wells had been connected to sustain productivity of the units and startup histories were initiated for these two wells. Greater detail was focused on the three units in the Maritaro zone, where aqueous chemistry data provided continuous history of the geothermometer reservoir temperature. The Student t-test was applied to several components in the four-year data compilation and contrasting changes were noted for some of the reservoir characteristics among the wells supplying the three Maritaro units. An analysis was initiated on the basis of a just-penetrating well using the hemispherical model of Muskat (1937) under which the annual integrated flow at each well can be considered as flowing from a series of concentric hemispheric shells.

The report given here under the DOE-CFE Geothermal Agreement extends this startup analysis to the integrated five-year production and chemical data compiled at the two sustained production wells, Az-5 and Az-13. These data are evaluated for changes occurring during the first two years compared to the last two years, silica data are evaluated with respect to the fluid specific volume in the reservoir, and the production data are evaluated by the Muskat hemispherical flow model with respect to changes in geothermometer temperatures.

DATA COMPILATION

As part of routine reservoir management practices at the field, the Los Azufres staff measures on a weekly basis flowing pressure at the wellhead, steam flowrate at the separator steam line, and brine discharge flowrate at the weir following pressure reduction at the silencer. These data are reported on a monthly basis. Brine samples for aqueous chemical analysis are obtained at atmospheric pressure for two-phase wells at the weir generally on a monthly basis. Non-condensable gases are measured occasionally. The brine flowrate data at the weir are corrected to separator conditions for calculation of wellhead steam fraction and fluid enthalpy. The aqueous chemical data include chloride as the major anion, several minor element constituents, and the geothermometer components sodium, potassium, calcium, and silica.

Semi-annual averaged production and chemical data were reported by Kruger et al (1987) over the first four years of operation of the initial five 5-MW wellhead unit wells. In the course of field development, flow from well Az-16AD was added to the flow from well Az-6 in the Tejamaniles zone and flow from well Az-28 was added to flow from well Az-19 in the Maritaro zone. Well Az-19 has since been shut-in due to a precipitous decline in wellhead enthalpy apparently caused by cold water entry around the well casing.

For analysis of the observable effects during the first five years of reservoir drawdown, only wells Az-5 and Az-13 in the Maritaro zone have a continuous production and chemical database. Wells Az-6 and Az-17 in the Tejamaniles zone have continuous production data, but as essentially steam wells, they do not have aqueous chemical data for similar analysis. Therefore, an analysis of the two two-phase wells in the Maritaro zone are featured in this report.

Figure 1 shows the monthly wellhead fluid temperature and enthalpy data for the first 5-year period of operation at wells Az-5 and Az-13. Superimposed on the data are the trend lines calculated by the graphics program. Table 1 shows the production data for these wells averaged on a semester basis to reduce the scatter due to large uncertainties in the individual measurements. Table 2 shows the aqueous chemical for the two wells also averaged on a semester basis.

DATA EVALUATION

The mean semester production data given in Table 1 show marked differences between wells Az-5 and Az-13. It was possible to maintain a wellhead pressure of 2.5 MPa at Az-5 while flowing the separated steam to the turbine above the minimum rated turbine pressure, whereas the wellhead pressure at Az-13 was just sufficient. The flowrates of the two wells were initially the same, but the steam fraction for Az-5 increased from 53 percent to about 60 percent, whereas the steam fraction at Az-13 declined rapidly after the first four years from 50 percent to less than 40 percent. This decline is noted more acutely in the enthalpy history. Enthalpy for Az-5 increased moderately over the five year period, while for Az-13, the enthalpy remained constant over the first four years and dropped precipitously over the fifth year.

The brine chemistry for the two wells are also somewhat different. The 5-year mean chloride concentration of 3020 mg/kg for Az-5 is higher than the mean concentration of 2880 mg/kg for Az-13. Table 2 also shows an apparent difference in mean silica concentration, indicating a cooler near-wellbore temperature for Az-13 compared to Az-5. Table 3 shows the semester averaged geothermometer data obtained by the Na-K-Ca (Fournier and Truesdell, 1973) and the SiO_2 (Fournier and Potter, 1979) geothermometer algorithms. The trends of these data are shown in Figure 2 and a summary of the linear regression analysis is given in Table 4. The results indicate a significant increase in fluid temperature with time as water further from the wellbore arrives. The reservoir and near-wellbore temperatures for Az-5 are both higher than for Az-13. It is noted in Table 4 that the regression coefficient for the two geothermometers as a function of time are not very significant, the one for SiO_2 much less than for Na-K-Ca.

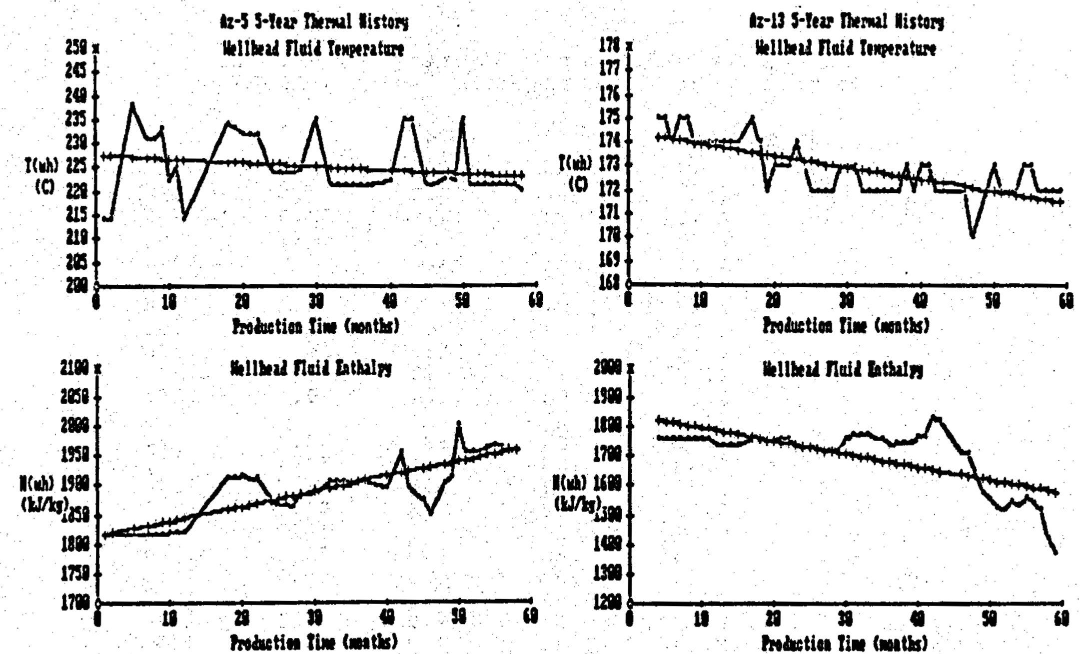

Figure 1. Monthly wellhead fluid temperature and enthalpy for the first five years at wells Az-5 and Az-13 with superimposed trend lines.

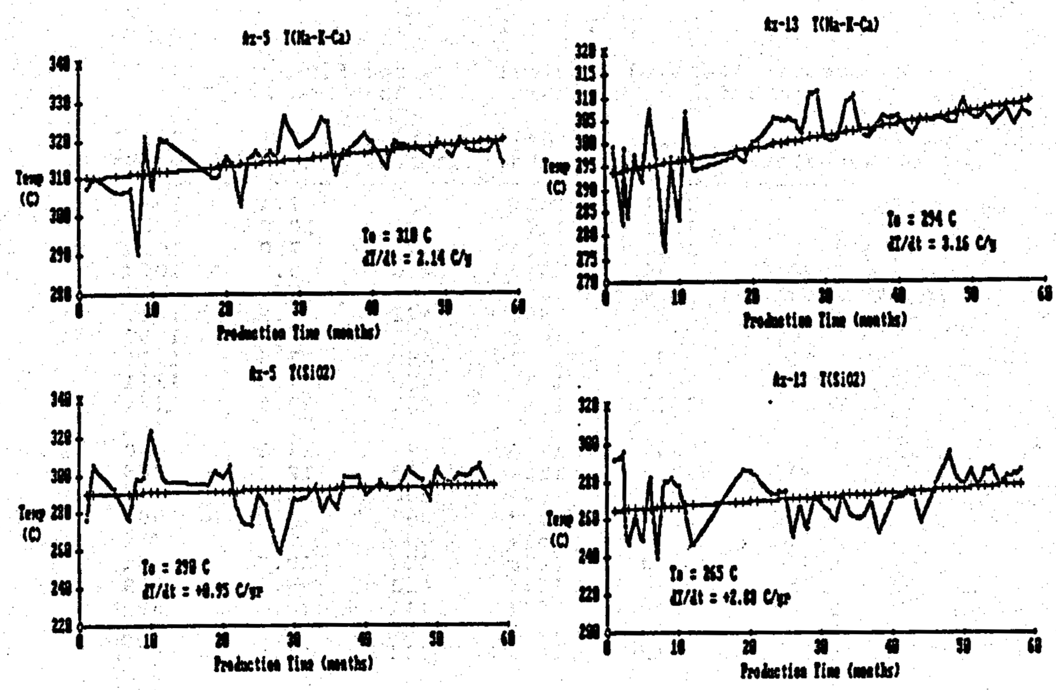

Figure 2. Monthly values for the Na-K-Ca and SiO_2 geothermometers at wells Az-5 and Az-13 with regression analysis of initial temperature and gradients with production time.

Table 1

Semester Averaged Production Data for Five Years of Operation at Maritaro Wells Az-5 and Az-13

Well No.	Semester	P(wh) (MPa)	P(sp) (MPa)	Q(wh) (kg/s)	X(v) (%)	H(wh) (kJ/kg)
Az5	2-82	2.46	0.88	31.5	53.0	1816
	1-83	2.71	0.92	31.6	52.9	1818
	2-83	2.07	0.94	29.8	55.1	1866
	1-84	2.93	0.91	28.0	57.5	1912
	2-84	2.50	0.98	32.5	55.1	1871
	1-85	2.49	1.01	32.4	56.5	1901
	2-85	2.36	1.02	32.0	56.5	1903
	1-86	2.66	0.95	31.7	56.4	1893
	2-86	2.50	0.95	30.3	58.9	1946
	1-87	2.35	0.98	30.4	59.5	1961
Az13	2-82	0.89	0.85	33.1	50.4	1760
	1-83	0.88	0.85	33.1	50.4	1759
	2-83	0.88	0.83	33.1	49.7	1744
	1-84	0.86	0.84	33.6	50.1	1752
	2-84	0.84	0.80	34.2	49.9	1726
	1-85	0.84	0.82	34.5	50.9	1766
	2-85	0.84	0.83	34.5	50.1	1751
	1-86	0.83	0.82	33.0	51.0	1768
	2-86	0.84	0.81	37.0	40.1	1544
	1-87	0.84	0.81	38.9	37.5	1490

Table 2

Semester Averaged Chemical Data for Five Years of Operation at Maritaro Wells Az-5 and Az-13

Well No.	Semester	[Cl] (mg/kg)	[Na] (mg/kg)	[K] (mg/kg)	[Ca] (mg/kg)	[SiO2] (mg/kg)
Az5	2-82	2857	1654	399	7.4	1064
	1-83	3081	1691	435	10.0	1168
	2-83	3058	1724	442	7.0	1099
	1-84	3039	1675	450	9.9	1079
	2-84	2924	1607	446	7.1	907
	1-85	3222	1680	472	7.5	1025
	2-85	2979	1678	461	6.8	1069
	1-86	3093	1723	468	7.5	1114
	2-86	3007	1648	456	7.3	1111
	1-87	3005	1613	451	7.8	1144
Az13	2-82	2951	1746	392	14.3	830
	1-83	2773	1507	355	12.0	865
	2-83	2895	1646	388	12.6	804
	1-84	2763	1578	397	9.0	963
	2-84	2725	1517	399	9.9	814
	1-85	2883	1498	392	10.9	804
	2-85	2866	1646	412	9.8	799
	1-86	2840	1634	411	10.0	892
	2-86	2966	1647	424	10.4	991
	1-87	3015	1625	428	11.6	985

Table 3

Semester Averaged Geothermometer Data
Los Azufres Maritaro Wells

Well No.	Period	No. Obs.	T(NaKCa) (C)	T(SiO_2) (C)	H(SiO_2) (kJ/kg)
	2-82	3	308±2	291±14	1293±72
Az-5	1-83	5	309±12	300±17	1344±97
	2-83	2	315±7	295±1	1311±6
	1-84	5	312±5	293±14	1300±69
	2-84	5	318±5	275±13	1214±63
	1-85	5	320±6	288±5	1274±26
	2-85	4	319±2	292±8	1295±39
	1-86	4	317±3	296±5	1318±25
	2-86	6	318±2	296±6	1316±29
	1-87	5	317±2	299±5	1332±24
Az-13	2-82	6	292±8	292±8	1172±105
	1-83	6	295±12	271±17	1191±83
	2-83	2	296±2	264±24	1158±120
	1-84	4	301±4	281±6	1244±30
	2-84	6	306±4	266±10	1166±49
	1-85	6	304±4	265±5	1162±25
	2-85	5	305±2	264±7	1159±36
	1-86	5	304±2	274±11	1207±52
	2-86	6	306±2	284±6	1257±33
	1-87	5	306±2	284±3	1255±15

Table 4

Los Azufres Maritaro Production Wells
Geothermometer Linear Regression Data

Well No.	Na-K-Ca			SiO_2		
	T(o) (C)	dT/dt (C/y)	r^2 (%)	T(o) (C)	dT/dt (C/y)	r^2 (%)
Az-5	310	+2.14	21.5	290	+0.95	1.3
Az-13	294	+3.16	39.6	265	+2.88	9.9

t-Test Analysis

To determine with greater precision the extent of change in the production and chemical measurements, the Student t-Test was used to evaluate the means at both ends of the five-year production period. Table 5 shows the t-statistic for the means of years 1 and 2 compared to years 4 and 5 for key wellhead, chemical, and geothermometer parameters. The a/2(to,v) value is for the two-sided level of confidence. The major changes indicated with high level of confidence by the t-Test are a 7 % decrease in wellhead enthalpy at well Az-13 and a 4 % increase in wellhead enthalpy at well Az-5 as well as the 10 degree change in Na-K-Ca reservoir temperature at well Az-5. The table also shows a constant chloride concentration at well Az-5 compared to a somewhat significant 3 % increase at well Az-13, the latter change occurring during a late period of decline in wellhead enthalpy. The two observations, if correct, imply a colder intruding water with a greater chloride concentration. The same t-Test observations hold for silica. However, the 6 degree increase in near-well bore temperature implies a hotter intruding water or a larger increase in reservoir fluid silica concentration. The silica concentration at Az-5 remained essentially constant during the same production time period while the wellhead enthalpy increased more than 4 percent.

Specific Volume Analysis

An additional use of the geothermometer data is the evaluation of the relationship between component concentrations observed in the wellhead brine to the specific volume occupied by the component in the reservoir. The concentration of a chemical component in wellhead geothermal fluid can be related to its concentration in the reservoir fluid by the ratio of specific volumes at the respective temperatures provided that the component is conserved between reservoir and wellhead. The concentration in the reservoir can also be related to the fluid specific volume if there is an equilibrium relationship between the component in the fluid phase and the reservoir rock. For example, Semprini and Kruger (1985) examined the relationship of radon partitioned between vapor and liquid pore phases as a linear function of specific volume of the two-phase fluid with the proportionality constant, k, given by

$$k = Em\ \rho r / \phi$$

where Em = emanation rate from the reservoir rock to the pore fluid
ρr = density of the rock
ϕ = porosity.

For a two-phase fluid, the specific volume is given by

$$v_f = x_l/\rho_l + x_v/\rho_v = (1-x_v)/\rho_l + x_v/\rho_v$$

The steam fractions are determined by the enthalpies at the reservoir temperature as

$$x_v = (H_f-H_l)/(H_v-H_l) \quad \text{and} \quad x_l = 1-x_v$$

where H_f, the enthalpy of the two-phase fluid in the reservoir is approximated by the enthalpy of the wellhead fluid assuming the wellbore system in isoenthalpic.

Table 5

t-Test Analysis of Bi-Annual Means

Well No.	Parameter	Units	Mean (yr 1+2)	Mean (yr 4+5)	Change (%)	t stat	$a/2(t_o,v)$
Az-5	T(wh)	°C	228±8	224±5	-1.8	1.66	0.95
	H(wh)	kJ/kg	1851±47	1931±40	4.3	-5.18	>0.99
	[Cl]	mg/kg	3019±172	3021±150	0.1	-0.03	<0.1
	T(NaKCa)	°C	311±8	318±2	2.3	-3.71	0.99
	$T(SiO_2)$	°C	295±14	296±6	0.3	-0.24	0.3
	$H(SiO_2)$	kJ/kg	1315±73	1317±30	0.2	-0.09	0.15
Az-13	T(wh)	°C	174±1	172±1	-1.1	7.42	>0.99
	H(wh)	kJ/kg	1753±10	1630±135	-7.0	3.96	0.99
	[Cl]	mg/kg	2844±168	2924±136	2.8	-1.65	0.95
	T(NaKCa)	°C	295±9	305±2	3.4	-5.13	>0.99
	$T(SiO_2)$	°C	271±17	277±11	2.2	-1.31	0.9
	$H(SiO_2)$	kJ/kg	1193±85	1222±53	2.4	-1.28	0.9

The expression for the specific volume is thus

$$V_f = (V_{fv}-V_{fl})[(H_f-H_l)/(H_v-H_l)] + V_{fl}$$

The relationship of the major aqueous components, Na for the cations, Cl for the anions, and SiO_2 to the reservoir specific volume were examined for the two production wells Az-5 and Az-13. Figures 3a,b, and c show the individual concentration data as a function of reservoir specific volume. The enthalpies for the liquid and vapor phases were taken at the silica geothermometer temperature as more representative of the ambient near-wellbore reservoir temperature. Figure 4 shows that the silica concentration does not correlate well with specific volume calculated with either the Na-K-Ca geotemperature or the wellhead fluid enthalpy. Figures 3a and b show that the sodium and chloride concentrations are essentially independent of the ambient thermodynamic conditions in the reservoir. Figure 5, however, shows that silica concentration for well Az-5 as an exponential relationship with specific volume, given by a regression equation of the form

$$[SiO_2] = [SiO_2]_o \exp(-kV_f)$$

where the coefficient k, has the dimensions of density. This coefficient can be considered as a distribution constant for the component between the rock and liquid phases in terms of $(kg/kg)_r/(kg/m^3)_l$. For the two wells, the results for the regression analysis are shown in Table 6.

An interesting observation for well Az-13 in Figure 6 is the apparent change in relationship for the more recent samples taken after the steep drop in observed wellhead fluid enthalpy. Figure 6a shows the five-year history with 51 samples compared to figure 6b which shows the four-year history with the first 40 samples. The

Table 6

Specific Volume Relationships
Exponential Regressions

Component	Geo Therm	Az-5 k (kg/m^3)	Az-5 r^2 (%)	Az-13 k (kg/m^3)	Az-13 r^2 (%)
SiO_2	SiO_2	-42.4	91.1	-29.6	90.1
	NaKCa	20.8	2.6	-20.6	7.6
Na	SiO_2	-8.1	19.6	-2.0	2.3
	NaKCa	3.3	0.4	0.2	0.0
Na/K	SiO_2	-11.0	18.4	2.5	2.5
	NaKCa	26.5	13.1	26.6	49.0
Cl	SiO_2	-6.3	8.7	-4.0	10.3
	NaKCa	-8.4	1.9	-6.0	4.0

specific volume coefficient changes to -37.7 kg/m3, but the regression coefficient increases to above 96 percent. The data for the fifth year indicates entry of colder water with smaller SiO2 concentration.

Hemispherical Flow Model

Fractured geothermal reservoirs may be considered to be the void volume surrounding the intersection of a wellbore with a network of connected fractures containing or conducting geofluids from some nearby thermal resource. As a simple description of such a geothermal reservoir, it may be possible to examine the thermodynamic changes in the reservoir by assuming that the reservoir around each well is a hydrologic system with a just-penetrating well. Under this assumption, the annual integrated flow is modeled as a series of concentric hemispheric shell volumes. 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

Table 7

Semester Averaged Hemispherical Flow Data at Maritaro Wells Az-5 and Az-13*

Well No.	Semester	Total Production (Tg)	T(r) (C)	P(sat) (MPa)	Outer Radius (m)	Shell Radius (m)
Az5	2-82	0.50	308	9.58	163	163
	1-83	1.00	309	9.72	205	42
	2-83	1.50	315	10.43	235	30
	1-84	1.95	312	10.06	257	22
	2-84	2.46	318	10.94	278	21
	1-85	2.98	320	11.23	296	18
	2-85	3.48	319	11.11	313	17
	1-86	3.86	317	10.83	324	11
	2-86	4.31	318	10.95	336	12
	1-87	4.77	317	10.85	348	12
Az13	2-82	0.53	292	7.66	163	163
	1-83	1.05	295	7.99	205	42
	2-83	1.58	296	8.11	235	30
	1-84	2.11	302	8.23	260	25
	2-84	2.66	306	9.33	279	19
	1-85	3.21	304	9.08	298	19
	2-85	3.75	305	9.20	314	16
	1-86	4.09	304	9.08	323	9
	2-86	4.66	306	9.33	338	15
	1-87	5.28	306	9.33	353	15

* based on porosity = 0.08 and T(r) = T(NaKCa)

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, z = depth, and the subscripts w and e refer to the well location and the effective external boundary where pressure is unchanged by drawdown. For a just-penetrating well, the annual production volume can be calculated by

$$Vi = 3.16\text{x}10^7 * Q_i/\rho\phi$$

and the outer effective radius by

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

Table 7 shows the hemispherical flow data for wells Az-5 and Az-13. The total semester productions were based on steam supply and weir flow rates (the latter corrected to separator pressure conditions before flashing to atmospheric pressure). The values for the concentric hemispheric radii were based on fluid density at the Na-K-Ca geothermometer reservoir temperature and a mean fracture porosity estimated by the Los Azufres staff as 8 percent. The reservoir pressure for the concentric shells is given as the saturation temperature at the Na-K-Ca geothermometer temperature.

Figure 7 shows the relationship between the estimated shell saturation pressure (MPa) and the reciprocal of the outer radius (as 1000/R(m)) for the semester production data of the two wells. Both wells exhibit about the same behavior, in showing a linear relationship between reservoir pressure at the outer radius and the reciprocal of the outer radius, offset by the difference in the observed wellhead pressure. The linear regression lines indicate an initial undisturbed reservoir pressure of 12.5 MPa for well Az-5 and 11.4 MPa for well Az-13.

CONCLUSIONS

This paper is an unfinished report. It evaluates the ability to examine the compilation of field data for wellhead production and chemical analysis of separated brine at the discharge weir following pressure reduction and cooling. Statistical analysis of the growing volume of data permit several observations to be made of the trend of the drawdown effects on the fractured-media reservoir.

Trends in the production data show an increase in wellhead fluid enthalpy as hotter fluid arrives from the thermal resourceand pressure reduction near the wellbore allows increased local boiling.

The entry of external colder water is evident in the fifth year of production at well Az-13 by the rapid drop in wellhead enthalpy and increased liquid fraction. It is noted that this time period is coincident with the shutin of nearby well Az-19 due to steam supply decline with rapidly decreasing fluid enthalpy. Evidence of the arrival of hotter fluid for both wells is indicated by the Na-K-Ca geothermometer with mean increases of about 2-3 ^{o}C/yr over the 5-year production period.

The thermodynamic regime near the wellbore is also manifest by the strong relationship between measured SiO2 concentration in the discharge weir brine and its specific volume in the reservoir calculated from the SiO2 geotemperature and wellhead enthalpy data. Since this relationship is specific for the SiO_2 geotemperature and not for the Na-K-Ca geotemperature nor the wellhead enthalpy, it may be assumed that the exponential relationship is governed by the rate of exchange of silica between reservoir fluid and rock in rapid equilibrium.

Further evaluation of the early drawdown effects on reservoir conditions can be examined with the simple hemispherical reservoir flow model in which the pressure can be linearly related in time to the reciprocal of the outer effective radius on the basis of a series of concentric hemispheric shells of production volume.

These techniques seem to offer a means for sparse data evaluation, especially where field data are obtained over long intervals with non-research grade equipment under difficult field operating conditions. For the two Los Azufres wells Az-5 and Az-13, in particular, it is evident that additional data collected over the next few years with greater frequency and accuracy will allow for more-detailed analysis of the reservoir drawdown effects and the ability to predict future conditions for optimum reservoir management.

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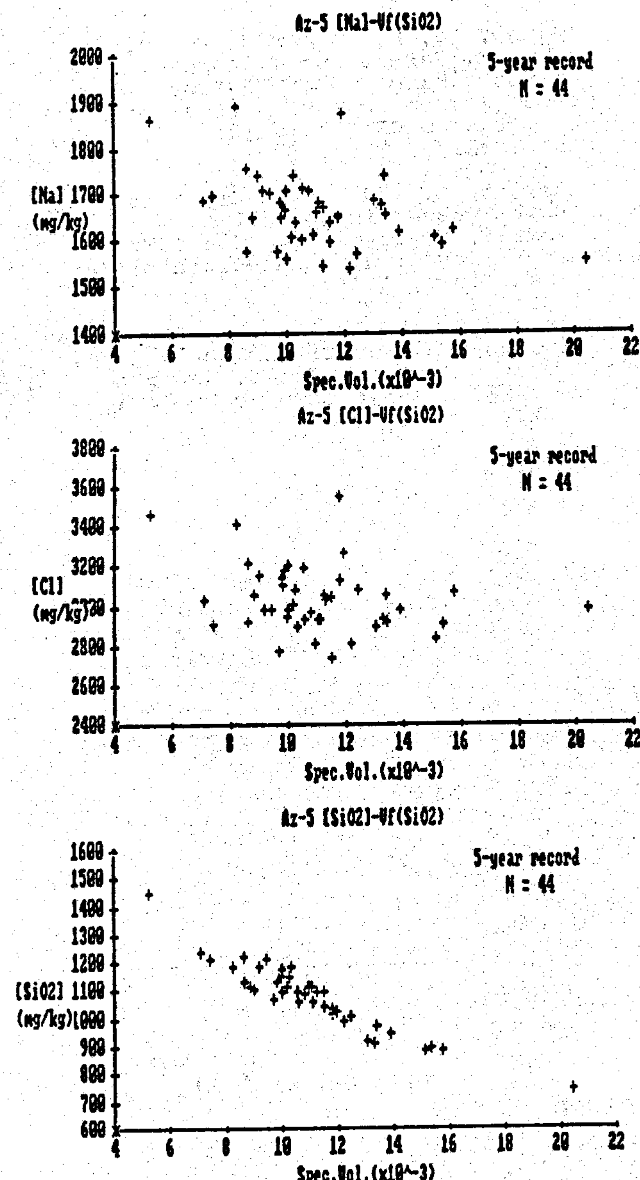

Figure 3. Scatter diagrams for (a) sodium, (b) chloride, and (c) SiO_2 for Az-5 as a function of fluid specific volume calculated with the SiO_2 geothermometer and wellhead enthalpy.

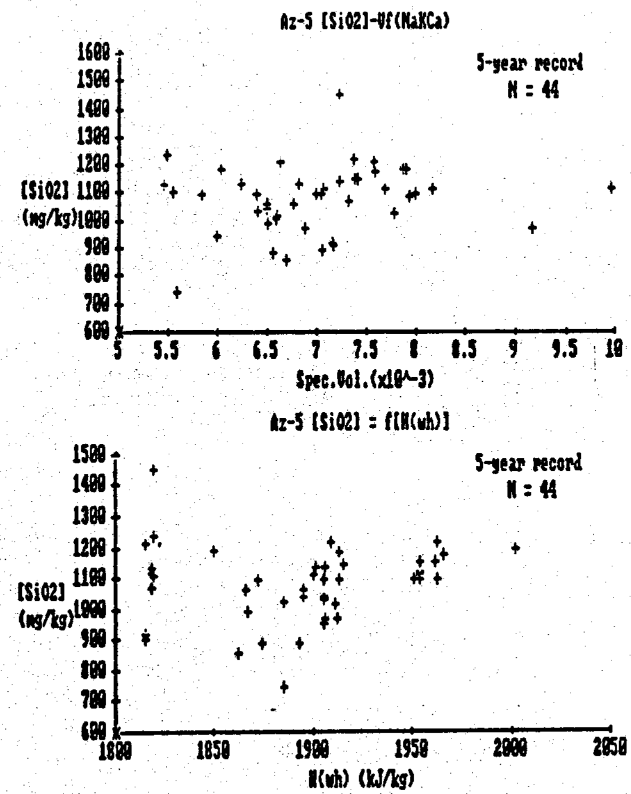

Figure 4. Scatter diagrams for SiO_2 and (a) specific volume as calculated by the Na-K-Ca geothermometer and (b) wellhead enthalpy.

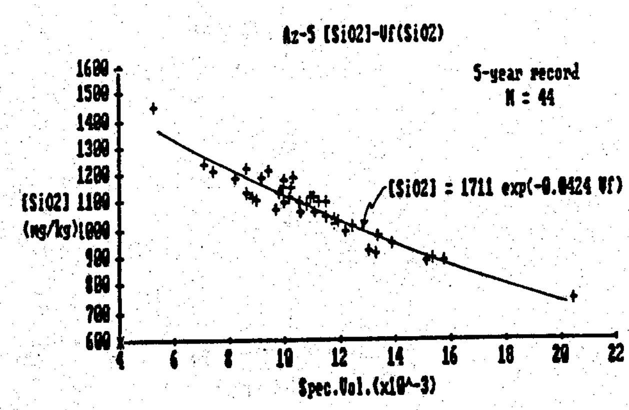

Figure 5. Exponential regression of the SiO_2 concentration data for well Az-5 as a function of specific volume calculated by the SiO_2 geothermometer and wellhead enthalpy.

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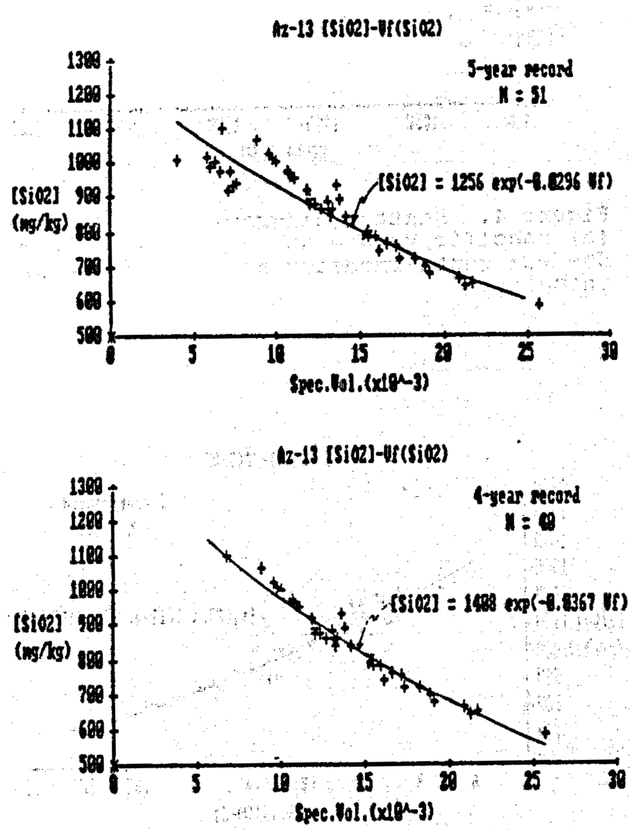

Figure 6. Exponential regression of the SiO_2 concentration data for well Az-13 as a function of specific volume comparing (a) the 5-year history to (b) the 4-year history.

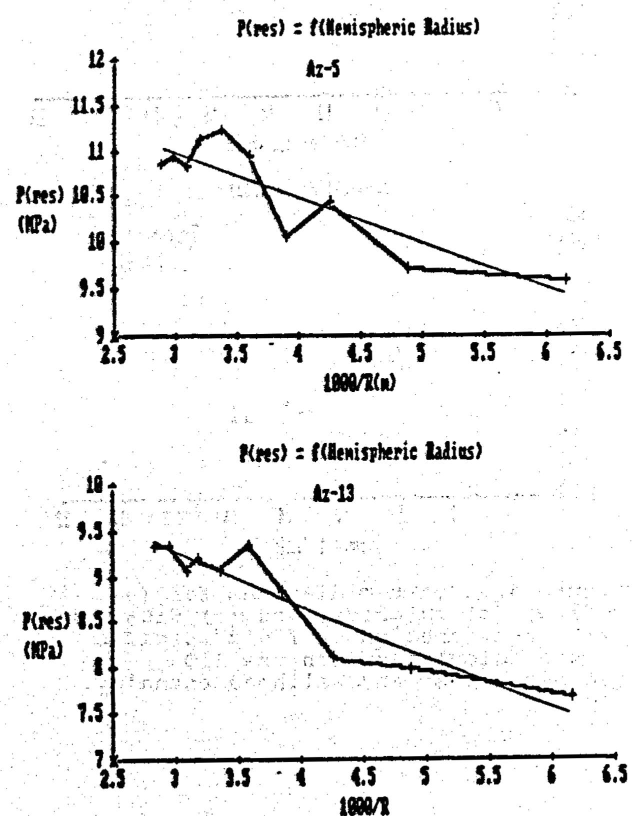

Figure 7. Semester-averaged reservoir pressure at the outer radius of the hemispherical production volume for a just-penetrating well and the linear trend lines through the data.