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THE NATURAL THERMODYNAMIC STATE OF THE FLUIDS IN THE LOS AZUFRES GEOTHERMAL RESERVOIR.

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ABSTRACT

We have devised a simple method to assess the natural thermodynamic state of two-phase reservoirs. This is usually a complex task. The method is based on inferring sandface flowing pressures and enthalpies from production output (deliverability) curves, and then extrapolating to shutin conditions in the pressure-enthalpy plane. The method was applied to data from 10 wells of the Los Azufres geothermal field. Comparison of the results with measured pressures and temperatures showed that the method is reliable. We present detailed thermodynamic properties of the unperturbed reservoir fluid in the neighborhood of the wells studied, in tabular form. Moreover, we present a match to these results with a very simple model that allows reasonable estimates of natural thermodynamic conditions as functions of height above sea level. The present results have important implications for the assessment of the fluid reserves, which are suggested to be greater than previously thought.

INTRODUCTION

Accurate assessment of reserves and producibility of geothermal reservoirs requires, as a key ingredient, detailed information about what was the thermodynanic state of the reservoir fluid before the initiation of large scale comercial exploitation. The required information can be embodied in the natural distributions of fluid pressure and fluid enthalpy throughout the reservoir; from them, the distributions of other variables of interest, such as temperature, steam quality, water saturation, etc., can be inferred.

In general, accurate detailed natural distributions of pressure and enthalpy are not easy to come by. Use of a potpourri of techniques from diverse disciplines such as reservoir engineering and geochemistry, and painstaking analysis is usally required. Determination of unperturbed enthalpy distributions in water-dominated reservoirs, such as Cerro Prieto, is facilitated by the fact that, at least for the lower flowrates, the enthalpy of the produced fluids remains constant (e.g. Iglesias et al., 1985). Assessment of natural enthalpy distributions in two-phase reservoirs is harder because the flowing enthalpy changes with flowrate and with wellhead pressure. As will be shown, Los Azufres is predominantly a two-phase reservoir.

In the same line of our previous efforts directed at making more efficient use of generally expensive-to-acquire geothermal field data (Iglesias et al., 1983a; 1983b; 1984; 1985), we have devised a relatively simple method to determine the natural ptessure and enthalpy distributions of two-phase reservoirs. The method is based on the analysis of production output data, which are complemented with pressure logs. This paper describes the method and its successful application to data from Los Azufres. Results for 10 wells, which have not yet been incorporated to comercial production, are presented. Another paper, which evaluates the natural conditions of the fluids feeding the wells already in comercial production (Kruger et al., 1985) is also presented in this Proceedings. The present work is part of a more comprehensive effort directed at establishing detailed initial conditions of the fluids for the whole reservoir.

METHOD

Briefly, the method consists of processing production output data to obtain sandface flowing pressures and enthalpies. These pressures and enthalpies, which vary with flowrate, are then extrapolated to shutin conditions. The shutin conditions are fixed by the shutin pressure obtained from pressure logs.

Production output curves are routinely determined for geothermal wells. These curves relate the wellhead pressure, the specific enthalpy, and the mass flowrate of the produced fluid. They are obtained by means of relatively short-termed output (deliverability) tests. These tests are usually run shortly after the completion of the well. For this reason, unless interference with other(s) well(s) has ocurred, the data produced by these tests reflect unperturbed reservoir conditions. Sometimes deliverability tests are run in wells that have undergone extensive comercial production. Obviously, in these cases the data do not generally reflect natural reservoir conditions. Figure 1 illustrates typical output curves from Los Azufres. Note the strong correlation between the enthalpy and the flowrate. This is characteristic of production from two-phase reservoirs (e.g. Grant et al., 1982).

Output curves contain mixed information about both the reservoir and the intervening wellbore. This information can be unscrambled by means of a wellbore flow numerical simulator. In this way, sandface flowing pressures and flowing enthalpies can be retrieved. Using this technique we have processed deliverability data from 10 wells. Their location in Los Azufres is shown in Fig. 2. The numerical simulator utilized has been described by Goyal et al. (1980; 1981). Typical results are illustrated in Fig. 3.

In previous papers (Iglesias et al., 1983a; 1983b; 1984) we have shown that the unperturbed reservoir pressure can be found from extrapolation to shutin conditions of processed deliverability data, for water- and steam-fed wells. Unfortunately, the wells involved in this work are fed by two-phase mixtures for most of the lower flowrates recorded in their corresponding deliverability tests (in some cases the flow is two-phase throughout the test). For two-phase flow we lack a simple model describing the relationship of the enthalpy and the pressure to the mass flowrate that would enable analytic extrapolation of these variables to shutin conditions. For that reason we chose to graphically extrapolate the trend exhibited by the processed results in the pressure-enthalpy plane, in the direction of decreasing flowrates (see Fig. 3). The end point is then determined by the intersection of the extrapolated line with the shutin pressure. The shutin pressure is obtained from carefully screened Pressure logs, In cases where the extrapolated line *goes* across the

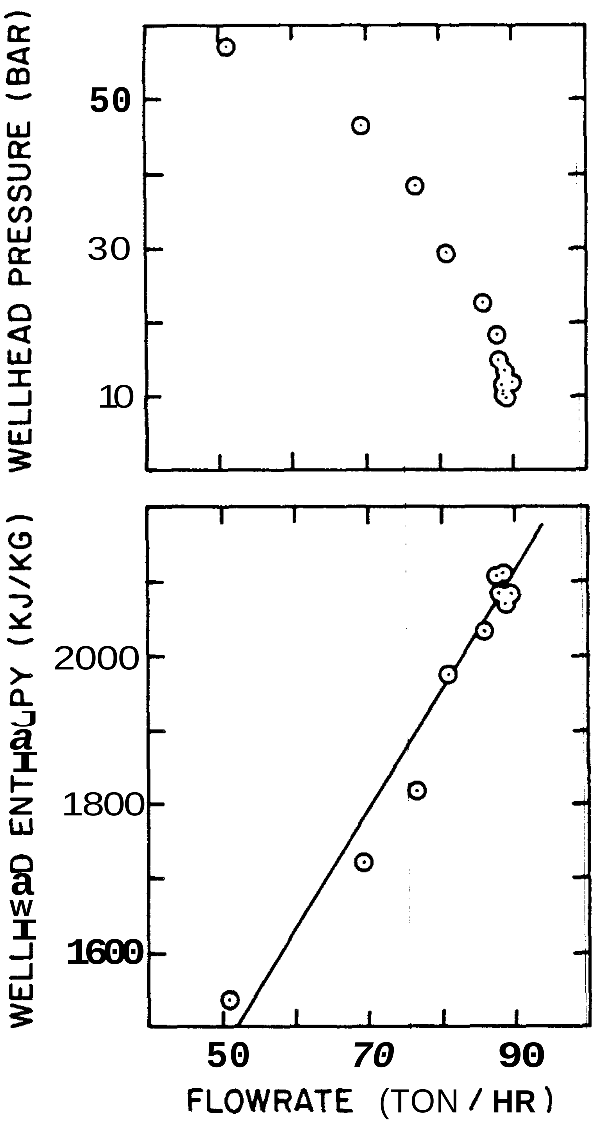

Figure 1. Production output (deliverability) curves of well A- 9.

saturation line before intersecting the shutin pressure, we take the intersected saturation enthalpy as the reservoir enthalpy, as shown in Fig. 3. This choice is justified because the flowing enthalpy in liquid-fed wells does not vary with flowrate (e.g. Grant et al., 1982; Iglesias et al., 1985).

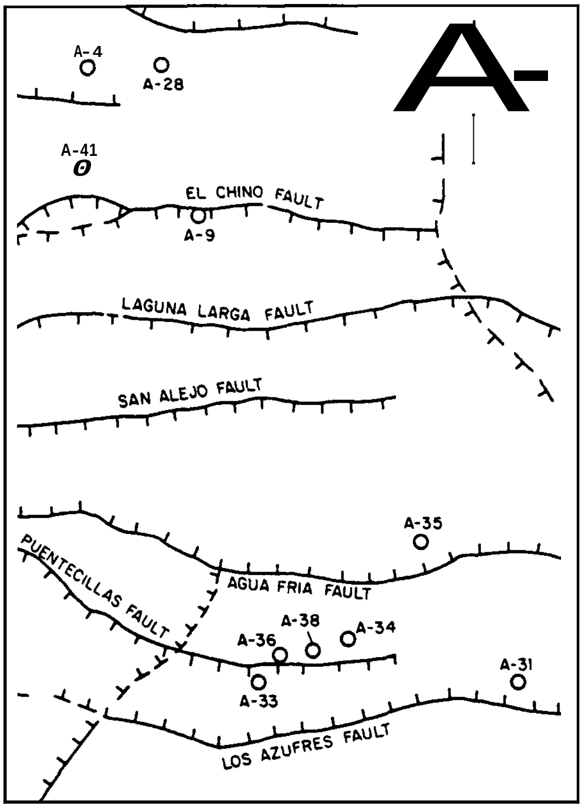

Figure 2. Location of the wells.

RESULTS AND DISCUSSION

Our main results are presented in Table 1. The last column of this table presents unperturbed reservoir temperatures inferred by Nieva (1984) by means of a cationic composition geothermometer. Comparison of these temperatures with the temperatures found with the present method shows that both sets of figures are highly compatible with each other, when the errors of both methods are considered. Comparison of inferred and measured pressures is also highly reassuring. The method is thus considered to be reliable

An important result shown in Table 1 is that, in its natural state, the fluid feeding the majority of the wells is a two-phase mixture, with varying degrees of steam quality. This is so even for the wells often believed to tape a "steam dome" (wells A-33, A-34, A-35, A-36, and A-38, see Fig. 2). Figure 4, an overall unperturbed enthalpy-depth profile for the reservoir, illustrates this feature. The "saturation line" depicted in this figure was obtained via the boiling-point-for-depth approximation (e.g. Grant et al.). Production causes drawdown and flashing of the liquid phase, thus increasing the enthalpy, which migrates towards higher values. In some cases, e.g. wells A-34, A-38, and A-41, at high flowrates the fluid close to the well crosses the saturation line into the superheated steam region. The rest. of the high steam saturation wells tape two-phase fluids even at their highest recorded flowrates.

For three wells (A-4, A-9, A-28) the natural state of the fluid is liquid (Fig. 4). However, under most production conditions these wells tape two-phase fluids.

The existance of an extended two-phase region in the so called "steam dome" implies that the fluid reserves in that part of the reservoir are orders of magnitude greater than what would be expected if steam alone were present.

Figure 5 represents an overall unperturbed pressure-depth profile of the field. A boiling-point-for-depth (BPD) curve has been matched to the point representing well A-36. With the exception of A-4, discussed below, the agreement of the present results with the BPD model for the low-steam-saturation points is very good. This static model, generally regarded as a good approximation to the

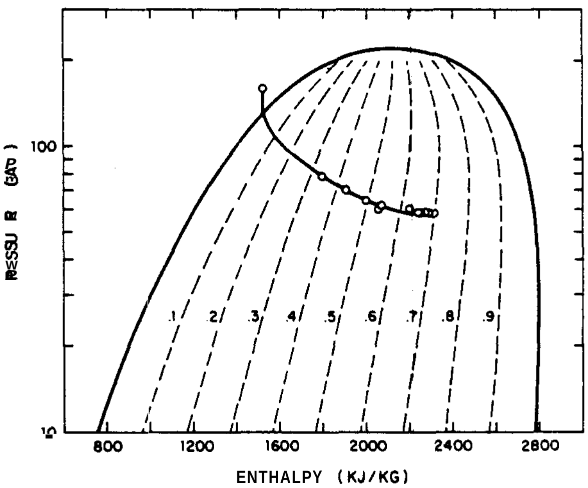

Figure 3. Bottomhole pressure-enthalpy diagram for well A-9, as inferred from the production output curves. The extrapolation line as well as the inferred unperturbed conditions for the fluid are also shown. The broken lines represent steam quality.

Table 1. Thermodynamic state of unperturbed reservoir fluid.

Well	Bottomhole height* (m)	Pressure (bar)	Enthalpy (kJ/kg)	Saturation (steam)	Quality	Temperature (oC)	T(Na-K)** (oC)
A-4	915	112	1382	0.0	0.0	307	294
A-9	350	158	1520	0.0	0.0	329	310
A-28	1170	110	1340	0.0	0.0	300	300
A-31	1600	67	1640	0.880	0.26	283	266
A-33	2140	53	2380	0.988	0.75	267	255
A-34	2093	53	2625	0.996	0.90	267	
A-35	1631	71	2230	0.972	0.64	287	274
A-36	1840	54	1800	0.946	0.39	269	
A-38	2128	52	2590	0.995	0.88	266	
A-41	2330	48	2290	0.986	0.69	261	-

* Above sea level
** Cationic composition geothermometer (Nieva & Nieva, 1982)

initial state of the reservoir, fails at high steam saturations (e.g. Grant et al., 1982). This happens because the model cannot accomodate the intrinsically dynamic characteristics of two-phase regions at low water saturations. In the present results the high-steam-quality wells A-33, A-34, A-38, and A-41 depart from the BPD curve, as expected, conforming a nearly vertical profile characteristic of vapor dominated reservoirs.

The point representing well A-4 in Fig. 5 is marginally on the wrong side of the BPD curve. The pressure is too small. However, this pressure is surely smaller than the unperturbed reservoir pressure(which thus must be closer than shown to the BPD curve) because it was taken from a log run with the well producing through a 1/4 in. line. Unfortunately, this was the best estimate of the reservoir pressure available at the time of writing this paper.

From the preceeding discussion we conclude that , if the wells studied in this work (10/40 = 25 %) are representative of the whole reservoir, the natural pressure of the fluids is approximately described by the BPD model shown in Fig. 5, up to a height of about 1800 m above sea level . From then up, to an unknown height above sea level, a nearly +vertical pressure profile. characteristic of vapor dominated reservoirs, applies. The pressures in this portion of the profile can be approximated by $p = -0.0113 z + 75.9$ bar, where z is the height above sea level, in meters. The reservoir enthalpies can be approximately described by a nearly vertical profile ($h \approx 1414$ kJ/kg, average from A-4, A-9, and A-28) up to about 1100 m above sea level (see Fig. 4). From then up, the enthalpy is approximately described by $h = 0.9102 z + 431.7$ kJ/kg. This very

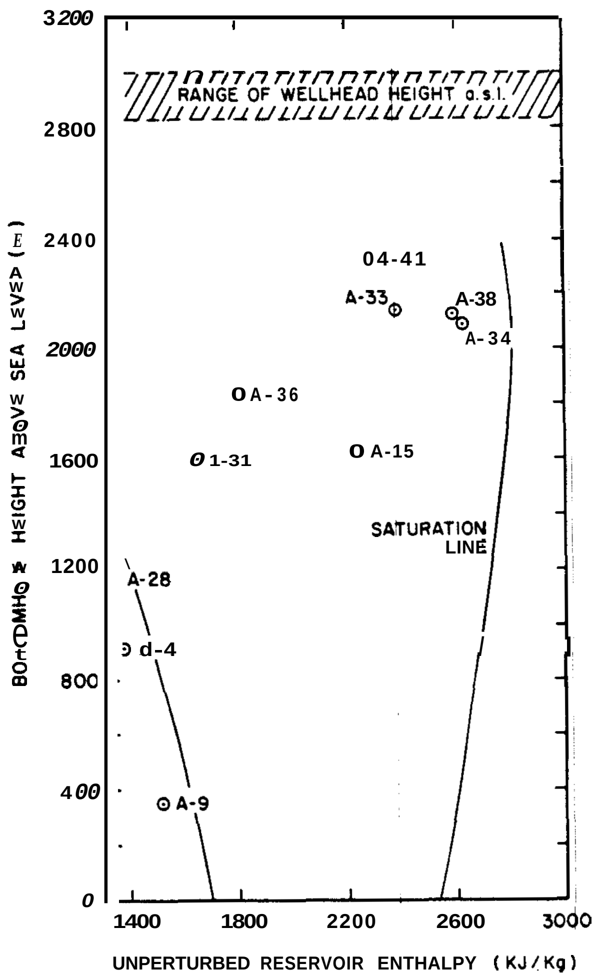

Figure 4. Unperturbed reservoir enthalpy-depth profile.

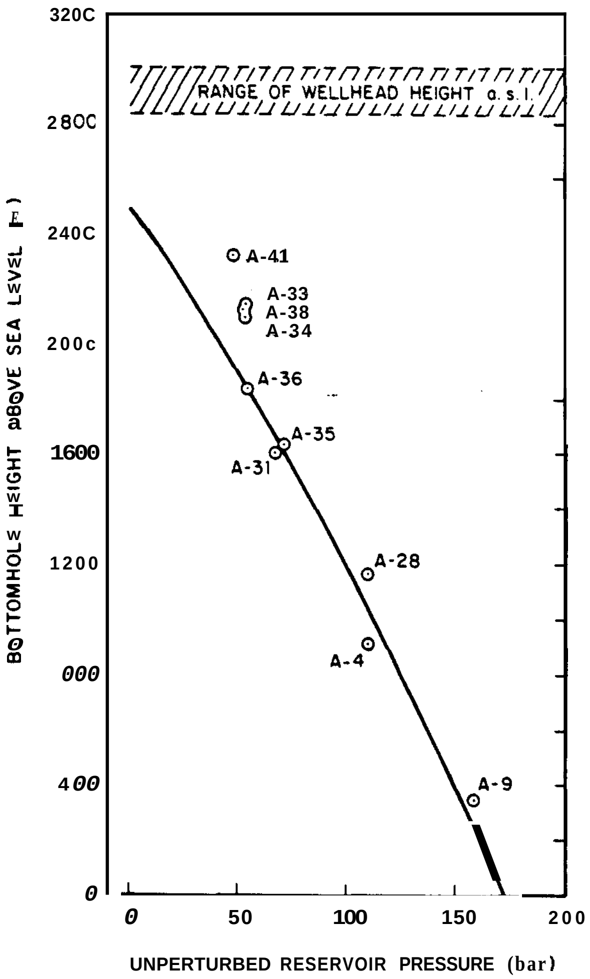

Figure 5. Unperturbed reservoir pressure-depth profile.

simple model provides an effective way to estimate unperturbed reservoir pressures and enthalpies for different depths.

The agreement of the present results with this simple model is somewhat surprising because the wells studied are scattered over an area of about 12 square kilometers, in a geological setting of E-W trending faults (see Fig. 2), which presumably might hamper N-S hydraulic communication over the considerable distances involved. For these reasons it will be necessary to confirm the accuracy of the present model with more field data. At this time our results suggest the existance of a deep and extended local water table at about 1100 m above sea level. The existance of that fluid may prove important for the comercial feasibility of this geothermal resource.

SUMMARY AND CONCLUSIONS

We have devised and denonstrated a simple method to assess the natural distributions of pressure and enthalpy in two-phase reservoirs. From its application to a relatively extense sample of wells from the Los Azufres geothermal reservoir, the followidg conclusions can be drawn.

The natural thermodynamic state of the fluid near the wells studied is as shown in Table 1.

The results of Table 1 are well described by the following very simple model. The pressure profile is as in Fig. 5 up to about 1800 m above sea level; from then up, to an unknown height, the pressure is approximately p = -0.01132 + 75.9 bar. The enthalpy profile is vertical with h = 1414 kJ/kg up to about 1100 m above sea level; from then up, the enthalpy is approximately h = 0.91022 + 431.7 kJ/kg. This simple model is very valuable for a multitude of applications.

The so called "steam dome" is actually a two-phase, vapor dominate4 region with quality and steam saturation in the approximate ranges 0.39 - 0.90, and 0.946 - 0.996 respectively. This result implies fluid reserves orders of magnitude greater than expected if only steam were present, for that part of the reservoir.

Our results suggest the existance of a deep extended (over 12 square kilometers) water table at about 1100 m above sea level. Such an extended aquifer might contribute Substantiallp to the fluid reserves of the reservoir.

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