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MEASURED ENTHALPY COMBINED WITH CHEMICAL CONCENTRATION DATA TO DIAGNOSE RESERVOIR BEHAVIOUR

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ABSTRACT: Concentrations of chemicals such as Cl and Na in a geothermal water separated at atmospheric pressure (at a silencer), or any other pressure, when related to the measured enthalpy of the produced steam/water mixture are indicative of reservoir production conditions. Achieving this relation by means of a mathematically meaningful graphical method, conditions in the reservoir such as boiling, steam gain or loss, heating or cooling (by conduction or mixing) can be inferred, and the fluids of different wells can be related. The method is illustrated with data obtained from Los Azufres Geothermal Field in Mexico.

INTRODUCTION: The relation between the enthalpy of a geothermal fluid and the concentrations of chemicals within the separated water has been long recognised and made use of. As early as 1967 Wilson et al.(1) used the changes in chloride concentrations of waters from Wairakei wells to calculate the underground changes in enthalpy, and by comparing their figures with the actually measured values they could comment on the production conditions within the reservoir. Later on Wilson (2) again dealt with the idea and published a graphical method by wich dilution of reservoir water or heat gain or loss by the reservoir fluid by means of conduction could be inferred.

The idea has been also applied by Truesdell and Fournier (3,4) and others (5) to relating boiling spring waters of an area and to calculation of their temperatures at depth, by making use of a graphical method, in wich enthalpy is plotted against chloride concentrations in spring waters with cartesian coordinates. The enthalpy is considered as that of water at an underground temperature indicated by geothermometers (silica or Na-K-Ca).

The method presented here and applied to Los Azufres wells has a similar graphical form to that used by Truesdell and Fournier, but with small modifications that make the form of the graph mathematically meaningful, and the enthalpy used is that of the steam/water mixture, as measured at the surface.

METHOD : When a geothermal fluid with an enthalpy of ho and Cl or Na concentrations of Co is produced and separated at atmospheric conditions (at silencer), the concentration of the water fraction would be (See Appendix for derivation and see nomenclature at the end):

$$\text{Cwa} = \left(\frac{\text{hsa} - \text{hwa}}{\text{hsa} - \text{ho}} \right) \text{co} \qquad \text{...............} \ (1)$$

This mathematical expression can be represented in graphical form as shown in Fig. 1. If the fluid is water at reservoir conditions, Co would be the concentration in the reservoir water. Starting from this initial condition defined as So in Fig. 1, we can examine what would happen to the enthalpy concentration relationship in different cases of reservoir behaviour:

CASE 1. Evaporation in Reservoir (Gain of heat from reservoir rocks). This normally happens when the pressure in the reservoir decreases sufficiently, due to drawdown, for the water to boil. Say the enthalpy of the produced fluid increases to h_1. If all the fraction of the steam formed as a result of this is produced with the associated fraction of water, the state of the fluid would be represented by pint S_1 immediately above So, as the concentration of the fluid in the reservoir (steam/water mixture) would stay the same. However, now, because of the increased enthalpy the concentration in the water separated at atmospheric conditions (Cwal) would be higher (Cwal > Cwa).Also due to the decrease in pressure, the temperature would decrease (assuming boiling in the formation), and the water fraction would have an enthalpy hwrl and a concentration Cwrl (where hwrl < ho and Cwrl > Co).

However,

$$\text{Co}=(1-\text{Xrl})\ \text{Cwrl}=(1-\text{Xal})\ \text{Cwal} \qquad \text{.............}(2)$$

$$\text{or Co}=\left(\frac{\text{hsrl} - \text{hl}}{\text{hsrl} - \text{hwrl}} \right) \text{Cwrl}=\left(\frac{\text{hsa} - \text{hl}}{\text{hsa} - \text{hwa}} \right) \text{Cwal}..(3)$$

Therefore, evolution of a well with the points plotted on a diagram like in Fig. 2, and moving along line SoS1 would be indicative of this particular case.

However, because of the relative permeability effects steam and water may not enter into the flow in the same fractions as they may exist in the reservoir around the wellbottom. In other words, although due to evaporation in the reservoir an average steam fraction of Xrl can exist around the wellbottom, corresponding to the entalpy hl, the fluid which enters the well may have a different steam qualite (Xrl') Then:

Xrl' > Xrl, if there is steam gain (relatively more steam enters the flow)

Xrl" < Xrl, if there is steam loss, (relatively more water enters the flow, that is some steam is lost to the formations above before it *can* enter into the flow).

CASE 1.1. Steam Gain (Xrl' > Xrl) (See Fig.2) In this case the entalpy of the production would be hl', with the state being defined by the point Sl'. Then,

hl' > hl > ho, and it can be shown that (See **Appendix**) :

$$Cwal' = Cwrl\left(\frac{hsa - hwa}{hsrl - hwrl}\right)\left(\frac{hsrl - hl'}{hsa - hl'}\right) \text{.......(4)}$$

But, from equation (3) :

$$Cwal = Cwrl\left(\frac{hsa - hwa}{hsrl - hwrl}\right)\left(\frac{hsrl - hl}{hsa - hl}\right)$$

However, $\frac{hsrl - hl'}{hsa - hl'} \simeq \frac{hsrl - hl}{hsa - hl}$

Then $Cwal' \ \square \ Cwal$ ....(5)

Also $\frac{Cl'}{Cwal'} = \frac{hsa - hl'}{hsa - hwa} \simeq \frac{Cl'}{Cwal}$ ....(6)

Therefore, **it** can be seen that Sl' is approximately on the hsa - Cwal line and movement of plotted points from Sl to Sl' along this line would indicate steam gain.

This condition is similar to the case where steam enters the production from another level and yet no boiling may take place in the formation, which is considered below as case 2.

~~CASE 1.2.~~ Steam Loss (Xrl" < Xrl) Similary **it** *can* be shown in this case that the points would move down the hsa - Cwal line, like the point Sl". The enthalpy hl" would be smaller than hl.

~~W-E-2.~~ Steam Gain or Loss without Boiling in the Reservoir As pointed out above this is very similar to Case 1.1. If the production enthalpy is h2 (h2 > ho) it can be shown that (assuming the temperature difference between the steam and water flows is negligible):

$$Cwa_2 = Co\left(\frac{hsa - hwa}{hsa - h2}\right)\left(\frac{hsr2 - h2}{hsr2 - ho}\right) \text{.........(7)}$$

(See **Appendix** for derivation)

But, $Cwa = Co\left(\frac{hsa - hwa}{hsa - ho}\right)$ (equation 1)

and $\left(\frac{hsa - ho}{hsa - h2}\right)\left(\frac{hsr2 - h2}{hsr2 - ho}\right) \simeq 1,$ ....(8)

Therefore, $Cwa2 \simeq Cwa$ ....(9)

This would mean that, the new condition point S2 is moving from So upwards along aproximately the hsa - Cwa line (See Fig. 3).

Therefore evolution of a well from the initial condition (So) along aproximately the initial condition line hsa - Cwa would mean steam gain from a different level with negligible or no additional steam forming in the formation from which the main water production comes. However, steam gain from evaporation in the formation would result in a path either like SoSlSI' or more likely move along SoSl' as the resultant of two componentprocesses. It is nevertheless obvious that **it** may be difficult to diferentiate between this case and the case 1.1, if the initial conditions of the well are not known.

In the case of steam loss the condition points would move downwards along the hsa - Cwa line.

CASE 3. Conductive Heating or Cooling Evaporation in the reservoir is really a special form of the conductive heating case. However, if the conditions do not permit evaporation and if there is conductive heating the condition of the well would evolve along So Sl, with an enthalpy hl, where:

$N \ \square \ hwrl > ho$

and $Cwrl \ \square \ Co \ \square \ Cl, \quad Cwal > Cwa$

As the relative permeability effects are normally present, a pure case of evaporation in the reservoir with condition points moving along So Sl would be unlikely. If, however, this behaviour exists it is more likely to point out to a conductive heating case without boiling taking place in the reservoir (However, this should also be checked by the enthalpy value).
The movement of the condition points in the opposite direction (with decreasing enthalpy) would indicate conductive cooling which may happen if a fluid has to travel across a cooler terrain to get to the well, as a result of the evolution of the field conditions. (See point S3 in Fig. 4).

CASE 4. Heating or Cooling by Mixing Depending on the enthalpy of the mixing fluids, heating or cooling may result. If the initial conditions of the mixing (contaminating), fluid are defined by a point M, the points defining the condition of the mixture would move along the line SoM, their exact positions depending on the mixing ratio. Here again evolution of the condition points (enthalpy - concentration relationship) would be diagnostic of what is happening in the reservoir (See point S4 in Fig. 4).
It is abvious that presence of other information would help to corroborate the deduction or inferences obtained by this method. Where possible this should be looked for in order to have more confidence in the results.

Also, **it** will be noted that when the initial

conditions of different wells are plotted on the *same* diagram, the conditions of production existing around the bottom of different wells *can* be identified with respect to the wells which seem to **be** producing the originally existing hot water.
In this way, wells within the *same* field, but producing with apparently different enthalpy - concentration relationships may be related.

EXAMPLES: The figures 5 through 9 show data plotted, as explained above, of several wells of Los Azufres Geothermal Field which is located in the state of Michoacan in Central Western Mexico. The geothermal reservoir is formed by volcanic rocks (mainly andesites) and seems to have a steam cap which at some locations is thick and results in *dry* steam production. The maximun temperature encountered is in the order of 300°C.

Figure 5 illustrates the relation between the initial production conditions at different wells. It appears that different wells display different degrees of steam gain or loss. The wells 2, 3, 4 and 18 indicate condition near to that of the hot water.
However, the wells **1**, 8, 13 and 19 show definite steam gain and the wells 7 and 15 indicate steam loss after boiling in the formation. Depending on the actual condition taken as representative of the undiluted hot water, possible conductive heating (4,18,5) or cooling (2,3) can also be inferred, but the data are not accurate enough to say anything definitly at this stage.
In figure 6 the behaviour of well 3 can be seen. It will be noted that the well produced a water which most probably was diluted with a water of similar temperature, but of low chemical concentration, possibly condensed steam. Over a period of two months the dilution gradually decreased and the well started producing the undiluted water with a small gain of steam.

Figure 7 shows the behaviour ***of*** well 5. It *can* **be** said that as the production rate increases the behaviour of this well is dominated by steam gain due to evaporation in the formation and probably also from a steam cap. This is confirmed by the production characteristics of the well presented in Fig. 10.

The behaviour of well 13 presented in Fig. 8 is similar, but indicates that the major part of the steam gain is coming from a steam level. The relatively high enthalpy also reflects this. Its production curves are shown in Fig. 11 and confirm these observations.
Finally, Fig. 9 show the behaviour of well 15 which originally produced a fluid which had lost steam. It seems that as the production time increased the well was producing a fluid which was gradually nearing to original reservoir water conditions (less steam loss).

CONCLUSIONS: It has been shown that concentrations of chemicals such as Cl **or** Na in a geothermal water separated at atmospheric conditions (at a silencer), **or** any other pressure, when related to the measured enthalpy of steam/water mixtures are indicative of reservoir conditions. Basis of this relationship at different reservoir conditions, a methodology for interpretation and examples of it from a geothermal field in Central Mexico have also been presented.

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The author also states that the opinions expressed are his own and not necessarily those of his company **or** of the C.F.E.

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NOMENCLATURE

C	Concentration (ppm) of a chemical like Cl or Na.
h	Enthalpy
X	Steam fraction

Subscripts:

s	Steam
w	Water
ws	Evaporation
o	Initial
a	At atmospheric conditions
r	At reservoir conditions
1, 2, 3, 4	cases considered

APFENDIX

Water fraction at atmospheric conditions: 1-Xa

$$Xa = \frac{ho - hwa}{hwsa} \quad \ldots\ldots\ldots (A.1)$$

$$1-Xa = \frac{hsa - ho}{hwsa} = \frac{hsa - ho}{hsa-hwa} \quad \ldots (A.2)$$

As all the Cl concentration intially in **a** unit mass of **fluid** muld now be concentred within this water fraction:

$$(1-Xa) \; Cwa = Co \quad \ldots\ldots\ldots (A.3)$$

$$Cwa = \frac{Co}{1-Xa} = \left(\frac{hsa - hwa}{hsa - ho}\right) Co \quad \ldots (A.4)$$

CASE 1.1. If the concentration around the well bottom within the reservoir is now Cl', with the same reasoning:

$$Cl'=Cwrl'\left(\frac{hsrl - hl'}{hsrl - hwrl}\right) = Cwal'\left(\frac{hsa - hl'}{hsa - hwa}\right)$$

$$\ldots\ldots (A.5)$$

The concentration within the water fraction does not change.

Therefore Cwrl' = Cwrl.

$$Cwal' = Cwrl\left(\frac{hsa - hwa}{hsrl- hwrl}\right)\left(\frac{hsrl - hl'}{hsa - hl'}\right). \; .(A.6)$$

CASE 2.

$$C_2 = Cwa_2 \; (1-Xa2) = Cwr_2 \; (1-Xr_2) \quad \ldots (A.7)$$

However if no boiling or negligible boiling in the formation, then

$$Cwr_2 = Co \quad \ldots\ldots\ldots (A.8)$$

Then:

=

$$Cwa2\left(\frac{hsa - h2}{hsa - hwa}\right) = Co\left(\frac{hsr2 - h2}{hsr2 - ho}\right)$$

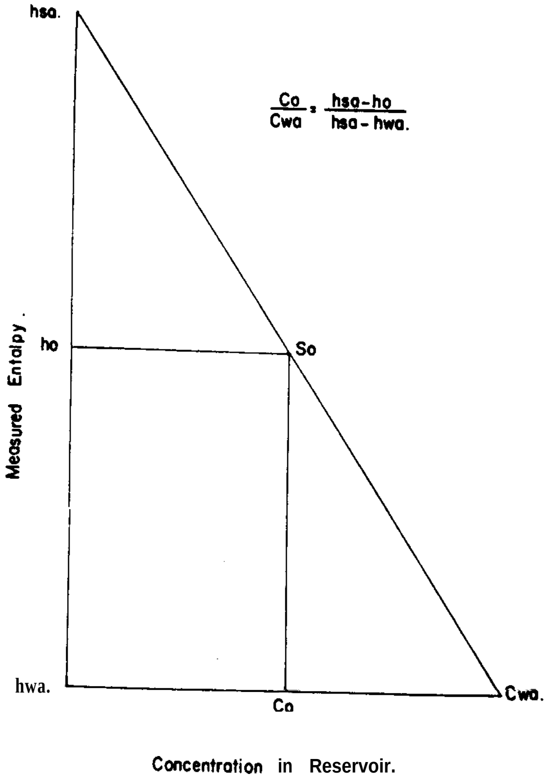


Fig: I Graphical Representation of the Method.

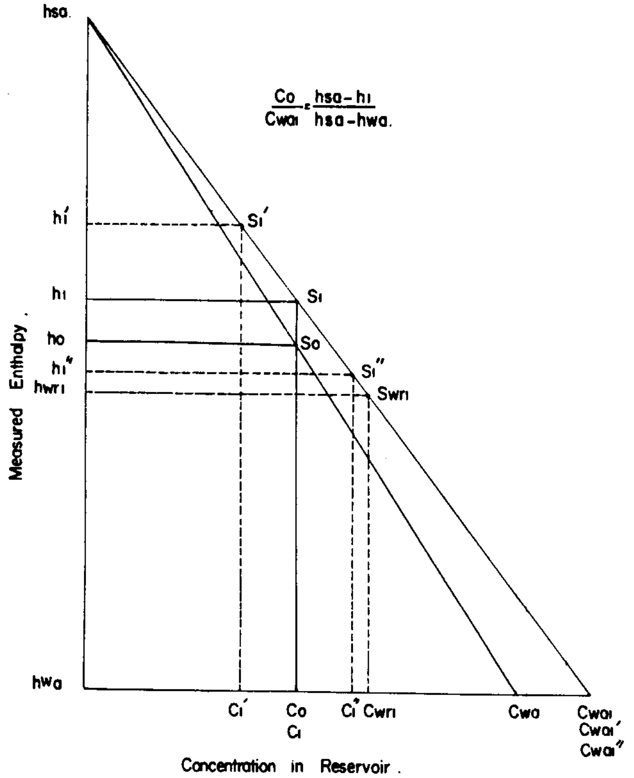


Fig. 2 Evaporation in Reservoir

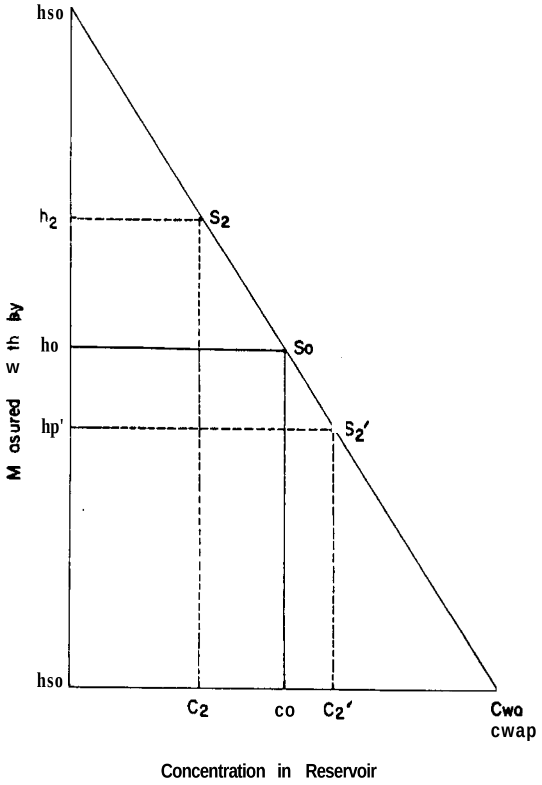


Fig. 3 Steam gain or loss without boiling in the reservoir

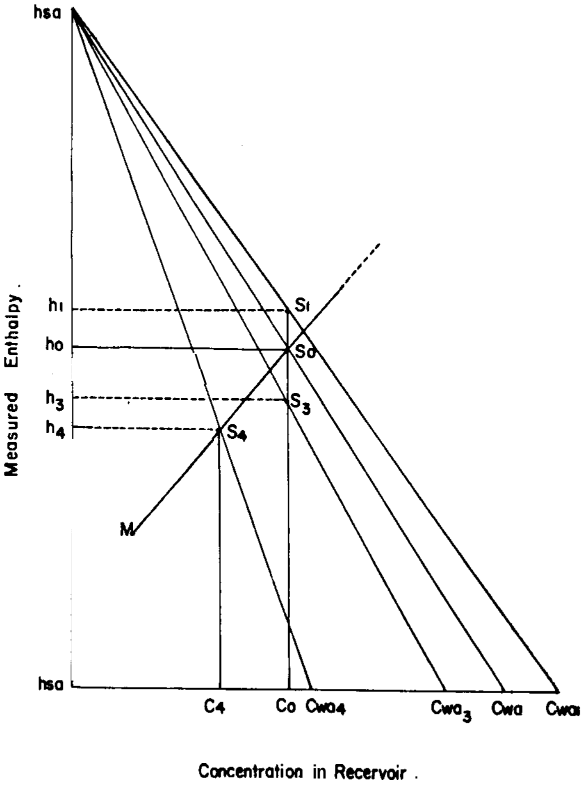
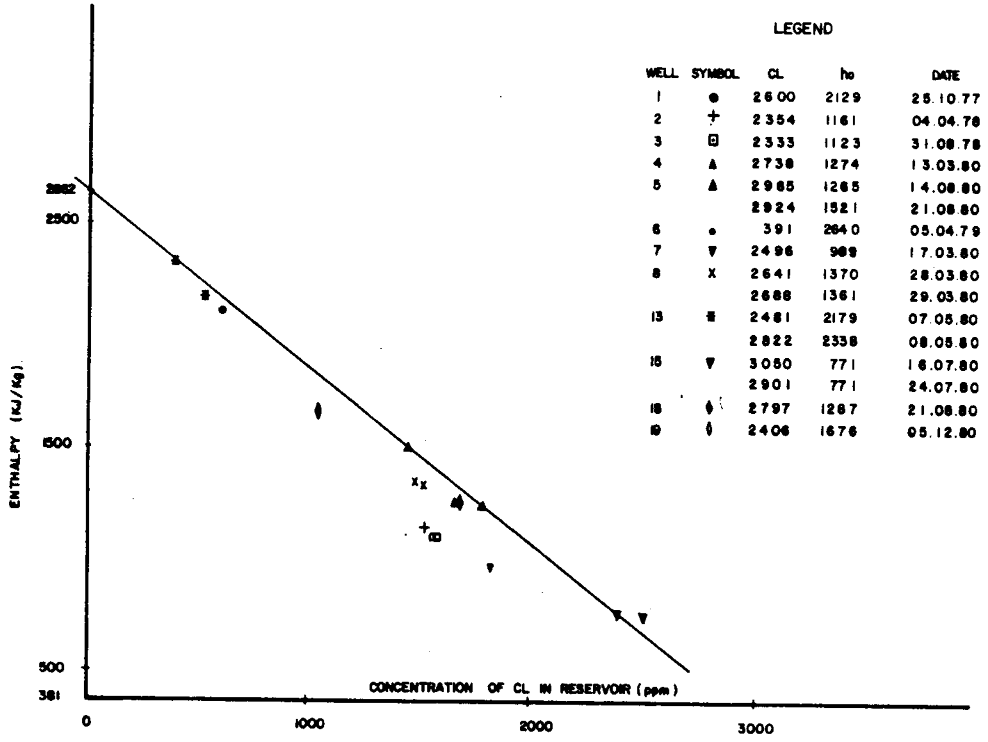


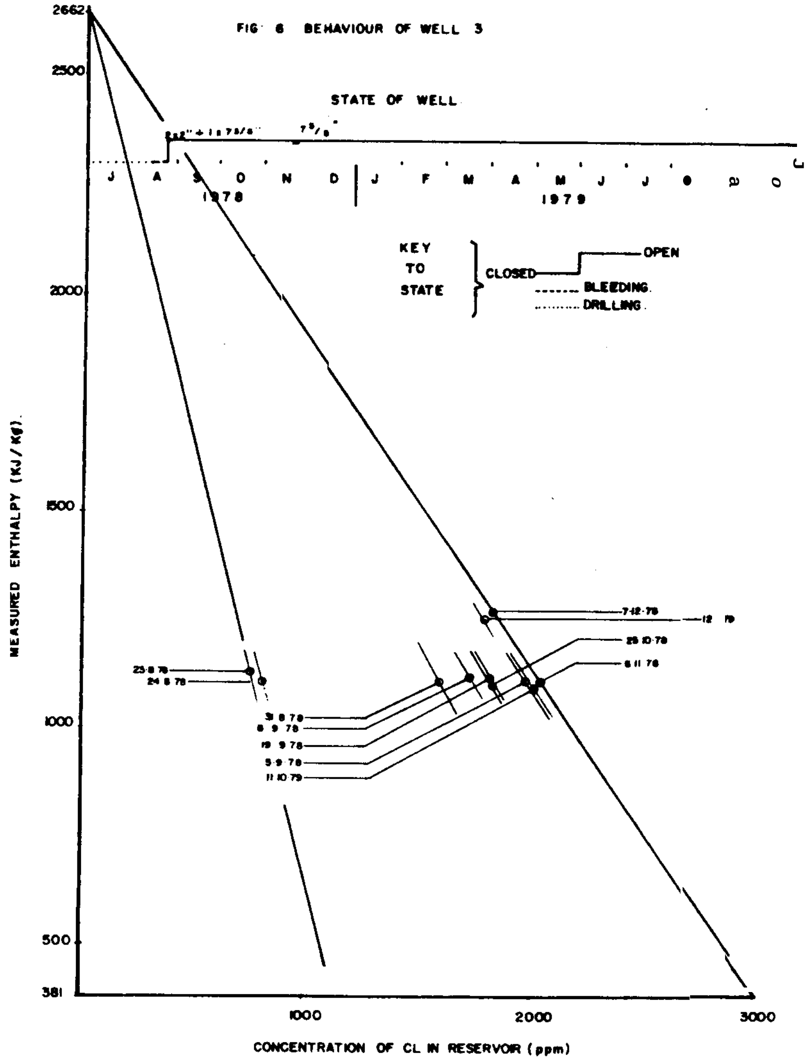
Fig: 4 Heating and cooling by conduction and mixing.

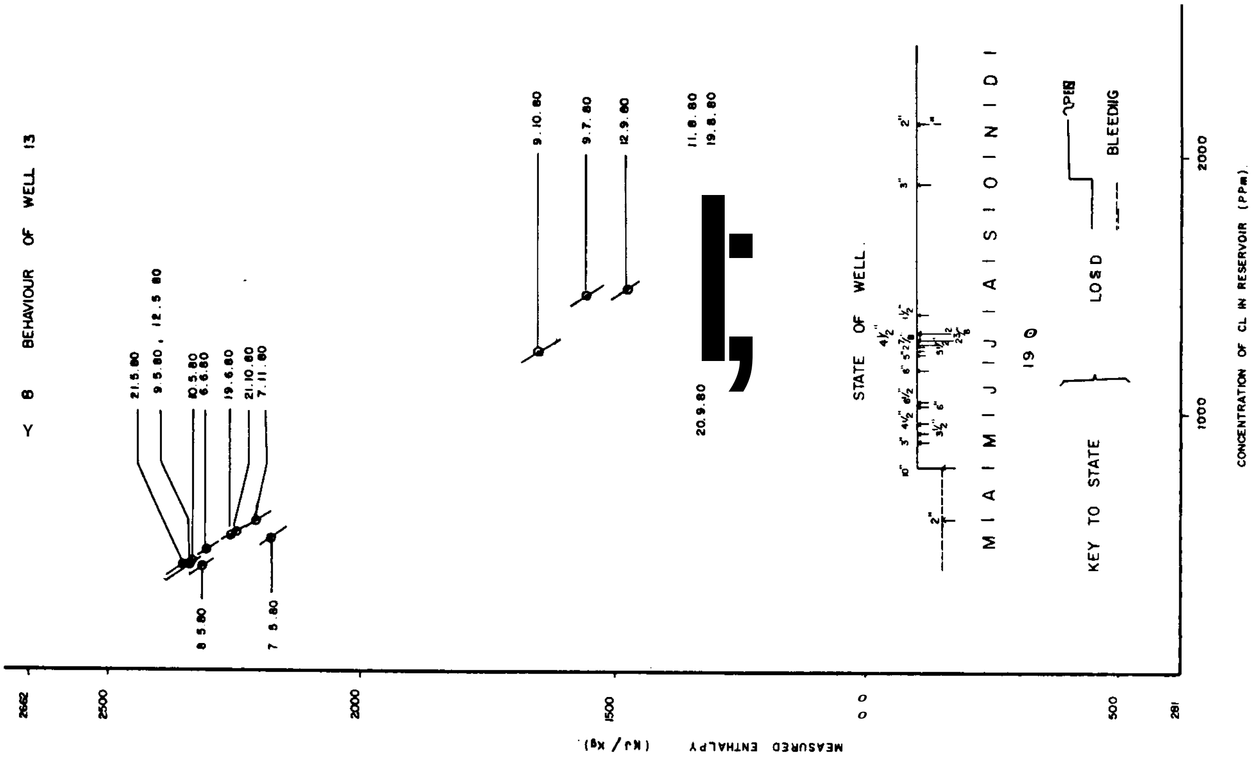
CD J INITIAL PRODUCTION CONDITIONS OF LOS AZUFRES WELLS.



WELL	SYMBOL	CL	ho	DATE
1	●	2600	2129	25.10.77
2	+	2354	1161	04.04.78
3	⊡	2333	1123	31.08.78
4	▲	2738	1274	13.03.80
5	▲	2965	1265	14.08.80
		2924	1521	21.08.80
6	•	391	2640	05.04.79
7	▼	2496	989	17.03.80
8	X	2641	1370	28.03.80
		2688	1361	29.03.80
13	#	2481	2179	07.05.80
		2822	2338	08.05.80
16	▼	3050	771	16.07.80
		2901	771	24.07.80
18	♦	2797	1287	21.08.80
19	◊	2406	1676	05.12.80

FIG 6 BEHAVIOUR OF WELL 3




Y 8 BEHAVIOUR OF WELL 13

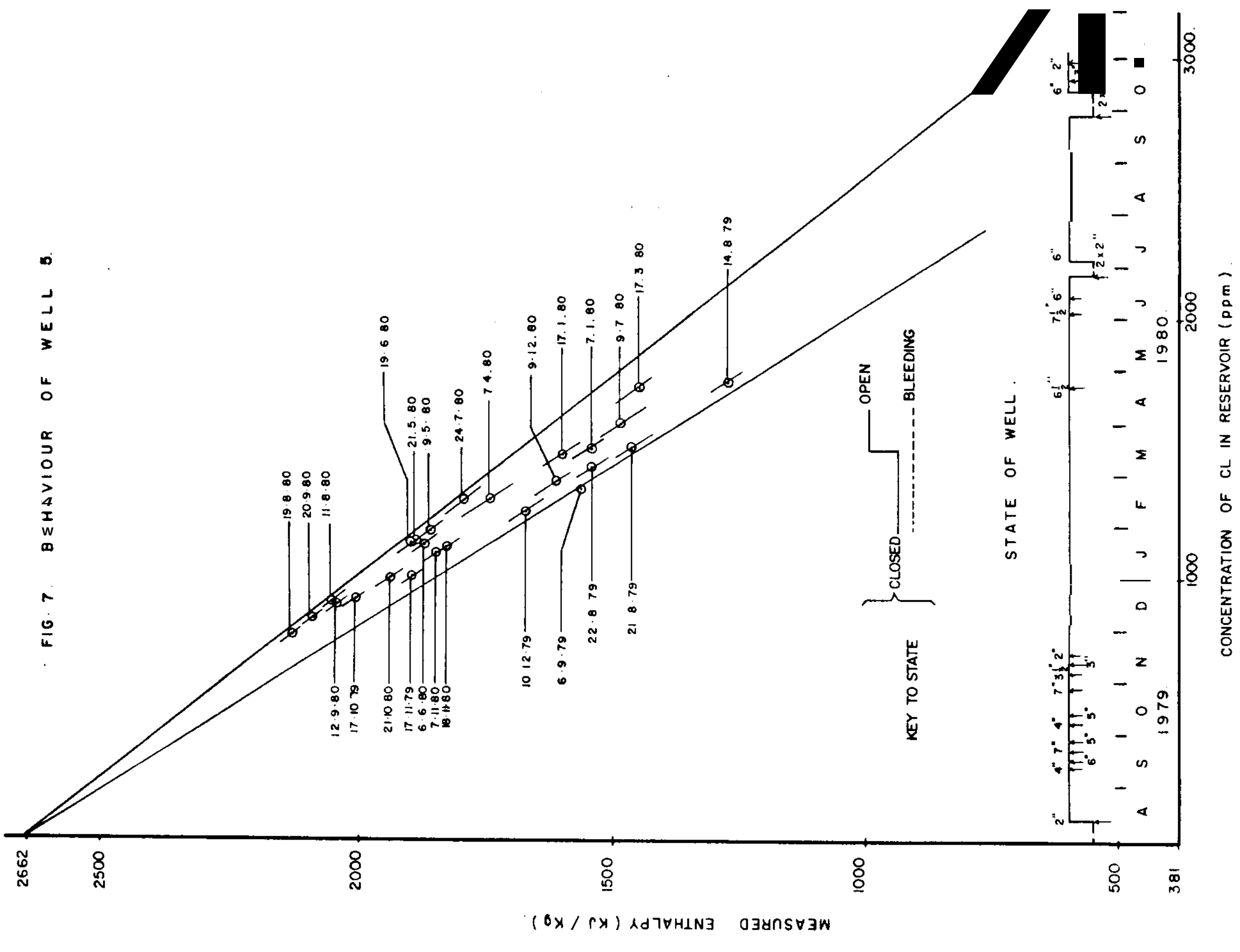


FIG. 7 BEHAVIOUR OF WELL 5

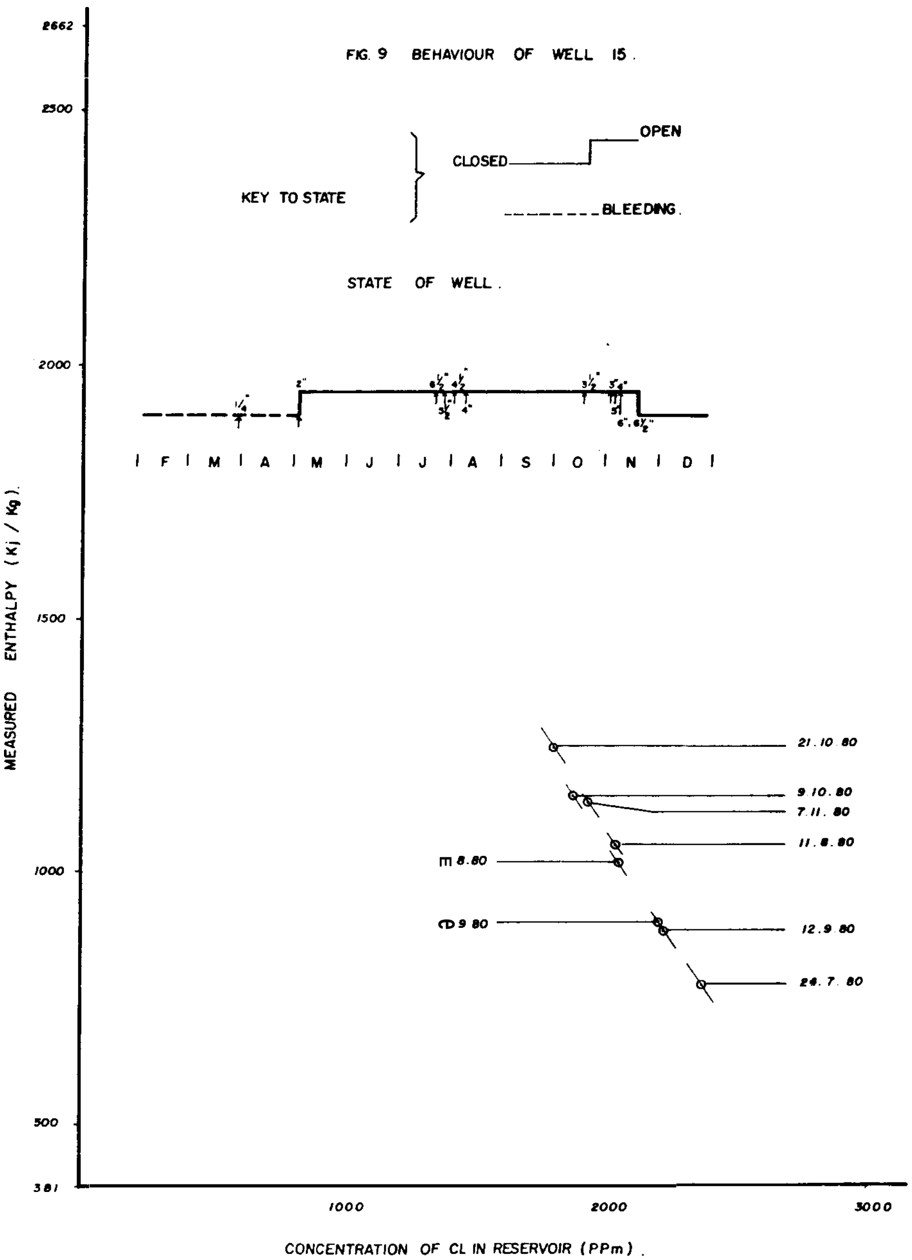


FIG. 9 BEHAVIOUR OF WELL 15.

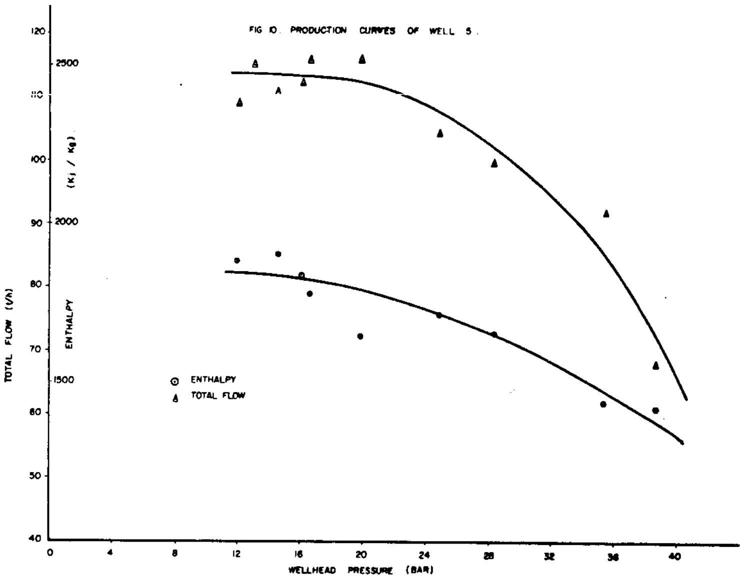
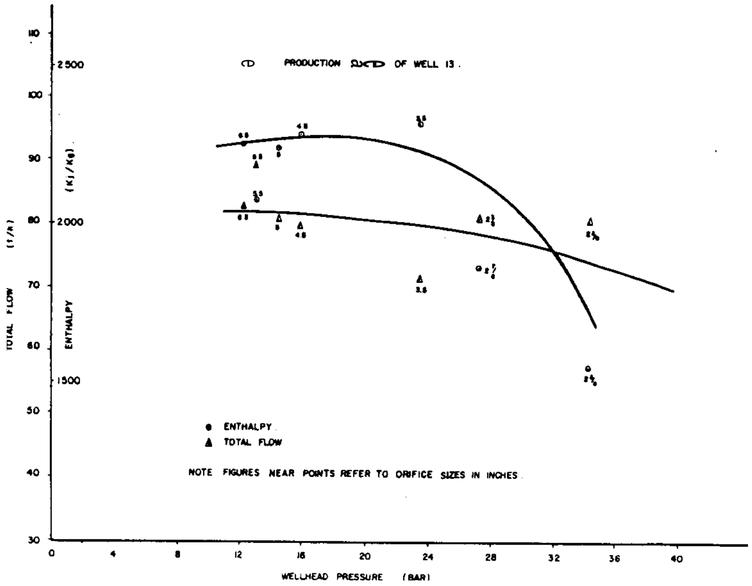


FIG 10 PRODUCTION CURVES OF WELL 5.



PRODUCTION [illegible] OF WELL 13.