

EVALUATION OF RESERVOIR PROCESSES USING FLUID ENTHALPY TRENDS : BACON-MANITO GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

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ABSTRACT

Variations in discharge enthalpy and fluid temperatures (from quartz and Na-K-Ca geothermometers) in the Palayang Bayan sector of Bacon-Manito Geothermal Production Field (BGPF) were examined to evaluate the response of the reservoir to exploitation. Comparison of measured enthalpy trends with those of enthalpy equivalent of geothermometer values provides indications of the physical processes occurring in the reservoir. These processes are: 1) boiling due to pressure drop, 2) cooling due to continuous boiling, 3) cold water inflow and 4) hot brine recharge. Study of individual wells confirms that a combination of these processes occur. For example, boiling in the reservoir is accompanied by cold water entry into the well. In such case where there is mixing of fluids, the concentrations of chloride in the water (total discharge and reservoir) and of carbon dioxide in the steam are of great value in the interpretation.

Pressure drawdown caused by continuous mass extraction in Palayang Bayan has induced migration of gas-depleted, cooler fluids from the western sector. This phenomenon, however, has minimized the decline of reservoir pressure in the southern sector and has resulted in minimal power output decline of 2.7 MWe during the first 3 years of field exploitation. However, a significant decline of power output by 12 MWe was experienced in the last quarter of 1996. This was attributed to: 1) massive local pressure drawdown in wells PAL-8D and PAL-20D and 2) colder water inflows in well PAL-14D through liner break. There are no chemical indications of reinjection fluid return in any of the wells.

1.0 INTRODUCTION

Since the commissioning of a 110 MWe power plant in September 1993, the production wells in the Palayang Bayan sector of BGPF (Fig. 1) show a general trend of declining total mass flows. In most wells, water flow declines while steam flow is either stable (PAL-18D, PAL-11D, PAL-13D, PAL-15D, PAL-4D, and PAL-9D) or slightly increasing (PAL-12D and PAL-21). There are wells that exhibit decline in both water and steam flow (PAL-3D, PAL-14D, PAL-19D, and PAL-20D). However, the changes in mass flows are characterized by fluctuations resulting to variations in discharge enthalpy and fluid temperatures.

The method of using enthalpy trends as indicators of near-well reservoir processes has been proven useful in monitoring the behavior of production wells in several high-temperature, liquid-dominated geothermal fields (Truesdell et al., 1995, Siega, et al., 1998). This paper presents the application of such tool in Bacon-Manito. The work done covers the period September 1993-April 1998, and considers only the well data under full-bore discharge conditions. The measured enthalpy values and mass flow data were taken from the results of Bore Output Measurements (BOM) conducted by the well-tests engineers in BGPF. For comparison with the discharge enthalpy, temperature values of (quartz and Na-K-Ca) geothermometers were converted to liquid enthalpy using the Geochemistry Information System (GCIS) software of PNOC-EDC.

Enthalpy Pattern	Interpretation
$H_{meas}=H_{nkc}=H_{sil}$	all-liquid, fully equilibrated reservoir fluid with no boiling or mixing
$H_{meas}>H_{nkc}>H_{sil}$	boiling due to local pressure drawdown
$H_{meas}>H_{nkc}=H_{sil}$	widespread boiling with phase segregation/separate entry of steam and water, mixing of equilibrated liquid with steam formed from boiling
$H_{meas}=H_{sil}>H_{nkc}$	thermal breakthrough of cooler water, H_{nkc} still partly retains the memory of equilibration at lower temperatures although the fluid has been heated by flow through hot rocks
$H_{meas}>>H_{nkc}>>H_{sil}$	high-temperature condensation at constant enthalpy, dilution of brine with condensate lowers H_{sil}
$H_{nkc}>H_{meas}=H_{sil}$	mixing with cooler water near the well with re-equilibration of silica
$H_{nkc}>H_{sil}>H_{meas}$	inflow of shallow, cooler, more dilute water into a well

3.0 DISCUSSION OF RESULTS

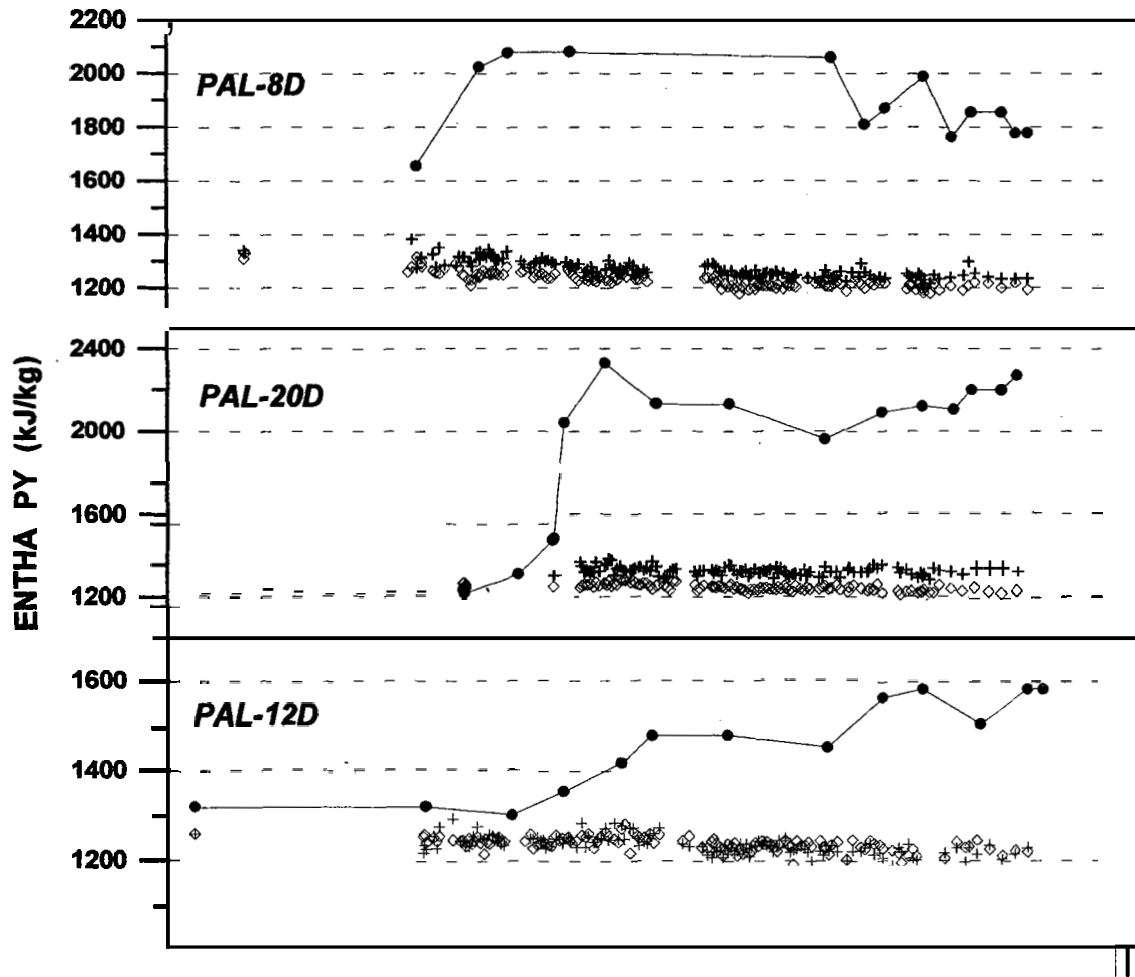
In general, the enthalpy patterns shown by the production wells in Palayang Bayan indicate that boiling and or pressure drawdown has been accompanied by α has induced several processes. These are: 1) near-well reservoir cooling, 2) interplay of, at least, two feed zones, 3) periodic recharge of hot brine and 4) inflow of cold fluids. In some wells, for instance, the changes in liquid enthalpy reflect mixing of cold and relatively hot fluids. The following discussion will focus on the most dominant process that affects the enthalpy trends of individual wells. The significance of other processes, however, was also assessed.

3.1 Local pressure drawdown and cooling

Boiling due to local pressure drawdown is distinct in wells PAL-8D and PAL-20D where the enthalpy patterns are **$H_{meas}>H_{nkc}>H_{sil}$** (Fig. 2). The gradual decline of H_{sil} in both wells indicates equilibration of silica as the near-well reservoir **cools** due to boiling. The H_{nkc} values are relatively stable due to slower equilibration of the cations (Truesdell, 1995). In PAL-8D, the pressure drawdown induced cold water inflow from the shallow reservoir. This is shown by the decline of H_{nkc} until about November 1996, corresponding to a drop in fluid temperatures by 12°C and with consequent drop of power output by 6.2 MWe. However, the output and H_{nkc} values stabilized when brine flow surged from 7.0 kg/sec to 24.6 kg/sec before the **start** of 1997. Apparently, there was a recharge of hot brine based on the increase in reservoir Cl **from** 9500 to 10200 mg/kg.

In PAL-20D, H_{meas} increased tremendously between March and July 1995 **from** 1530 kJ/kg to 2330 kJ/kg due to rapid depletion of liquid. Brine flow dropped from 21 to 11 kg/sec. Nevertheless, the well has recovered through recharge of hot brine. Reservoir Cl increased from 8200 to 8800 mg/kg as brine flow increased progressively to 18.6 kg/sec. This liquid recharge reduced the intensity of boiling **as** shown by the decline in **H_{meas}** . Subsequent boiling during the year 1997 increased **H_{meas}** as indicated by the rising trend.

Well PAL-12D shows increasing **H_{meas}** because of continuous boiling due to local pressure drawdown. The decline of H_{sil} , which suggests cooling of the reservoir near the well was somehow interrupted and obscured by a recharge of hot brine. The recharge resulted to mixing **as** indicated by the variations in liquid enthalpy values. However, the H_{sil} values show a decline from the baseline value of about 1262 kJ/kg in 1993 to around 1210 kJ/kg in 1998. This corresponds to cooling by **as** much **as** 10°C.



32 Interplay of feed zone

This process *can* be represented by the enthalpy trends of well PAL-18D (Fig. 3). It is only in PAL-18D that *H_{nkc}* values are consistently lower than *H_{sil}* values. This can be attributed to the major contribution from the **bottom feed** zone where there is temperature reversal. Although the fluid gets heated during flow through the hotter upper feed zone, the *H_{nkc}* values retain the equilibration condition at the **bottom** while silica equilibrates continuously with **boiling**. This is shown by the pattern **H_{meas} > H_{sil} > H_{nkc}**. The increasing trend of measured enthalpy indicates boiling due to **local** pressure drawdown.

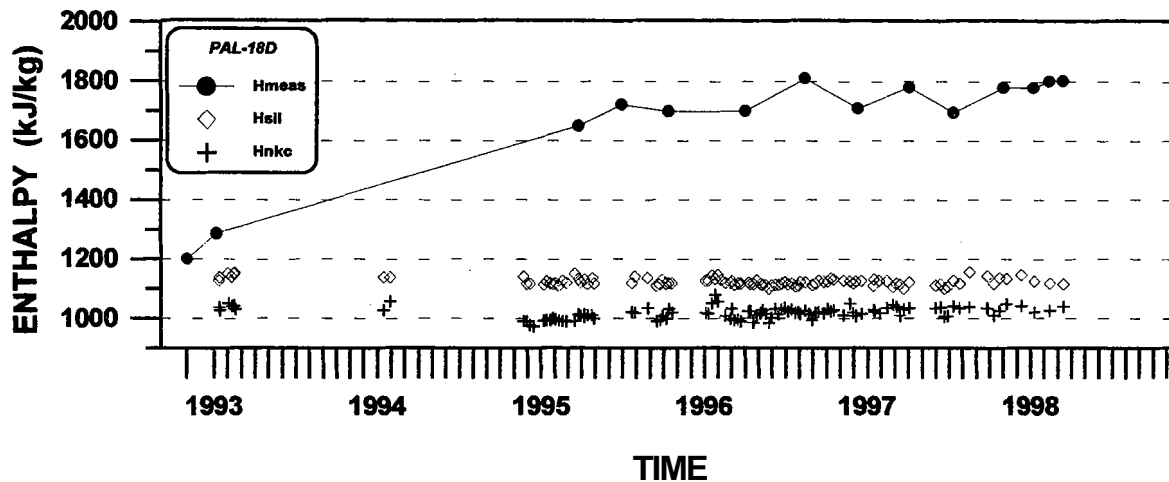


Figure 3. Enthalpy trends of PAL-18D. The pattern $H_{sil} > H_{nkc}$ is due to major contribution from the bottom feed zone where there is temperature reversal.

3.3 Recharge of hot brine

This process occurs in wells PAL-19, PAL-11D, PAL-15D and PAL-9D. In PAL-11D and PAL-15D, the liquid enthalpy trends are relatively stable, with minor pulse of increase in H_{nkc} , while H_{meas} fluctuates significantly (Fig. 4). In PAL-9D, this process is obscured by the occurrence of cold water inflow, which leads to mixing of fluids.

The initially high and increasing H_{meas} in PAL-19 (until Oct. 1995) was due to entry of highly two-phase fluids from just below the production casing shoe where there was liner break. After work-over operation, H_{meas} became lower as the bottom feed zone dominated the discharge. Since then, H_{meas} has been relatively stable at around 1600 kJ/kg, with minor fluctuations. The liquid enthalpy pattern ($H_{sil} = H_{nkc}$) indicates equilibrated liquid. The stable values of H_{sil} and H_{nkc} and the variations of H_{meas} suggest that the recharge of hot brine from the bottom feed zone is persistent, resulting to stable output of the well.

During the first year of power plant operation, the discharge enthalpy (H_{meas}) of PAL-11D surged from 1200 to 1800 kJ/kg while H_{nkc} increased from 1187 kJ/kg to 1233 kJ/kg. The increase in H_{nkc} indicates an increase in fluid temperature from 270°C to 280°C. This was, probably, caused by a shift in contributing feed zone. The well was initially producing from the upper feed zone at 1100 mVD where measured temperature prior to exploitation was 270°C. Then the bottom feed zone (at 1492 mVD) dominated the discharge. The shift in feed zone is evinced by the increase in Cl_{res} from 6300 mg/kg to 6800 mg/kg. Between October 1994 and April 1995, however, H_{meas} plunged from 1800 kJ/kg to 1430 kJ/kg while H_{nkc} declined slightly from 1246 to 1210 kJ/kg. These enthalpy trends suggest inflow of liquid with slightly lower temperature. In fact, Cl_{res} level declined from 6800 to 6600 mg/kg as brine flow increased from 22 kg/sec to 41 kg/sec. Between April 1995 and May 1998, the H_{meas} trend indicates a series of drawdown and recharge as the liquid enthalpy are relatively stable. In general, the well exhibits a cyclic behavior due to depletion and recharge of liquid from near the well bottom.

Well PAL-15D shows a general pattern of $H_{meas} > H_{nkc} \geq H_{sil}$, which indicates boiling due to local pressure drawdown. However, discharge enthalpy shows a series of fluctuation while the liquid enthalpies are almost stable. These trends indicate changes in the intensity of boiling due to periodic recharge of liquid phase. In fact, the brine flow and total mass flow in PAL-15D has increased progressively since the beginning of field exploitation, resulting to stable output of the well.

The enthalpy trends of PAL-9D, on the other hand, suggest that recharge of hot brine and cold fluid inflow occur simultaneously. Between April and November 1994, H_{meas} declined significantly from 1413 kJ/kg to

1240 kJ/kg, suggesting an inflow of liquid that reduced the intensity of boiling. Brine flow increased while *steam* flow declined within the same period. The *Hmeas* came very close to *Hsil* and *Hnkc* in November 1994, indicating a near-equilibrated state of the liquid. However, the *Hnkc* values were relatively unstable, suggesting that there is mixing of fluids with different temperatures. Between January 1995 and May 1998, the discharge enthalpy values show a cyclic trend. These cycles indicate increase and decrease of intensity of boiling caused by periodic recharge of near-well fluids. The liquid enthalpies are slightly unstable due to mixing of hot recharge and cold inflow. Nevertheless, the overall effect of these processes is a stable output of the well.

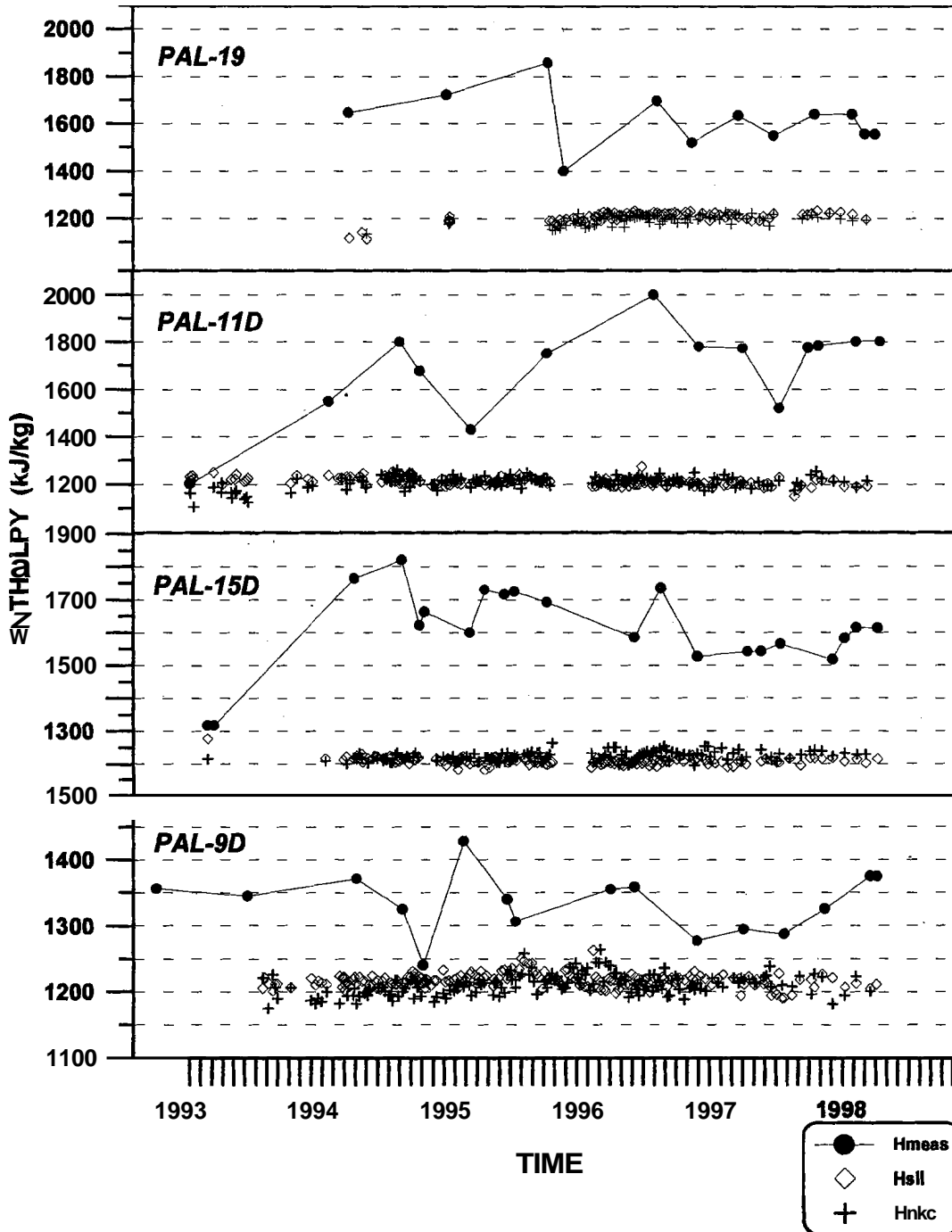


Figure 4. Enthalpy trends in PAL-19, PAL-11D, PAL-15D and PAL-9D. There is persistent recharge of hot brine in these wells that stabilizes the output

3.4 Cold fluid inflow

Lateral migration & peripheral waters

Inflow of cold fluids is prevalent in wells PAL-3D, PAL-4D and PAL-21. The common enthalpy pattern shown by these wells is $H_{meas} > H_{sil} > H_{nkc}$ (Fig. 5). The liquid enthalpy values exhibit large variations and unsteady trends, which are indicative of mixing. The thermal breakthrough of cold fluid inflow in PAL-3D and PAL-4D was evident, shown by the pattern $H_{meas} = H_{sil} > H_{nkc}$. The entry of cold fluids has been continuous, and has reduced the intensity of boiling in PAL-3D and PAL-4D. It has resulted to significant cooling in PAL-4D by, approximately, 6-10°C based on H_{nkc} .

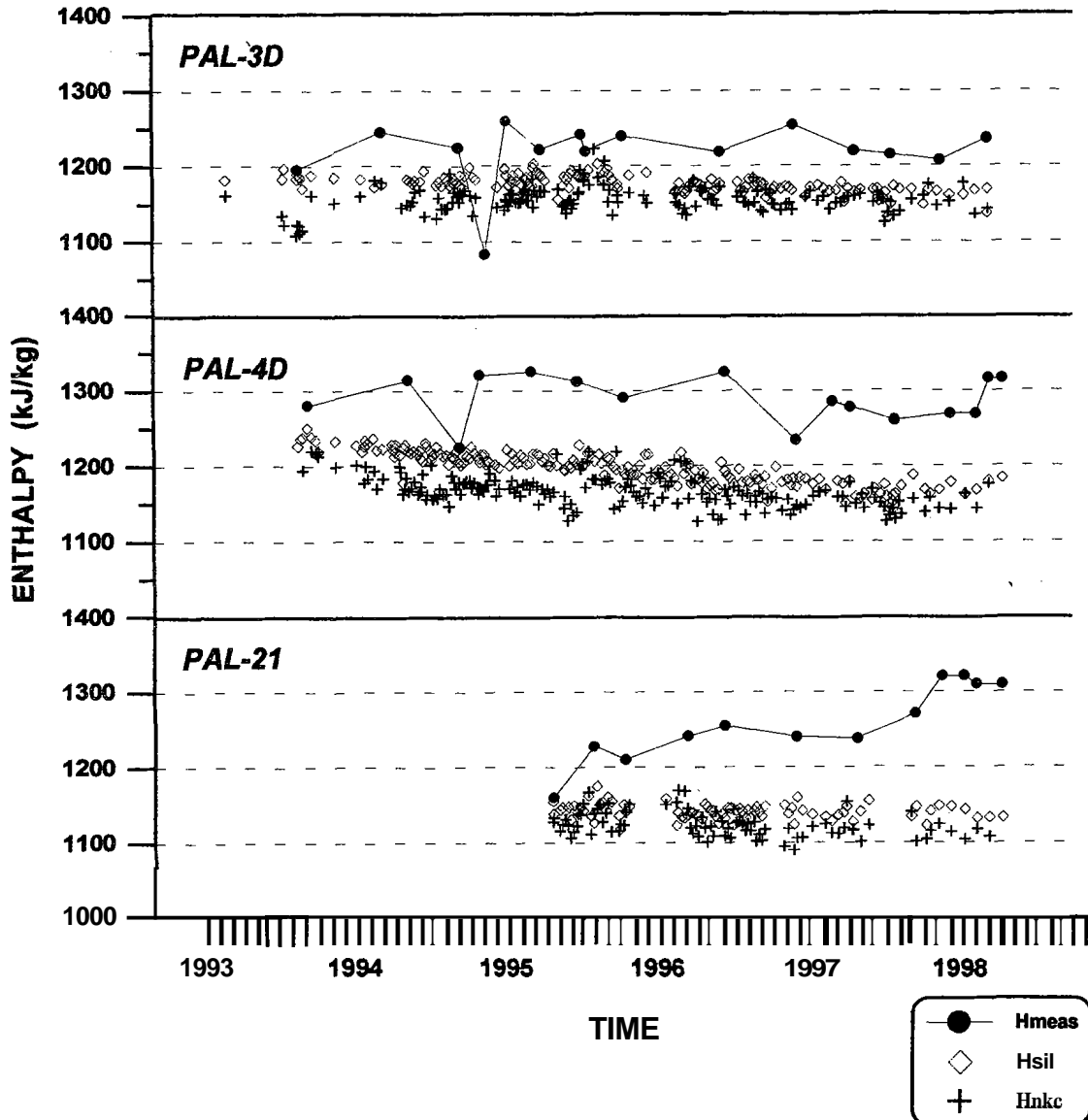


Figure 5. Enthalpy trends of PAL-3D, PAL-4D and PAL-21. Unstable H_{nkc} values indicate mixing of fluids.

The ingress of cold fluids caused significant chemical changes in the discharge chemistry of the wells such that the source was established. The major chemical change observed was the continuous decline in the boron concentrations, which results to increasing Cl/B molar ratios (Solis et al., 1998). This is attributed to migration of cooler (240°-250°C), degassed fluids with high Cl-B ratio from an area called Masakrot, west of Palayang Bayan. These Masakrot fluids serve as natural recharge in the western sector of the production field. It has been effective in reducing pressure drawdown in the affected wells, thus, minimizing output decline of the sector during the first three years of exploitation.

Coldwater entry through liner break

Unlike in wells PAL-3D and PAL-4D, the thermal breakthrough of cold fluids in PAL-14D occur more than two years since the discharge enthalpy started to decline (Fig. 6). The inflow of cold fluids in PAL-14D lowered the brine temperature by 13°C based on quartz geothermometer. It reduced steam availability by 15.4 kg/sec or by 7.0 MWe in power equivalent. Based on downhole survey, the cold fluids are entering the well, most likely, through the liner break at 1618 mMD (Solis et al., 1998).

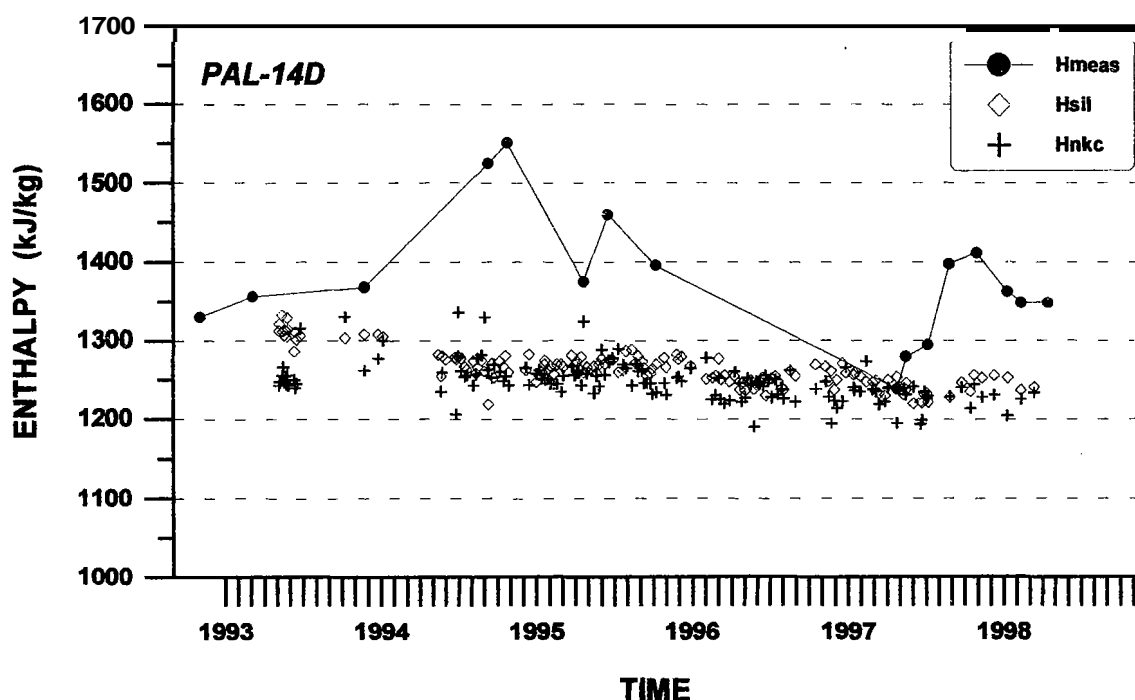


Figure 6. Enthalpy trends of PAL-14D. Downhole survey detected liner break at 1618 mMD, which is the likely entry point of cold fluids into the well.

Formation of mineral blockage

In PAL-13D, the increasing Hmeas values during the first two years of field exploitation, apparently, indicate boiling due to local pressure drawdown (Fig. 7). However, since then, Hmeas and liquid enthalpies have shown steadily declining trends. The linear decline of enthalpies could be an indication of gradual shift from a lower to an upper feed zone. Such phenomenon in PAL-13D can be attributed to the formation of blockage at 2353 mMD. Thus, the cold fluids are coming from, apparently, an upper feed zone of the well. However, the inflow seems to be so slow and at constant rate such that the output of the well has not been affected significantly. Nevertheless, the brine temperature has declined by about 17°C based on TSiO₂.

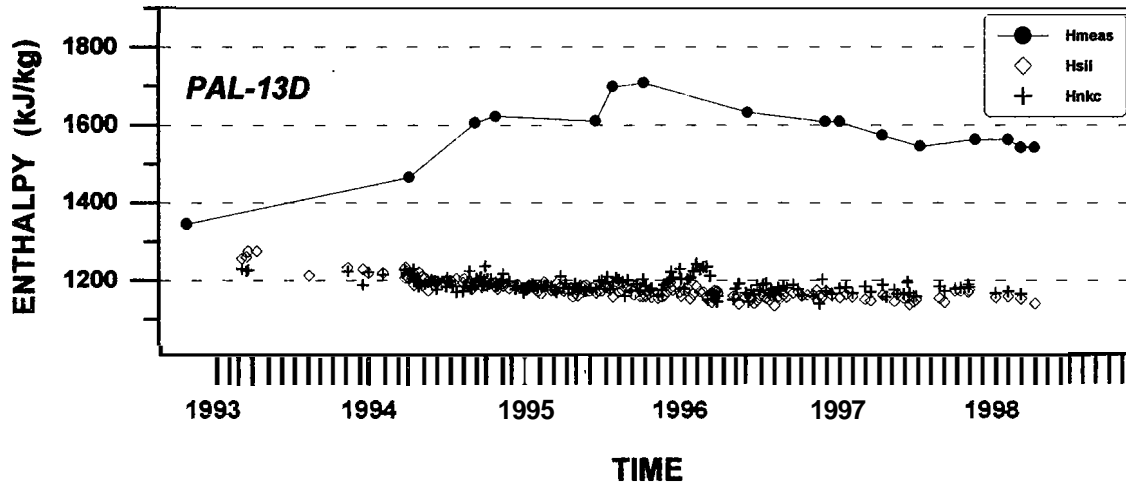


Figure 7. Enthalpy trends of PAL-13D. Steady decline of liquid enthalpies suggests cooling of the discharge fluids. This is caused, apparently, by formation of blockage at the bottom feed zone and subsequent domination of upper feed zone.

4.0 SUMMARY

The fluid enthalpy trends provide details of near-well processes in the Palayang Bayan sector of BGPF. They provide indications of hot brine recharge, cold fluid inflow as a result of pressure drawdown, casing/liner damage and formation of blockage in the well. The thermal breakthrough of cold water entry in wells PAL-3D, PAL-4D and PAL-14D are shown by the pattern $H_{meas} = H_{sil} > H_{nkc}$. The ingress of cold fluids in PAL-3D, PAL-4D and PAL-21 is attributed migration of cooler, gas-depleted fluids from the western part of the field. Solis and others (1998) refer to these fluids as the Masakrot fluids. Apparently, this fluid migration was induced by field-wide pressure drawdown, which is highest in wells PAL-8D and PAL-20D. Despite of this occurrence, the output of the affected wells remains relatively stable. In PAL-14D, cold water inflow is due to the liner break at 1618 mMD, which was detected by downhole surveys. This has resulted to decline of well output by about 6.0 MWe.

The gradual decline of both discharge and liquid enthalpy in PAL-13D suggests formation of blockage in the major feed zone such that the upper feed zone is slowly becoming dominant. This problem decreased the output of the well by 2.0 MWe.

The gradual and continuous decline of Hsil values in PAL-8D, PAL-20D and PAL-12D indicates near-well reservoir cooling because of continuous boiling due to local pressure drawdown. On the other hand, the stable liquid enthalpy values in PAL-11D, PAL-15D and PAL-19 while discharge enthalpies fluctuate indicate periodic recharge of hot fluids. The changes in the discharge enthalpies reflect changes in the intensity of boiling due to variations of liquid fraction.

The variations of fluid enthalpy in PAL-9D indicate occurrence of both cold fluid inflow and hot brine recharge. Based on the liquid enthalpy trends, the recharge of hot brine outplays the inflow of cold water and probably sustain the stable output of the well.

However, despite of the periodic recharge from the deep reservoir and the migration of Masakrot fluids, depletion of the liquid phase due to continuous boiling and steam extraction is evident. Bore output measurements (BOM) indicate a cumulative decline of brine flow in the entire Palayang Bayan sector by about 12.7% during the last three years (Sept. 1994-May 1998). There is also a subsequent decline in steam flow from 1131 tonshour to 990 tonshour. This corresponds to a decline in output from 143 MWe to 125 MWe based on the steam rate of 2.2 kg/sec-MWe.

5.0 CONCLUDING REMARKS

Considering the adverse effect of cold inflow to the output of a well and of the field as a whole, the wells that exhibit this process should be monitored closely. It should be established whether the cold inflow is acidic or meteoric in character to help determine the appropriate remedies (i.e. options for work-over), especially where the cold water entry is caused by partial mineral blockage and casing or liner damage. This *can* be done through downhole sampling whenever feasible during continuous power generation. The wells recommended for downhole sampling are PAL-3D, PAL-4D, PAL-13D and PAL-14D.

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