PROCEEDINGS, Twenty-Fourth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 25-27, 1999
SGP-TR-162

RESERVOIR RESPONSE AND BEHAVIOR TO FIVE YEARS OF EXPLORATION OF THE BACON-MANIT0 GEOTHERMAL PRODUCTION FIELD ALBAY, PHILIPPINES

by

V.L. Relativo-Fajardo, P.P. Gerona and D.O. Padua

PNOC Energy Development Corporation
PNPC Complex, Merritt Road, Ft. Bonifactio
Makati City, 1201, Philippines
buning@edc.energy.com.ph

ABSTRACT

Large scale exploitation of the Bacon-Manit0 geothermal production field commenced after commissioning the first 110-MWe power plant (BacMan 1) in September 1993 and the 20-MWe Cawayan modular plant (BacMan 2) in March 1994. The BacMan 1 power plant utilizes fourteen production wells and the separated brine is injected into three injection wells located northwest of the production sector. The BacMan 2 modular plant in Cawayan is supported by four production wells and two injection wells in the southwest portion of the field. The other 20-MWe Botong modular plant was commissioned in April 1998, utilizing the remaining production wells drilled in the BacMan 2 area.

The five-year behavior of the entire BacMan field is shown in various parameters as pressure, temperature, and enthalpy. The field is divided into six sectors, each responding distinctively to production. There is a wide range of pressure drawdown measured across the field, indicating non-uniform field-wide permeability distribution. The measured pressure decline closely agrees with the enthalpy rise in most production wells. The pressure trend also infers the degree and direction of recharge to the production sector. The enthalpy increase favors a rise in the field steam supply and a reduction in the brine flow. No direct connection between the production and reinjection sectors has so far been established. Several operational problems encountered during the five years of field exploitation are also discussed and solutions to these reservoir management problems are presented.

INTRODUCTION

Bacon-Manit0 Geothermal Production Field is located in the boundary of the towns of Bacon in Sorsogon province and Manito in Albay province in the Philippines (Fig. 1). It covers approximately 16 sq. km of reserve area. Initial reconnaissance survey started in May 1977, followed by full-scale geoscientific surveys over an area of 18,800 hectares. From May 1979, when the first exploratory

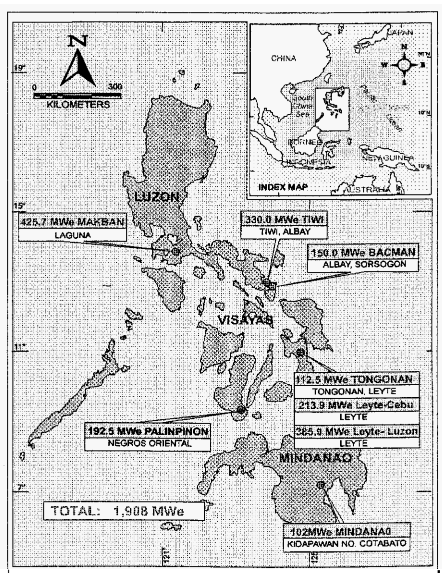

Figure 1. Philippine Geothermal Fields.

well (MAN-1) was drilled, up to 1993, several stages of development of the BacMan field were undertaken.

BacMan Geothermal Production Field (BGPF) is divided into two: BacMan 1 within the Palayan Bayan region and BacMan 2 Cawayan and Botong 20-MWe modules (Fig. 2). Exploitation in BacMan 1 dates back to February 1993 when only one well (PAL-10D) was commissioned for steam blowing and backheating of the Fluid Collection and Disposal System (FCDS). More wells were added in time for the system testing and the loading up of the turbine-generator (T/G) units.

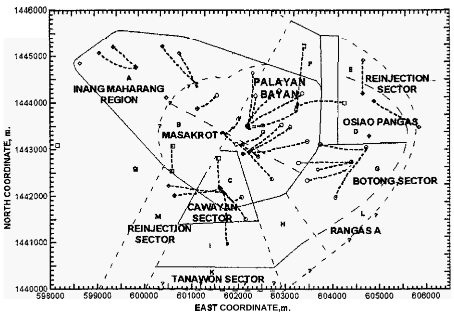

*Figure 2. BGPF Well Location **Map***

In September 1993, CN-1 in Cawayan started supplying steam to the FCDS 2 for backheating, steam blowing and system testing. Additional wells were put on-line when the 20-MWe modular power plant started operating in March 1994. The other 20-MWe modular power plant in Botong was commissioned in April 1998.

CONCEPTUAL MODEL

The Bacon-Manito Geothermal Field is one big liquid-dominated hydrothermal system (Fig. 3). The main upflow zone is in Palayan Bayan where the highest temperatures and chloride concentrations were mapped. Rapid cooling of temperatures towards Inang Maharang describes the preferential flow of upflowing fluids towards the reinjection/outflow sector. Cawayan area was earlier perceived to be a separate upflow but cooling is not as rapid as towards Northwest which strongly implies that Cawayan is still within the area of the main upflow zone. The area in Botong is separated from Palayan Bayan by a geologic barrier which explains the unusually higher pressures in the Osiao-Pangas wells.

BacMan field is characterized by the presence of west-northwest and northwest-southeast trending structures. These faults have strong influence on the flow of fluids within the formation.

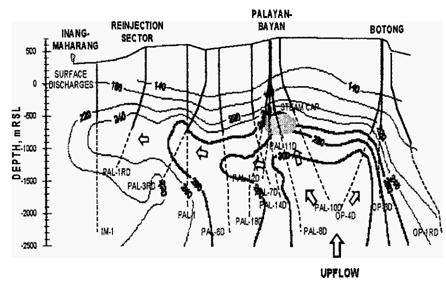

***Figure** 3. BGPF Conceptual Model*

STEAM/POWER GENERATION

BacMan 1 FCDS is a baseload station which supplies steam to the 110-MWe (two 55-MWe turbine-generator units) power plant of the National Power Corporation (NPC). Fourteen production wells are connected to the FCDS, five injection wells for the waste brine disposal and one cold injection well for NPC's cooling tower blowdown.

Turbine-generator (T/G) units 1 and 2 were synchronized to the power grid on 10 September 1993 and 12 December 1993, respectively. As of 25 November 1998, total power generation reached 2,563,767.0 MWh (1,272,734.8 MWh for T/G #1 and 1,291,032.1 MWh for T/G #2). This is 24,320,455.3 tonnes in terms of steam supply to the power plant. The highest average plant load attained was 106.79MWe.

The failure of the power plant to operate at 110-MWe baseload **is** attributted to various problems, e.g. the use of steam gas ejector (SGE), and problems in its cooling system like limited number of operational cooling tower fans.

Cawayan FCDS in BacMan 2 is designed to continuously supply steam to NPC's 20-MWe modular power plant. Commissioned in 1993, it has four production wells, two hot injection wells, one cold injection well and one dual hot/cold injection well for the waste brine and cooling tower blowdown disposal.

The turbine-generator (T/G #3) was synchronized to the Luzon grid in March 1994. Total power generation as of 25 November 1998 was 588,017.9 MWh with 4,918,211.3 tonnes of steam supplied to the power plant.

BacMan 2-Botong FCDS is a 20-MWe module with four production wells and two injection wells. Because of the very high Silica Saturation Index (SSI) of the discharge fluids, the Botong Effluent Disposal Scheme (EDS) adopts a low-temperature injection of the brine with a chemical inhibitor.

T/G #4 was commissioned in April 1998. Total power generation as of 25 November 1998 was 95,280.3 MWh, equivalent to 916,697.9 tonnes of steam supply.

MASS AND HEAT EXTRACTION

From day 1 to 25 November 1998, total mass extraction in BacMan 1 is 94,833,933.2 tonnes which is about 36,520,135.1 tonnes of steam and 145,323.2TJ of heat.

In Cawayan, total mass extracted to-date is 27,167,244.9 tonnes which equates to 6,946,269.5 tonnes of steam and 33,456.6TJ of heat.

After less than a year **of** producing from Botong, mass extraction is 2,089,880.6 tonnes which corresponds to 1,509,245.2 tonnes of steam and 4,622.4 TJ of heat.

MASS AND HEAT INJECTION

For BacMan 1, total mass injected as of 25 November 1998 was 58,360,356.7 tonnes. In Cawayan, a total of 20,136,977.8 tonnes of mass was injected. This is about 14,184.8TJ of heat. The lone well with higher water fraction, OP-4D has the biggest share (75%) of the 580,636.6tonnes of injected mass **in** Botong.

RESPONSE TO EXPLOITATION

The five-year behavior of the entire BacMan field is shown in various parameters as pressure, temperature, and enthalpy. The production wells have been grouped according to their location and response to continuous field exploitation.

Enthalpv Resoonse

The general trend in BacMan 1 enthalpy is increasing (Fig. 4). The measured increase, is pressure-drawdown related.

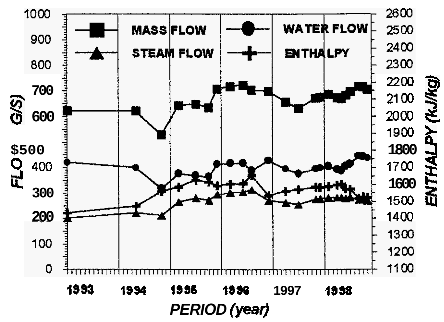

Figure 4. BacMan 1 Field Output Trends

Situated closest to the outflow area north **of** the field and the reinjection sector to the west. Sector 1 wells (PAL-12D, PAL-14D, PAL-18D, and PAL-19) have shown slight increases in enthalpy with no sigmficant mass flow reduction (Fig. 5). Average enthalpy **is** around 1500 kJ/kg. PAL-18D continues to improve in enthalpy with corresponding increase in mass flow, suggesting significant contribution from the top two-phase zone.

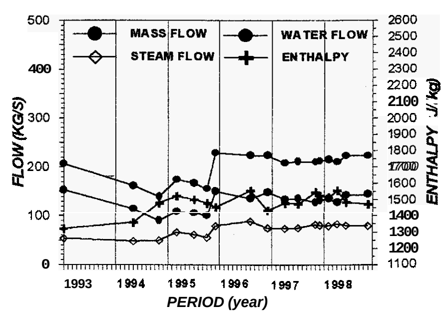

Figure 5. Sector 1** Output **Trends

Bounded to the north **by** the geologic barrier, wells in sector 2 exhibited the biggest enthalpy increase and mass flow reduction (Fig. 6). This **is** where mass extraction is at its fullest and recharge is minimum, thus the substantial pressure drawdown. In the first three years of field exploitation, enthalpy in this sector reached a maximum of 2417 kJ/kg. The subsequent drop in enthalpy, **to** 1983 kJ/kg, is associated with the entry of natural recharge fluids from the north (PAL-16D) sector which is believed to be an outflow area. This corresponds with an increase in PAL-16D's downhole pressure showing pressure stabilization.

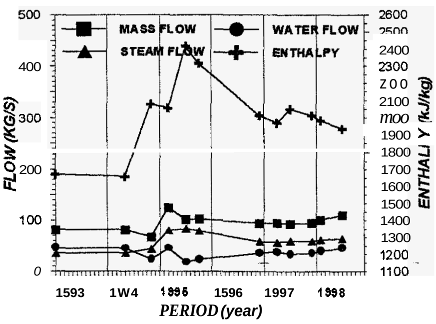

Figure** 6. **Sector 2 Output Trends.

Sector 3 is closest to the Botong area. All four wells showed enthalpy increases but not as great as that measured in sector 2 wells (Fig. 7). Enthalpy in these wells ranged from 1542 to 2182 kJ/kg with wells showing fluctuations in output due to cycling.

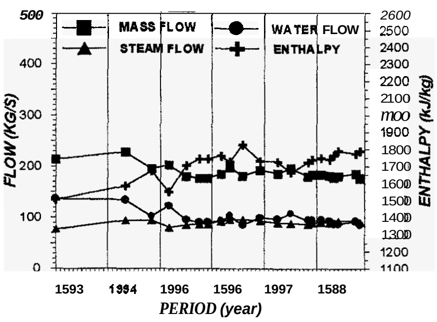

Figure** 7. **Sector 3 Output Trends.

The low-enthalpy wells are grouped in sector 4. These wells have consistently showed lower-than-baseline enthalpies due to the continuous influx **of** relatively cooler fluids from the West (Masakrot). The enthalpy declines were coupled with increases in mass flows **(Fig.** 8).

Cawayan sector enthalpy remained almost stable with time **(Fig.** 9).

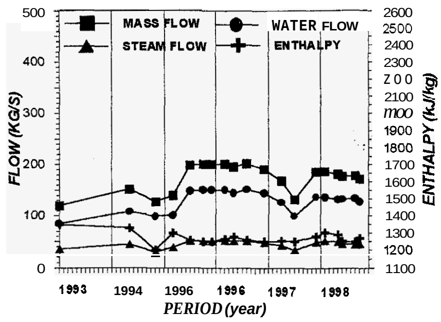

Figure 8. Sector 4 Output Trends.

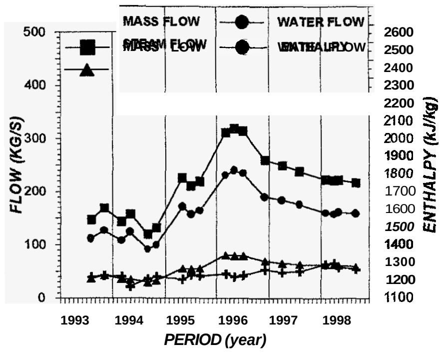

Figure 9.** Cawayan **Sector Output Trends.

Enthalpies in Botong (Fig. 10) have been high as most wells discharge high-enthalpy two-phase fluids. Current enthalpy is 2218 kJ/kg as compared to a baseline value **of** 1962 kJ/kg.

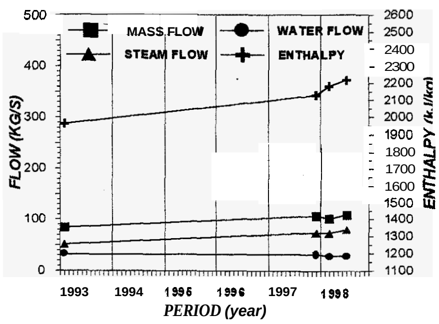

Figure 10. Botong Sector Output Trends.

Pressure Response

The fieldwide pressure drawdown distribution shows a wide scatter of pressure decline across the field. This is likewise related with the enthalpy increases measured in most production sectors. The data (Table **1)** are plotted to show the field pressure contours (Fig. **11).** Maximum pressure drawdown was measured in sector **2** where mass extraction was concentrated. The geologic barrier between Palayan Bayan and Botong likewise limits the entry of recharge fluids to the northern production sector of the field.

WELL	mVD	BASE PRES. MPag	CURR. PRES. MPag	ΔP MPag
PAL-1	1584.5	9.16	9.08	0.08
PAL-3D	1665.9	9.79	8.58	1.21
PAL-6D	1546.4	9.07	9.07	0.00
PAL-7D	1613.0	9.53	8.76	0.77
PAL-8D	1662.4	9.73	6.21	3.52
PAL-16D	1639.9	9.80	7.23	2.57
PAL-17D	1639.9	10.80	10.76	0.04
PAL-18D	1662.4	9.53	8.11	1.42
CN-1	**1731.6**	**9.89**	**9.82**	**0.07**
OP-4D	**1679.0**	**11.15**	**11.12**	**0.03**
OP-5D	**1740.0**	**10.23**	**9.20**	**1.03**

Table 1. BacMan Field Drawdown Distribution at -1000 mRSL.

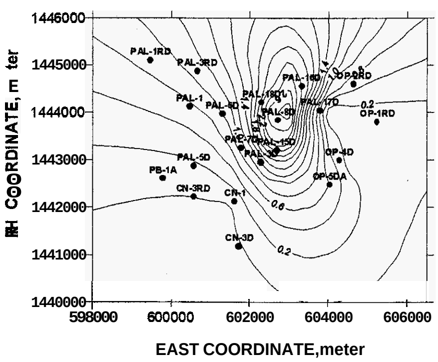

Figure 11. BGPF Pressure Drawdown Contour at –1000 mRSL.

The pressure decline in well **PAL-7D** (Fig. **12)** shows an initial gradual decline approaching steady state due to natural recharge. The minimal pressure decline is consistent with the estimated recharge constant of **914.50** kg/s-MPa. This is much bigger than the estimated recharge constant in **PAL-16D (249.7** kg/s-MPa) which showed rapid linear decline in pressure indicating minimum recharge coming in the well (fig. **13).** In **1996,** however, pressure initially showed recovery, suggesting recharge.

Minimum pressure drawdown was measured in Cawayan and in Botong. There has been no over pressure within the reinjection sectors of the field.

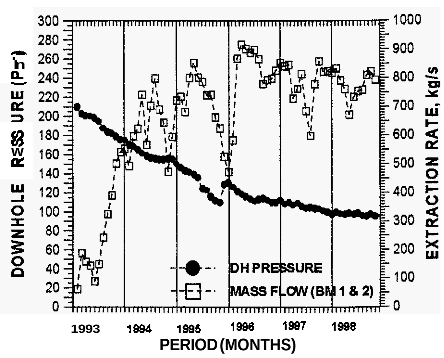

Figure 12. PAL-7D Interference Test Plot.

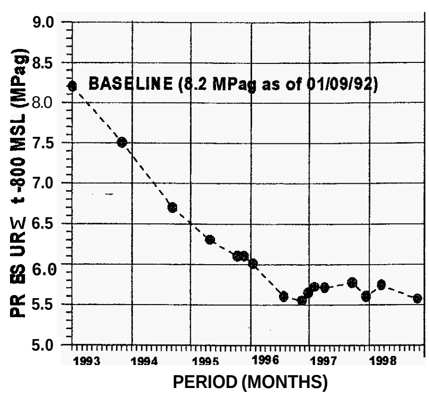

Figure 13. PAL-16D Pressure Trend.

Figure **14** shows the changes in the wells' water level with time. Regardless of the structural connections between the wells, there is a good outflow of fluids towards the injection sector.

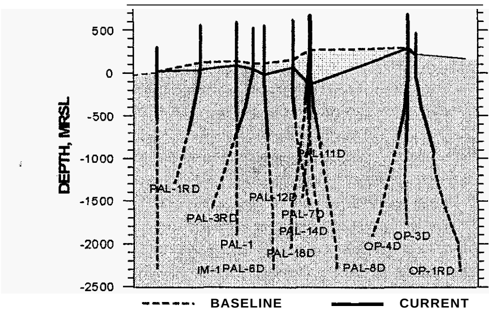

Figure 14. BGPF WaterLevel Contour.

Temperature Response

The measured thermal decline in most production wells are pressure-drawdown related. At the bottom of PAL-8D in sector 2, a 6^0C thermal drawdown was recorded. PAL-18D consistently showed thermal inversion at the bottom indicating dominance of the two-phase zone in the discharge. The cooling observed in the injection wells is the effect **of** the waste brine injection.

SUMMARY OF RESPONSES

The individual responses **of** the production sectors are summarized in figure 15. The figure compares the baseline and current field scenarios. Average mass extraction rates, pressure, and enthalpy trends are presented. The wide range of pressure drawdown measured across the field indicates non-uniform field wide permeability distribution. The field enthalpy trend conforms with the measured pressure

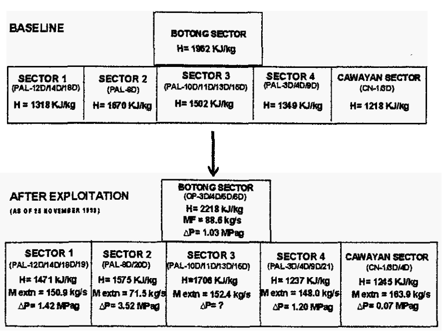

Figure 15. BGPF Field Representation.

drawdown. The biggest enthalpy increase was measured in sector 2 where pressure drawdown is maximum (3.8 Wag). Sector 4 wells have enthalpies lower than baseline values as a result of the influx of relatively cooler fluids from the nearby western Masakrot sector. These fluids serve as a natural recharge to the production wells. Pressure drawdown is minimum at this sector, likewise in the Cawayan (0.03 Wag) and Botong (0.80 Wag) sectors.

PROBLEMS ENCOUNTERED

Casing Damage

After five years **of** continuous field exploitation, twelve wells developed casing and/or liner damage that can be associated with corrosion, thermal expansion of trapped **fluids** (poor cement bonding), compression failure due to temperature changes in the well and mechanical clearing during work-over. Although relining of the existing casing with a smaller diameter casing results to reduction in the well output, it stops the risk **of** a well or even a pad blowout. Currently, production wells with casing damage, PAL-11D, PAL-15D, and OP-4D, have yet to show decline in output associated with the casing damage.

Mineral Deposition

Anhydrite is the most common mineral deposition in BacMan production wells. Four anhydrite wells have been mechanically cleared to recover their output. Calcite is mostly formed in the low-enthalpy injection wells with bicarbonate-rich fluids. Among the wells with Calcite are PAL-6D, PAL-3RD, and OP-1RD. The blockage in OP-1RD was removed during the work-over/acidizing in 1997.

High Non-condensible Gas

In BacMan 1, the problem on high NCG has been recognized from the early exploration stage **of** the field. The 3.5% NCG concentration measured at the interface is higher than the 2.5% contracted value. Whereas in Cawayan, the %NCG at 0.40-0.6% is below the 2.5% interface limit. The NCG in Botong was calculated at 6.57-7.48% with all production wells at full-open condition. The turbine-generator unit in Botong uses a hybrid gas extraction system.

High Plant Steam Rate

In BacMan 1, plant steam rates were higher than the agreed rate of 2.2 kg/s-MWe due to low average plant load., the use of steam gas ejector (SGE) and the **high** %NCG.

High Mass Extraction Rate

Despite low plant load, mass extraction has been maintained high, resulting to excessive steam wastage. Non-self-discharging wells were maintained flowing in preparation for instantaneous loading up of the power plant. Anhydrite wells were kept on full-open discharge to prevent recurrence of blockage. Throttling **of** wells with casing damage has been avoided ***so*** as not to trigger geysering activity due to pressurization. High-NCG wells were likewise maintained on full-open discharge at least a week prior to hook-up to the system for gas clearing. Similarly, high extraction rate is a direct consequence of high plant steam consumption.

Silica Deposition in the Botong Effluent Disposal System

The high rate of silica in the Botong EDS has been expected considering the very high Silica Saturation Index (SSI) of the Botong discharge fluids. The cold injection system was adopted and a silica inhibitor is being used to address the problem. It was observed, however, that the silica inhibition system is only partially working. With less than a year of continuous FCDS operation, Botong EDS has been confronted with problems like clogged injection lines, excessive silica deposits in the thermal pond and silencer weirbox. The injection well was also blocked, affecting its brine acceptance. A permanent line for injection line flushing was installed in the Botong FCDS. **A** back-up RI line was also constructed to allow continuous operation even when one RI line gets clogged **by** silica. Acid stimulation was also conducted in the injection wells for capacity recovery (Malate, et. al. : Stanford Workshop, 1999).

PRODUCTION ENHANCEMENT

To ensure continuity of sufficient steam supply to the power plant, production and injection wells with suspected wellbore problems, e.g. mineral deposits, mud damage and silica deposits, were either mechanically cleared or acid-stimulated. Anhydrite wells, PAL-4D, PAL-9D, PAL-13D, PAL-21, and CN-1, were mechanically cleared of blockage to regain the original production output. In Botong, production wells, OP-3D and OP-5D, and injection wells OP-1RD and OP-2RD were acid-stimulated. Prior to acid injection, mechanical clearing of blockage was caried out. The acid stimulation proved to be successful as .the wells significantly improved in output and injection capacities. Post-acid injectivity tests showed increase in injectivity index and reduction in downhole pressures, indicating permeability enhancement.

CONCLUSION

After five years, the field still delivers steam enough to sustain operation of the 110-MWe powerplant. The measured rise in enthalpy has been contributory to the increase in the field's steam supply. No direct connection between the production and reinjection sector has been established. The problems on casing damage and chemical deposition have **been** manageable. Despite the acid fluids, Cawayan module continuously operates at 20 MWe. The wells have remained quite stable except for the anhydrite wells, CN-1 and CN-3D. The Botong FCDS continues to supply steam to the power plant. The problem on silica deposition has been manageable

ACKNOWLEDGEMENT

The authors wish to thank PNOC Energy Development Corporation for allowing us to publish this report.

REFERENCES

Fajardo, V.L.R., and Gerona, P.P. (1993), Bacon-Manito Geothermal Field Baseline Data Prior to Commercial Exploitation, PNOC-EDC Internal Report.

Fajardo, V.L.R., et al.. (1994), The First Year of Exploitation of the BacMan Geothermal Field, PNOC-EDC Internal Report.

Fajardo, V.L.R., and Gerona P.P. (1995), BacMan Geothermal Production Fields Second Year **of** Exploitation, PNOC-EDC Internal Report.

Fajardo, V.L.R., et al.. (1996), BacMan Geothermal Production Fields Initial Response to Exploitation, PNOC-EDC Internal Report.

Fajardo, V.L.R. (1997), BacMan Geothermal Production Field's Lumped-Parameter Model, PNOC-EDC Internal Report.

Grant, Malcom, et al. (1982), Geothermal Reservoir Engineering.

Padua, D.O., et al. (1996), BacMan Geothermal Production Field's Blockage Histories and Casing Configurations, PNOC-EDC Internal Report.