The United Nations
University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

20th Anniversary Workshop
October 1998

# LONG-TERM RESPONSES OF GEOTHERMAL RESERVOIRS IN THE PHILIPPINES

**Zosimo F. Sarmiento**
PNOC Energy Development Corporation
Merritt Road, Fort Bonifacio, Makati City,
PHILIPPINES

## ABSTRACT

The response to exploitation and changes in reservoir management strategies of four geothermal fields in the Philippines have been closely monitored to keep up the long term reliability of steam supply to the power plant. Experiences indicate that reinjection is a critical component in the maintenance of the geothermal fields, both in sustaining long term production and in evading reservoir cooling due to communication in the production and injection wells. Some of the major causes of well output declines are associated with calcite mineral deposition, influx of cooler re-injection fluids, natural leakage from cold aquifers, obstruction in the casings and natural reservoir drawdown. Increased enthalpies are observed in most wells in Tongonan in response to the additional 600 MWe load, while relatively stable outputs are recorded in Bacman and Mt. Apo fields.

## 1. INTRODUCTION

The Philippines is now (1998) in its 22nd year in the utilization of geothermal energy for power generation. Exploration works commenced after the oil crisis in the '70s marked with the commissioning of the first commercial pilot plant (3 MWe) in 1977 by PNOC Energy Development Corporation (EDC) in Tongonan. Subsequently, two 110 MWe plants in Tiwi and Makiling-Banahaw were commissioned in 1979 by Philippine Geothermal Inc., a wholly owned subsidiary of UNOCAL, USA and another 3 MWe pilot plant in Palinpinon field by PNOC-EDC in 1980. These were followed in 1983 by the commissioning of the next 2x112.5 MWe power plants in Tongonan and Palinpinon geothermal fields, both operated by the PNOC EDC. The national government resolved to pursue its development by introducing to Congress legislation bills that grant incentives to companies engaged in geothermal activities. The installation of a total 650 MWe has been merely due to the recent liberalization of the power and energy sector which paved the way for the private and the international power companies to finance and construct additional plants. Republic Act 6957 (Build-Operate-Transfer Law) mandates a cooperation that calls for PNOC

Energy Development Corporation to develop the steam-fields while the BOT contractor assumes the construction of the power plant. This agreement lasts for 10–15 years after which the plant will be transferred to PNOC for their management and operation. Thus, the Philippines is able to maintain its second position to the United States in terms of total installed capacity and remains on top of those countries utilizing the liquid-dominated type of reservoirs (Table 1).

Table 1: Installed geothermal plant capacities of various countries worldwide (Stefansson, pers. comm.)

| Country | Installed capacity (MWe) | Country | Installed capacity (MWe) |
|---|---|---|---|
| USA | 2849 | El Salvador | 105 |
| Philippines | 1861 | Iceland | 80 |
| Mexico | 753 | Costa Rica | 60 |
| Italy | 742 | Kenya | 45 |
| Indonesia | 589 | Nicaragua | 40 |
| Japan | 530 | Others | 77 |
| New Zealand | 365 | Total | **8096** |

## 2. RESERVOIR CHARACTERISTICS

High-temperature liquid-dominated reservoirs are being developed and exploited in the Philippines for power generation. Temperatures encountered at depths range from 280–350°C. They are typically situated at elevated regions along the volcanic center of the country. The Mt. Apo geothermal field, in the southern part of the country in Mindanao (Figure 1), is located at elevation 1800m above sea level (ASL) (the deepest well is drilled to a depth –1230 m below sea level) while wells in other geothermal fields are drilled at elevation 700-800m ASL. For this reason, most of the wells have water levels perching at about 600-800m from the surface. These reservoirs have distinctive upwelling regions that surge vertically at the top of the resource, rushing towards the outflow regions (Figure 2). In the natural state, the onset of the two-phase zone at deeper levels coincides with the top of the upwelling zone and to some extent to the shallow depths in the outflow zones as seen in the Tongonan geothermal reservoir (Sarmiento et al, 1993). The geologic faults control the main permeability in the field with minor contribution from the formation transition zones as well as those from the fractured rock matrix. The wells are, thus, usually completed with production coming from multiple feed-zones.

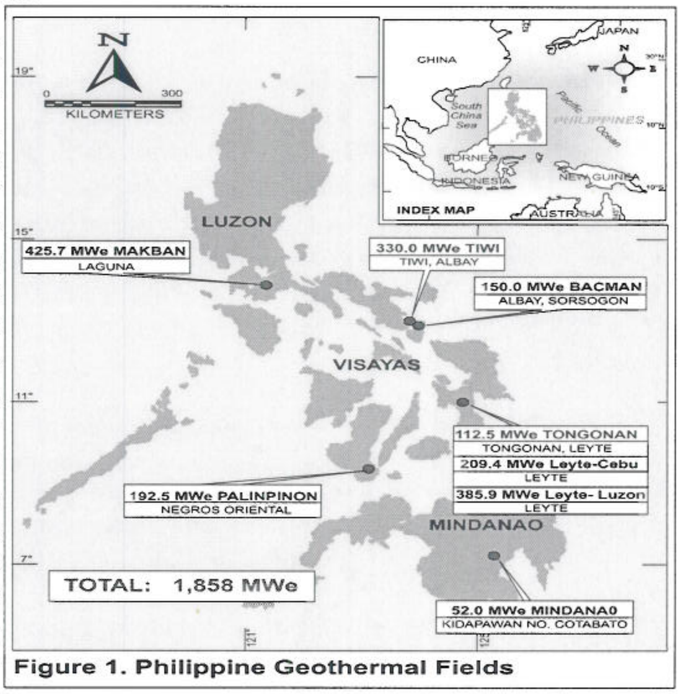

Figure 1: Philippine geothermal fields

## 3. POWER STATION MODELS

The soaring power demand and the existent competing sources of energy in the early 1990's presented a new challenge in developing other geothermal resources especially in the expansion of the capacity of the Tongonan field. The resulting consumer electricity price from these geothermal sources should be low enough to compete with coal and other alternative sources such as natural gas, hydro and oil. A new approach in optimization of the power plant allowing for lesser steam consumption was thus enunciated. In 1992, a study on the use of high-pressure turbines was commissioned to evaluate feasibility and

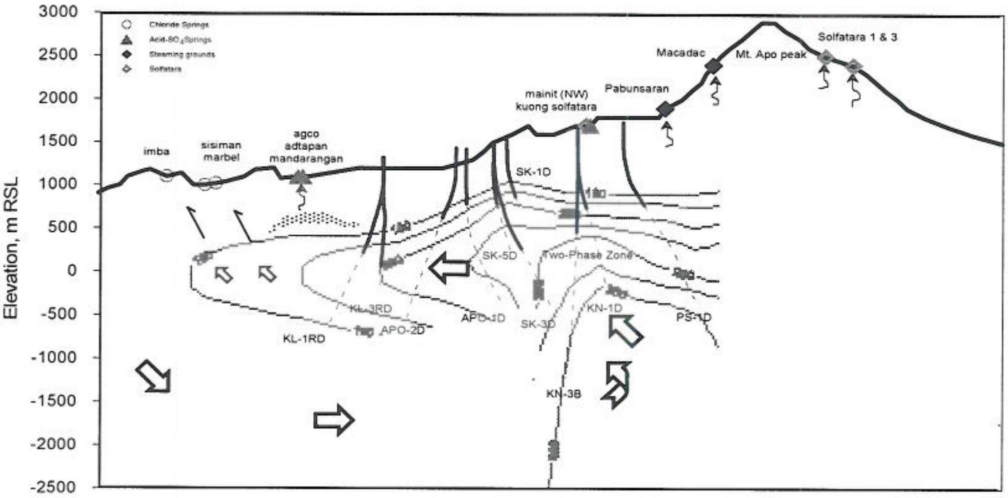

Figure 2: Mt. Apo geothermal resource conceptual model showing upflow and outflow features (Esberto et al., 1998)

minimize the long term risks associated in operating the field at elevated pressure condition. Sarmiento et al. 1993, presented the various power station models that were adopted to match the expected performance of the field during its exploitation. The results of the study, which indicate that Upper Mahiao and the Lower Sambaloran sectors of the Tongonan field were able to maintain relatively higher pressures for the first ten years, were taken into account in deciding to install additional high-pressure turbine units to optimize the power output from the field. This marked the company's aggressive posture towards optimizing and setting higher turbine inlet pressures, a radical departure from the usually conservative approach of *steam-field* developers in specifying lower turbine inlet pressures than what the reservoir can support.

The 200 MWe Leyte-Cebu interconnection was inaugurated in June 1996 supplying power via the submarine cable from the Upper Mahiao and the Malitbog sectors of the Tongonan field. High-pressure steam from the Upper Mahiao runs the 127.3 MWe geothermal combined cycle units while the 4.6 MWe Ormat energy converter unit utilizes the brine component. The additional 77.5 MWe Fuji turbine unit also utilizes the high-pressure steam supplied from the Malitbog sector.

On the other hand, the 440 MWe Leyte-Luzon interconnection that was inaugurated in 1997 but became operational in May this year conveys power coming from the additional 2 x 77.5 MWe HP turbines from Malitbog/South Sambaloran, 3 x 60 MWe intermediate pressure turbines from the Mahanagdong sector, 36.3 MWe topping plants from the Tongonan I and the Mahanagdong sectors and the additional 14.6 MWe from the intermediate pressure second flash unit in Malitbog sector.

The application of a dual pressure turbine was also adopted in the second Mitsubishi turbine unit for the 50 MWe Mindanao II power plant utilizing the intermediate steam pressure of 0.70 MPaa and the second flash low pressure steam of 0.30 MPaa from the separated brine. Table 2 summarizes the interface pressure of these turbines. A substantial improvement in the power recovery was, thus, achieved with the combination of HP-IP-LP turbines in each corresponding sector.

## 4. LONG-TERM RESERVOIR RESPONSES

### 4.1 Mass extraction rates

The Tongonan and Palinpinon geothermal fields have been in operation since 1983 while the Bac-man and the Mt. Apo geothermal fields were commissioned in 1993 and 1997, respectively. Figure 3 shows

Table 2: Interface pressures of PNOC-EDC and BOT geothermal plants

| **Field/Sector/Plant** | **Plant capacity (MWe)** | **Interface pressure (kg/cm$^2$)** | | |
|---|---|---|---|---|
| | | **Low** | **Intermediate** | **High** |
| Palinpinon | | | | |
| Palinpinon I | 3x37.5 | | 6 to 7 | |
| Nasuji | 20 | | 6 to 7 | |
| Balas-balas | 20 | | 6 to 7 | |
| Sogongon | 2x20 | | 6 to 7 | |
| Greater Tongonan | | | | |
| Tongonan I | | | | |
| Main | 3x37.5 | | 6 to 7 | |
| Topping plant | 17.25 | | | 10 to 11 |
| Upper Mahiao | | | | |
| Main (Combined cycle) | 4x31.815 | | | 10 to 11 |
| Brine OEC (Binary) | 4.6 | | | 10 to 11 |
| Malitbog/S.Sambaloran | | | | |
| Main | 3x77.5 | | | 10 to 11 |
| Bottoming Plant | 14.56 | | 6 to 7 | |
| Mahanagdong | | | | |
| Main Plant A | 2x60 | | 6 to 7 | |
| Main Plant B | 60 | | 6 to 7 | |
| Topping Plant A | 2x6.35 | | | 10 to 11 |
| Topping Plant B | 6.38 | | | 10 to 11 |
| Bacman | | | | |
| Bacman I | 2x55 | | 7 to 8 | |
| Bacman II | | | | |
| Cawayan | 20 | | 7 to 8 | |
| Botong | 20 | | 7 to 8 | |
| Mindanao | | | | |
| Mindanao I | 52 | | 6 to 7 | |
| Mindanao II (IP-LP unit) | 50 | 3 to 4 | 6 to 7 | |

the mass extraction rates corresponding to each plant's load and generation. As a management philosophy, one hundred percent of the wastewater is re-injected back to the formation as a means of disposing of the unspent brine and to serve as a pressure support to the reservoir. The percentage brine in the total mass discharge ranges from 40 to 60 % during the initial production period and up to only 10–30 % in the high-enthalpy sectors. In general, a mass extraction rate equivalent to 8-10 kg/s-MWe is estimated with the highest equivalent rate calculated for Palinpinon, and the lowest equivalent rate of 7.4 kg/s-MWe for Bacman. One of the main characteristics in Palinpinon and Tongonan plants is that they are *load-following-plants* which means that mass extraction would vary within the 24 hour period depending on the consumers' demand. The load average during the last 15 years should be from 60-80 MWe.

The projected cumulative generation for Tongonan and Palinpinon is calculated to be 14,125 GWh and 13,797 Gwh, respectively, during the last 14 years. However, because the two plants operate at variable loads and have not really realized the initial projected consumers demand, the total generations only reached 7,172 GWh and 7,112 GWh, respectively. But because the plants are not operated efficiently, both from the point of view of the steam field and the power plant, the total estimated generations corresponding to the total mass and steam produced approach 11,799 GWh and 13,474 GWh respectively for Tongonan and Palinpinon. These figures are very close to the estimated full load generation of the two plants. Hence, for 15 years, the two plants appear to be operating at full capacity in terms of the total mass withdrawal.

Bacman and Mt. Apo are more or less *base-load plants* because they are connected to the main Luzon and Mindanao power grids. Any demand above the base capacity of the plant can be absorbed by other plants in the grid. However, because of the prolonged operational problems in the power plant, Bacman I has been averaging only about 40-50 Mwe.

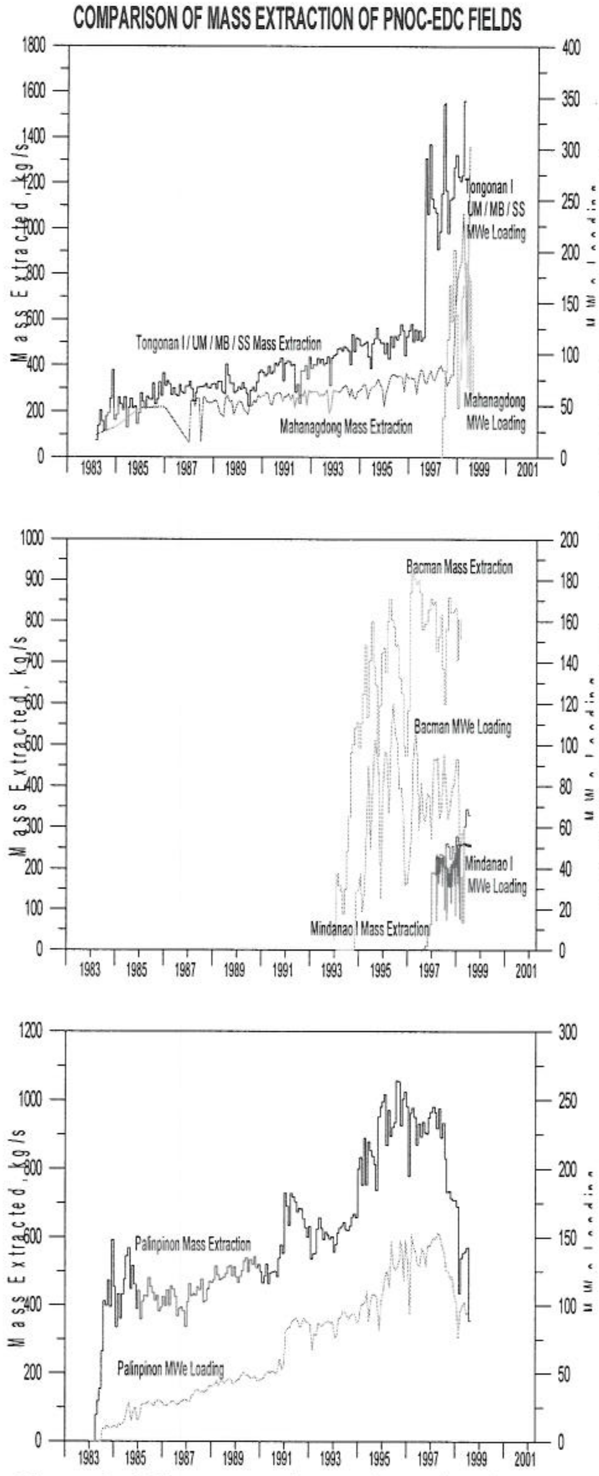

Figure 3: Mass extraction against plant loading for various PNOC-EDC plants

Figure 4 shows the historical trend in the various fields as they compare with the load demand requirement. The expansion of the two phase-fluids in the Upper Mahiao and the South Sambaloran sectors results in the discharge of high-enthalpy fluids from the top zone in most wells. An increase in enthalpy from 1600 kJ/kg to 2600 kJ/kg, before

### 4.2 Enthalpy trend and field steam supply

One of the main objectives of field management is to ensure that adequate steam is supplied at the power plant at all times. Any outages attributed to the shortfall in steam has political, social and financial implications, especially in the island grids in the Visayas supplied by Tongonan and Palinpinon. It is, thus, important that spare capacities exist to meet the peak demand of the grid as determined from the load forecast of the power firm. A reliable steam forecast based on the results of the regular bore output monitoring is prepared which becomes the basis for programming any work-over or additional drilling to augment steam supply.

The experience, to date, is that there has been some decline in the wells' output in Tongonan and Palinpinon with respect to the total mass directly associated with reservoir boiling and chemical and mechanical problems. However, the corresponding increase in enthalpy in the wells' discharges have not significantly diminished the total steam available to the system compared to baseline, even though the total mass extraction is comparable to the full load requirement of the two plants.

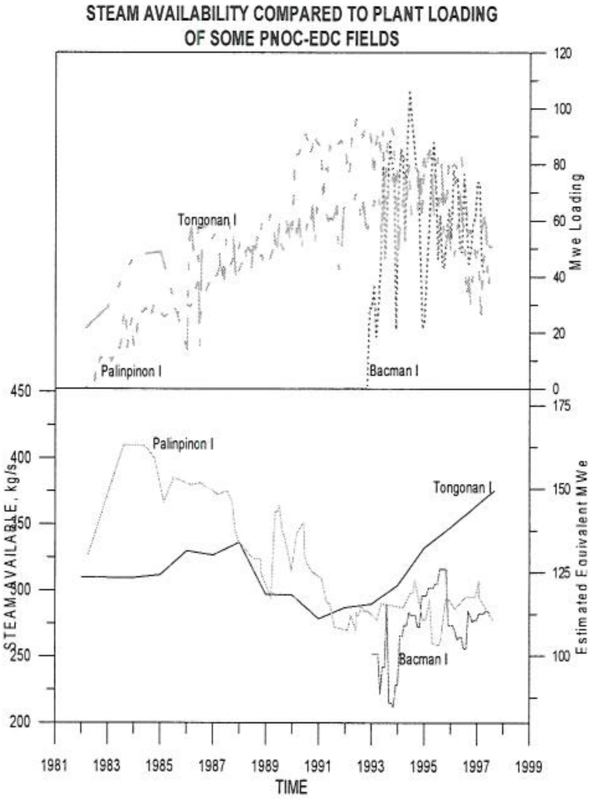

Figure 4: Steam availability vs. actual plant loading and equivalent load normalized at steam rate of 2.5 kg/s-MWe

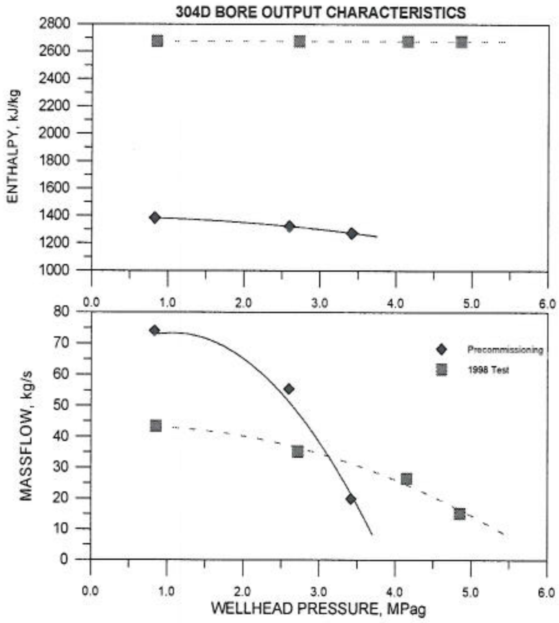

Figure 5: Bore output comparison for pre-commissioning and current data

the full commissioning of the plants, has been measured without any associated decline in wellhead pressure (Figure 5). Hence, the total output available at the wellhead in both sectors is exceeded by 60 MWe.

### 4.3 Reservoir pressure

Figures 6 to 8 depict the pressure changes from the selected wells in the various fields. Well Pal-7D demonstrates a particular well response close to the main production sector of the 110 MWe power plant. This response is characteristic of a gradual decline which approaches steady-state after 5 years of exploitation. It is believed that no re-injection well is yet communicating in this sector and that the flattening of the pressure data in the latter period is due to natural recharge which is estimated from the single tank model to be in the range of 230-840 kg/s-MPa. This recharge coefficient is considered to be very large but is consistent with the minimal pressure decline throughout the field as seen in Figure 7. This observation also coincides with the interpretation that there must be a huge flow from the Palayan Bayan sector to support the geothermal outflow to the Manito lowlands.

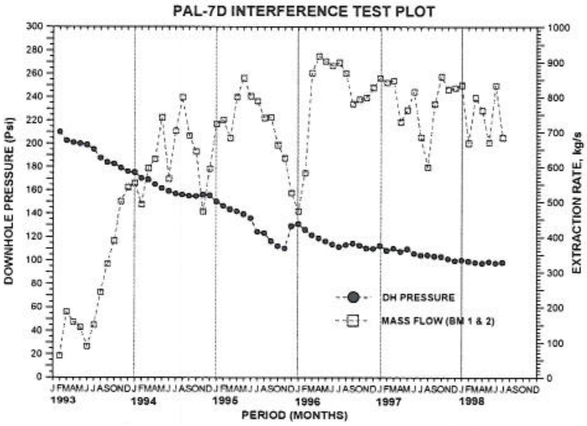

Figure 6: Bacman I well Pal-7D pressure trend with time

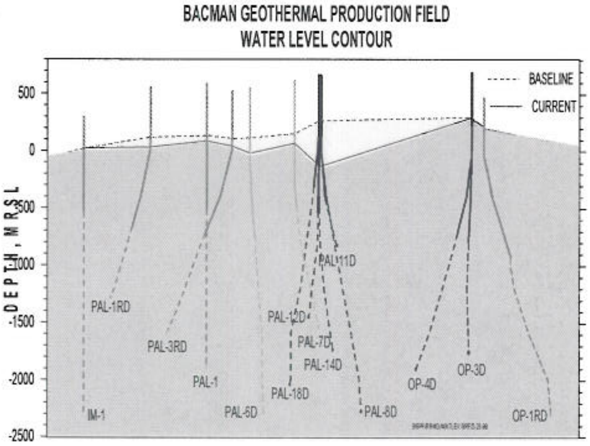

Figure 7: Change in Bacman well water level with time

On the other hand, well OK12RD in Palinpinon demonstrates the impact of shifting away the re-injection fluids from the main production sector in the middle of 1989 to arrest the negative effects or the declining output of the production

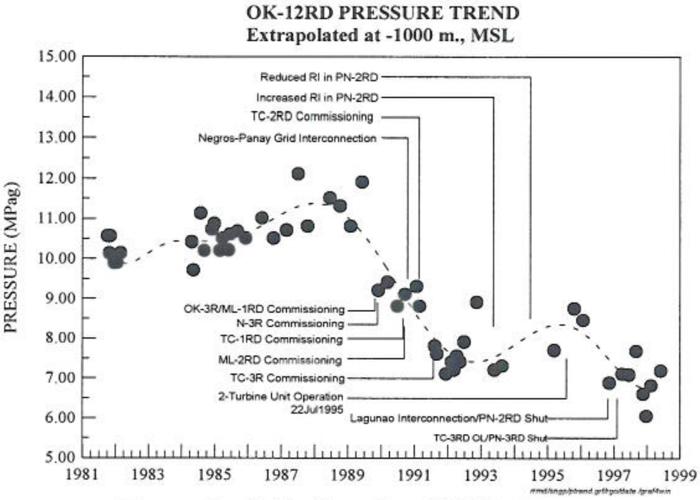

Figure 8: Palinpinon I well OK-12RD pressure trend with time

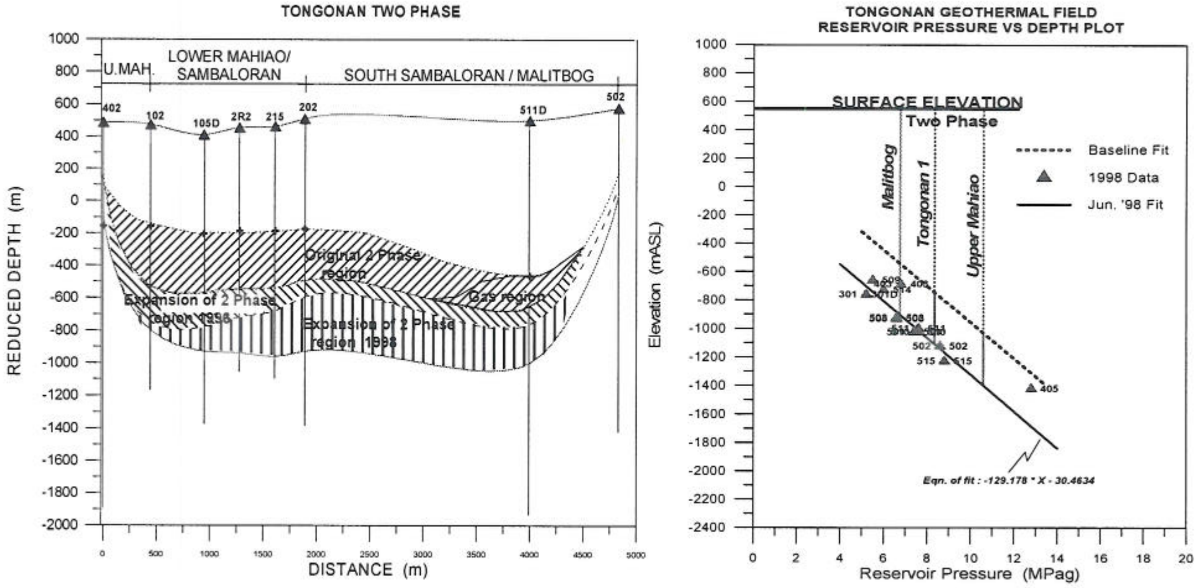

Figure 9: Expansion of two-phase region with time across the Tongonan field, a) with depth, and b) with pressure

wells. Further pressure drop was observed when a load of 80 MWe was added to Palinpinon's 112.5 MWe power plant in 1993. However, a steady state condition was also attained indicating continuing returns of re-injection fluids. The same plot also shows an increasing pressure in the re-injection sector of Palinpinon from 1983 to 1989 prior to the shifting of the reinjection block.

## 4.4 Reservoir temperature

Most of the temperature changes observed during exploitation in the Philippine geothermal fields are associated with cooling due to boiling in the reservoir and the negative effects of reinjection fluids returning to the production sector (Sarmiento et al., 1993; Amistoso et al., 1993). Cross-flows and down-flows of relatively cooler fluids have been prevalent in the Palinpinon field, rendering some wells non-commercial after 6 months of production. This condition has become irreversible despite adjustments in the re-injection strategy to some wells i.e., OK-7D and PN-26D in the central part of Puhagan sector. There appears to be evidence showing some cooling in the Mahanagdong wells as a result of the influx of cold water from the overlying cold aquifer modelled by Clothworthy (1997). In the Mt. Apo geothermal field, evidence of reinjection fluids returning to the production sector has recently been confirmed causing a decline in well output at SK-2D.

Within a year of commissioning additional plants in Tongonan, fluids have attained a saturated condition in large portions of the reservoir. Recent downhole logs in the Lower and Upper Mahiao sectors show that the expansion of the two phase fluids has become more pronounced as shown in the lowering of the vapor and brine interface (Figures 9a amd 9b). This has led to a reduction in the mass extraction in the field and consequently a significantly lower brine for re-injection. Maximum discharge pressure however, has not declined and in fact has increased reflecting the relatively high-pressure potential of the reservoir.

## 4.5 Mass and energy balance

Daily mass and heat extractions are computed as part of the overall field monitoring and accounting of the resource. From these data , the *overall field steam utilization efficiency* (i.e. ratio of theoretical steam rate per MWe and actual steam rate per MWe) is determined and used in guarding against excessive use of steam in operating the power plant, i.e. exceedingly high *blow-off* to the atmosphere. It also indicates the percentage of the mass and heat extracted from the resource at any given period which can account for the total energy balance in the remaining plant life based on the original stored heat calculation. It is a first approximation that can assist in determining future actions required to sustain production.

The total recoverable heat and mass used in standard reserve estimation is assumed to be about 10- 20 percent of the total mass, assuming some porosity distribution in the reservoir (Nathenson, 1975). After 15 years of exploitation, approximately 160% and 141% of the total *mass-in-place* from Tongonan and Palinpinon have been extracted. It shows and confirms that reinjection returns and fluids outside the delineated boundaries of the original resource are replenishing the two reservoirs in order to sustain production to be sustained. In Bacman and Mt. Apo, 25% and 30 % of the estimated recoverable *mass-in-place* have been produced after 5 years and 3 years, respectively, implying that the two reservoirs would run out of brine before full plant lives are attained. Hence, natural recharge or re-injection fluids would also be critical in sustaining production from these two fields. It is also likely that there will be drilling in the deeper portion of the Tongonan resource below the Lower and Upper Mahiao sectors to check whether this untapped portion of the reservoir can still deliver steam in the future.

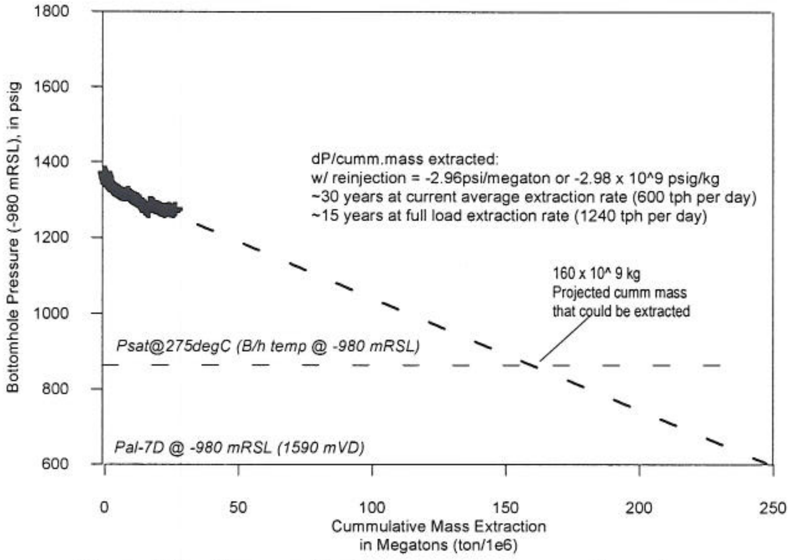

Figure 10: Bacman decline curve, pressure draw down vs. extraction

Figure 10 shows a plot of pressure vs. the cumulative mass extraction. This graph reflects the total brine that can be extracted from the reservoir before it turns two-phase and reaches an assumed abandonment pressure. It would, thus, be possible to determine the total amount of brine that could be useful for estimating the extractable brine for a second flash plant or binary plant requirement. An exception to this prediction is when recharge or reinjection return sets in before the fluid turns two-phase as the pressure would stabilize as shown in the latter part of the data points. Again, the projected total brine can be matched with the recoverable *in-situ* fluid originally estimated from the resource. It could then be used to check if there is an overestimation of the reservoir properties or whether additional influx of fluids is leaking into the system. In this particular case in Bacman, the preliminary data suggests that the field can sustain full plant capacity for the next 30 years if reinjection fluids are co-produced with the parent fluids; otherwise, the field's life might last 15 years.

## 5. STEAM SUPPLY MAINTENANCE

Some of the problems associated in the maintenance of the steam supply to the power plant, other than the natural output decline due to drawdown, are more or less associated with mineral deposition, casing failures, influx of cold water and, in some cases, reduction in the pH of the fluids below acceptable level.

### 5.1 Scaling

Calcite and anhydrite deposition in producing wells have been encountered in Palinpinon and Bacman wells but in minor proportions compared to the overall capacity of the field. Their rate of deposition is slow and usually takes years before the wells become non-commercial. Therefore, no chemical treatment is needed for prevention. In the Mt. Apo geothermal field, calcite deposition has been found to be the main cause of production decline in three wells (APO-1D, SP-4D and APO-3D) after about 3-6 months. This necessitates installation of a calcite inhibition system at APO-1D to arrest its output decline. There are also indications that some wells (MG-19D, MG-23D and MG-18D) in the Mahangdong sector of the Tongonan field are exhibiting calcite scaling, as shown by the rapid decline in the wells' output without significant change in enthalpy. Obstructions in the wells have been tagged as well with calcite minerals scraped in the casings. It is believed that the influx of cold water and the mixing of calcium rich fluids in the Mahanagdong sector cause this deposition of calcite in the flash-point in the wellbore.

## 5.2 Silica scaling and acidizing

Silica deposition has not posed any risks yet in the operations of any field in the Philippines. Major silica scaling as only experienced in the re-injection wells where *spent-brines* are re-injected at slightly supersaturated conditions at a silica saturation index range of 1.0-1.2. Acidizing jobs were thus programmed on re-injection wells that suffered significant decline in their injection capacities.

The majority of the acidizing treatment were done to treat wells found to be damaged by mud during well drilling. It is programmed after a well has been tested and found to be producing below the expected production level. Malate et al. (1997) and Buning et al. (1995) discussed in detail the acidizing jobs in the Philippines and the techniques used in selecting candidate wells for acidizing.

## 5.3 Maintenance and replacement (M & R) wells

Additional well drilling in Tongonan and Palinpinon has been done as a last resort in conjunction with changes in the production and reinjection strategy to *a*) minimize reinjection returns to the production sector and *b*) tap wells producing highly two-phase fluids and minimize the volume of brines for re-injection

In the Cawayan sector of the Bacman field, additional wells were drilled to provide spare capacities to take care of any shortfall in case one of the wells with acid feeds is cut-out from the system due to casing collapse and output decline. Additional wells were also drilled in the Palayang Bayan to dilute the existing wells with relatively low gassy fluids to meet the required gas interface at the power plant.

Early indications after the commissioning of the bulk of power plants from the Upper Mahiao and Malitbog sectors contradict what had been predicted with respect to the M&R well requirements which should have been about 4-6 wells by now. After a year of discharge to the power plants, there has been no sign of output decline from the wells and, in fact, the contrary is being observed. As mentioned above there is about 60 MWe in excess of the total capacity at the wellhead. Some adjustments may have to be made with respect to the model used in the simulation but the earlier indications is that additional wells may not be required in the next 3-5 years assuming the current trends in the discharge continue. Figure 11 shows the historical maintenance and replacement well drilling in both fields.

## 5.4 Work-over drilling and casing perforation

Figure 11 also shows the work-over history schedule of the wells in the fields. These work-over jobs were usually done using a rig by mechanical clearing of blockages and obstructions, relining the wells with smaller diameter casings and/or strengthening the cement behind the casing through perforation and squeezed cementing.

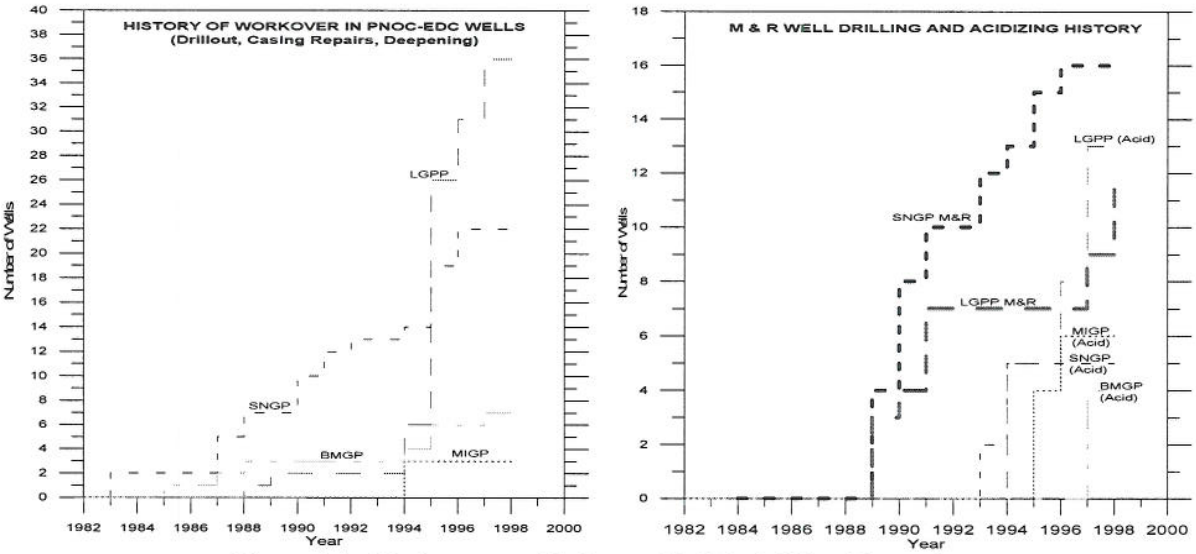

Figure 11: Work-over, acidizing and M&R drilling history in Palinpinon, Tongonan, Bacman and Mindanao fields

Buning et al. (1997) presented the results of some casing perforation jobs in the Mt. Apo geothermal field to boost production from the shallow cased-off portions of the reservoir. As much as 400% increase in production has been attained by this method and is usually considered when conditions warrant in lieu of a M&R well.

### 5.5 Pipe networking

For long term sustainability and flexibility in supplying the power plants in Tongonan, it is likely that a pipe network that connects all the sectors in the Tongonan geothermal filed will be constructed. This would allow utilization of the *buffe*r production sectors in the field to supply steam in any sector that might experience a shortfall.

In Mt. Apo, the fluid collection and disposal system for Mindanao I and II provides for interconnection that would allow steam supply from one sector to the other in case of any problem in one. With the design, provision for spare capacities and blow-off steam is reduced.

## 6. CONCLUSIONS

The recent upsurge in the geothermal program in the Philippines has marked a new milestone in the industry's geothermal development with an additional aggregate installed capacity of about 650 MWe. These additional capacities require monitoring reservoir performance and adjusting field management strategies to minimize operational costs and maintain steam supply to the power plant.

Most of the changes observed in the field are found to be consistent with a depleting reservoir characterized by reservoir cooling due to boiling and expansion of two-phase fluids and falling water levels, incursion of cold fluids and deposition in the well-bore. The addition of 600 MWe capacity in Tongonan has caused the upper two-phase section throughout the field to dominate the discharge resulting in significant increase in enthalpy (range 2300-2600 kJ/kg).

## ACKNOWLEDGEMENTS

I wish to thank the United Nations University and the Government of Iceland through Orkustofnun for providing the excellent opportunity to come back and celebrate the 20th anniversary foundation of the UNU Geothermal Training Programme in Iceland. I am especially grateful to Dr. Ingvar Birgir Fridleifsson for his unwavering support to the Filipino engineers and scientists. The Philippines have greatly benefited from the training and courses offered by the UNU and is now providing its expertise and services to other countries. I also thank PNOC-EDC for their permission to present and publish this paper.

## REFERENCES

Amistoso, A.E., Aquino, B.G., Sarmiento, Z.F., Jordan, O.T., Sta.Ana, F.X.M., Bodvarsson, G.S., and Doughty, C. 1993: Reservoir analysis of the Palinpinon geothermal field, Negros Oriental, Philippines. *Geothermics, 22-5/6,* 555-574.

Buning, B.C., Malate, R.C.M., Lacanilao, A.M., Sta.Ana, F.X.M. and Sarmiento, Z.F., 1995: Recent experiences in acid stimulation technology by PNOC-Energy Development Corporation, Philippines. *Proceedings of the World Geothermal Congress 1995, Florence, Italy, 3,* 1807-1812.

Buning, B.C., Malate, R.C.M., Austria, J.J.C., Noriega, M.T., and Sarmeinto, Z.F., 1997: Casing perforation and acid treatment of well SK-2D Mindanao I geothermal project, Philippines. *Proceedings of the $22^{nd}$ Workshop on Geothermal Reservoir Engineering, Stanford University, California,* 273-277.

Clotworthy, A.W., 1997: *Report on Mahanagdong 3-D tetrad simulation.* PNOC-EDC, internal memorandum, $2^{nd}$ June 1997.

Esberto, M.B., Nogara, J.B., Daza, M.V., and Sarmiento, Z.F., 1998: Initial response to exploitation of the Mt. Apo geothermal reservoir, Cotobato, Philippines. *Proceedings of the $23^{th}$ Workshop on Geothermal Reservoir Engineering, Stanford University, California,* 3-10.

Malate, R.C.M., Yglopaz, D.M., Austria, J.J.C., Lacanilao, A.M., and Sarmiento, Z.F., 1997: Acid stimulation of injection wells in the Leyte geothermal power project, Philippines. *Proceedings of the $22^{nd}$ Workshop on Geothermal Reservoir Engineering, Stanford University, California,* 267-272.

Nathenson, M., 1975: *Physical factors determining the fraction of stored heat recoverable from hydrothermal convection systems and conduction dominated areas.* USGS, Open file report 38.

Sarmiento Z.F., Aquino, B.G., Aunzo, Z.P., Rodis, N.O., and Saw, V.S., 1993: An assessment of the Tongonan geothermal reservoir, Philippines, at high-pressure operating conditions. *Geothermics, 22-5/6,* 451-466.