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# RESERVOIR MANAGEMENT IN MINDANAO GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

by

Rogel G. Trazona, Benson Ma. G. Sambrano and Miguel B. Esberto

PNOC Energy Development Corporation
PNPC Complex, Merritt Road, Fort Bonifacio
Makati City, 1201, Philippines
email: trazona@energy.com.ph

## ABSTRACT

The Mindanao Geothermal Production Field (MGPF) is on its fifth year of commercial operation this March 2002. Steam supply is sustained by production in M1 power plant (M1GP) and M2 power plant (M2GP) despite effects of injection returns and calcite deposition. The Total mass extracted is 7.5E10 kgs, with steam delivered to M1GP at 1.3E10 kgs, and 6E9 kgs to M2GP.

Injection returns from Matingao were detected on 1998 affecting the Marbel wells. At the onset of M2GP production at Sandawa in 1999, massflows have increased caused by hot recharge. Present temperature and geochemical trends imply recovery from injected fluids in Marbel and deep hot recharge from Sandawa.

Drilling of an injection well targeted at Sudsuwayan, north of Kullay injection sink will provide operational flexibility, mitigating thermal decay caused by massfront at the northwest of Marbel production wells. On the other hand, the recharge at Sandawa resulted to excess brine disposal due to limited acceptance of the sole injection well KN-1RD. This will necessitate drilling of an injection well.

## INTRODUCTION

The Mindanao Geothermal Production Field (MGPF) is located in northwestern flank of Mt. Apo, situated in Central Mindanao, Philippines (Fig. 1). The initial geothermal resource only covered 8.2 $km^2$ for reserved estimation based on the area accessible for drilling. There are already 30 wells drilled, 23 production wells and 7 injection wells. The first 1x 52 MWe power plant was commissioned on 1997, and the second in 1999.

There are three principal features in MGPF namely, the Sandawa Collapse, Marbel Corridor and Matingao Block. Ten production wells and four injection wells are linked in the first 1 x 52 MWe Fluid Collection and Disposal System (FCDS), and nine production wells and one infield injection well for the second FCDS. One cold injection well contains all cold wastewater from the FCDS and power plants. An interconnection between the two FCDS's interfaces allows the steam to be transported, vis-à-vis, for operational flexibility.

This paper presents the operational strategies employed corresponding to the reservoir processes observed during the commercial exploitation of the field since 1997. The overall steamfield performance during the 5 year production is discussed, and reservoir management strategy for future works is established.

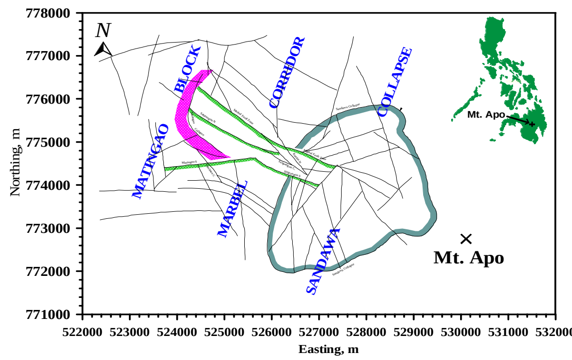


*Figure 1. Map of MGPF*

## INITIAL STATE OF THE RESERVOIR

MGPF has two production fields known as Mindanao 1 Geothermal Production Field (M1GPF) and Mindanao 2 Geothermal Production Field (M2GPF). The fields share a homogeneous resource referred as the Mt. Apo geothermal reservoir (Fig. 2). The productive sector which covers more than 8 $km^2$, is a liquid-dominated, fracture-controlled, hydrothermal system. The parent fluid that upflows within the Sandawa Collapse is closely represented by the discharge fluid of the deepest well KN-3B drilled some 1600m below sea level. The fluid has a temperature in excess of 300°C characterized by 6,000 ppm Cl content, and 80 mmols/100 mols $CO_2$. Further neutralization is achieved as the fluid laterally flows and boils through the numerous NW-SE faults outflowing towards Marbel and Kullay

The Sandawa wells have multi-feed zones and discharge highly two-phase fluids to steam. Discharge enthalpies (Hd) of these wells range from 1320-2700 kJ/kg. Nearly all of the discharge enthalpy of Marbel wells range from 1030-1200 kJ/kg, only one well is noted to be steam-dominated at this part of the reservoir, namely, SK-1D. The wells at Mandarangan sector indicate two-phase discharges with an enthalpy range of 1300-2030 kJ/kg.

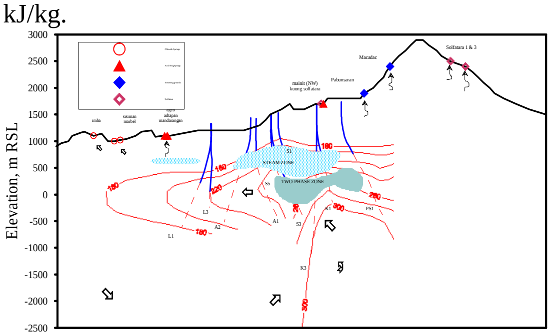


*Fig. 2 Hydrothermal of MGPF*

## FIELD UTILIZATION SCHEME

The first conventional 1 x 52 MWe power plant (M1GP) was commissioned in March 1997, and the second conventional dual-flash 1 x 52 MWe power plant (M2GP) on June 1999.

Ten production wells from Marbel are hooked in the FCDS of M1GPF, four hot injection wells and one cold injection well KL-2RD. The latter accepts waste water from surface discharges including the condensates from the power plants. The initial flashed confluent brine of M1GPF at 0.72 MPaa yields 0.8 silica saturation index (SSI). The first flashed brine is mixed with the separated water from MD-1D and APO-2D, and cascaded at a rate of 250 kg/s at 142°C. This second flashed brine then is mixed with the by-passed brine, finally yielding an SSI of ~1.0, and injected to the hot injection wells. The non-condensable gases (NCG) of the steam is <1.0% by weight. The second flashed steam from M1GPF at 4 MWe is supplied to M2GP.

Seven wells from Sandawa and the two wells, APO-2D and MD-1D supply steam to M2GP. As Sandawa fluids are highly two-phase, separated brine is injected infield in well KN-1RD. Excess brine is temporarily contained in sumps which is then injected to KL-2RD injection well in Kullay.

Current scheme being employed in M1GPF is to put on-line production wells with large massflow and with low to medium discharge enthalpies, in order to steadily supply the brine requirement of the dual-flash M2GP power plant. The nine production wells adequately supply the net capacity of 48 MWe to M1GP. However, due to calciting in the wellbore of some Marbel wells, calcite inhibition system (CIS) is installed in APO-1D. In M2GPF, wells with excess enthalpy are prioritized to minimize the total separated water injected in KN-1RD. Only eight production wells and second-flashed steam supply the 48.25 MWe net requirement of M2GP. Due to the considerable liquid contribution, wells TM1D and TM-2D are intermittently put on-line.

## MASS EXTRACTION AND INJECTION

Table 1.0 presents the mass extraction and injection in M1GPF and M2GPF, as of September 2001. The portions of mass extracted are expressed as gross and net extraction based on the initial resource assessment on 1994. The calculated gross extraction is 11.0 % by weight, and assumes no injection and recharge. The net extraction is 3.8% by weight and assumes injection return. This indicates that, at the present extraction rate of the field, the mass resource could still sustain its economic life beyond 25 years.

*Table 1. Mass Extraction in MGPF*

| | M1GPF (Kg) | M2GPF (Kg) | Total |
|---|---|---|---|
| Mass Extracted | 5.9E10 | 1.5E10 | 7.5E10 |
| Mass Injected | 4.3E10 | 5.4E9 | 4.9E10 |
| %Gross | 8.7 | 2.3 | 11.0 |
| %Net | 2.3 | 1.5 | 3.8 |

## STEAM AVAILABILITY

The steamflow trend in M1GPF is primarily affected by wells experiencing calcite deposition in the bore (Fig. 3). There is only a minimal steamflow loss in wells that underwent work-overs. Steam availability has been steady at 55 MWe since the installation of the CIS in APO-1D in June 2000.

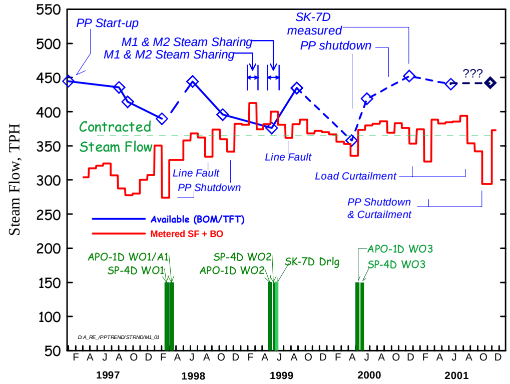


*Fig. 3 Steamflow trend of M1GPF*

An increasing steamflow trend is indicated in M2GPF due to the increases in the massflows of Sandawa wells, despite output decline in MD-1D (Fig. 4).

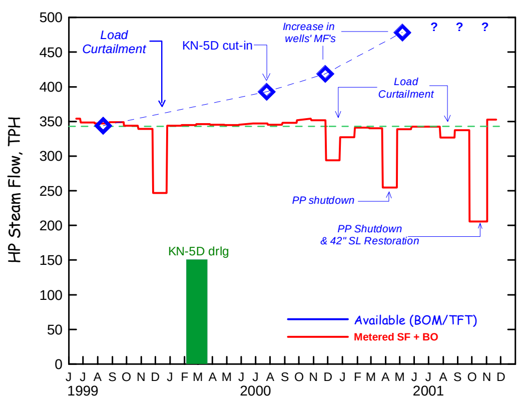


*Fig. 4. Steamflow trend of M1GPF*

The steamflow trend of the fields is adequate to supply the net power requirement of M1GP, and M2GP (Table 2). With the total output of the production wells, three wells could still be put off-line to sustain steam supply in both power plants. The interconnection between M1GP and M2GP FCDS allows transport of steam at about 20 kg/s (9-10 MWe).

*Table 2. Steam availability of MGPF*

| | Required | Available |
|---|---|---|
| M1 HP Steam | 52 MWe (385TPH) | 55 MWe (403 TPH) |
| M2 HP Steam | 48.25 MWe (343 TPH) | 67 MWe (470 TPH) |
| LP Steam | 4 MWe (52 TPH) | 4 MWe (52 TPH) |
| **Total** | **104.25 MWe (780 TPH)** | **126 MWe (925 TPH)** |

## INJECTION LOADS

Four hot injection wells are utilized in M1GPF to contain a rate of 320 kg/s of separated brine. About 65% by weight is injected in MT-1RD and MT-2RD, and 35% by weight in KL-1RD and KL-3RD.

The acceptance of the sole infield injection well KN-1RD in M2GPF varied with time. Initially, the well accepted fluid at a rate of 65 kg/s, and lately its capacity reduced to 5 kg/s (Fig. 5). This decrease in capacity was experienced after the FCDS was fully cut-out from the system during the power plant shutdown in M2GP in October 2001. The probable causes of its decline in capacity are still under investigation. Table 3 summarizes the injection loads in MGPF.

*Table 3. Injection loads in MGPF.*

| Well | WHP (kscg) | Waterflow (kg/s) |
|---|---|---|
| KL-1RD | 6.9 | 60 |
| KL-3RD | 7.3 | 57 |
| MT-1RD | 3.3 | 107 |
| MT-2RD | 3.4 | 95 |
| KL-2RD | Vac | 60 |
| KN-1RD | 4.5-8.5 | 5-65 |

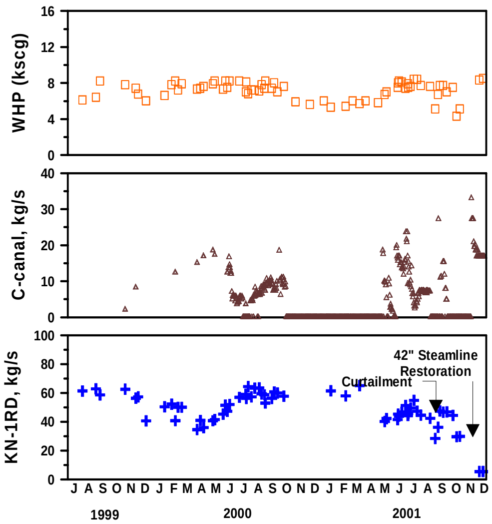


*Figure 5. KN-1RD WHP and injection load, and dumping in site C1*

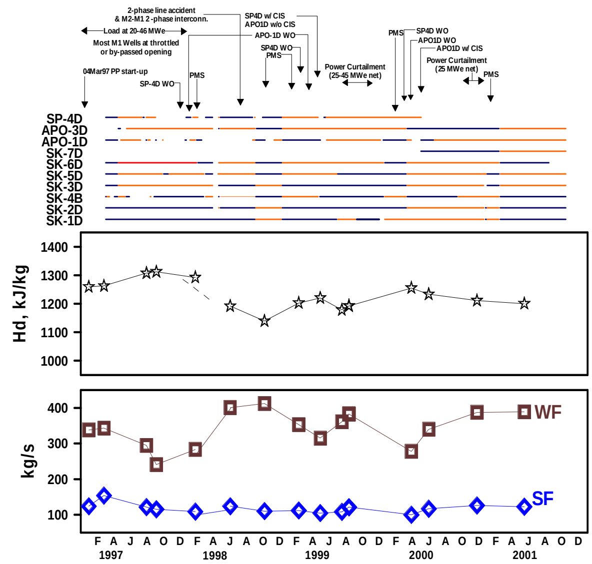


*Figure 6. M1GPF field trends*

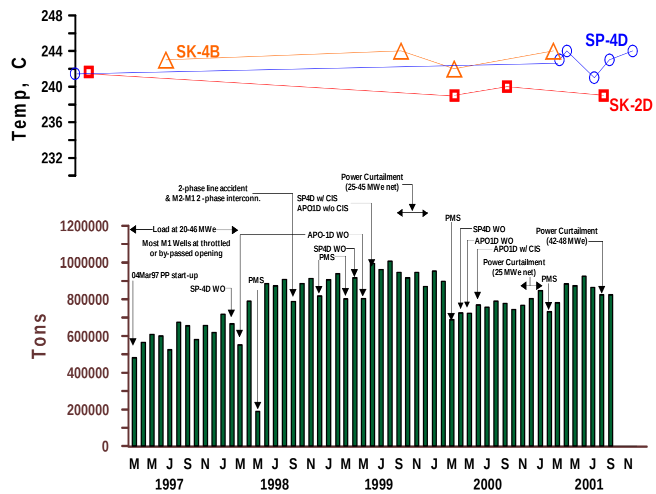


*Figure 7. Temperature trends of SK-2D, SK-4B and SP-4D*

## RESERVOIR RESPONSE

Operation requires the production of 1560 TPH (tons/hr) in M1GPF and 600 TPH in M2GPF to supply steam to 2 x 52 MWe power plants. These scales still enable three production wells to be put in shut condition as reserves. About 1150 TPH of hot brine and 180 TPH of cold condensate are injected in M1GPF, and about 18-215 TPH of hot brine in M2GPF.

The initial field enthalpy of M1GPF ranged from 1250-1300 kJ/kg. Then at the onset of injection returns in 1998 resulting from the increase in mass extraction, a corresponding decline in field enthalpy to 1150-1200 kJ/kg ensued during this period as shown in Figure 6. Thermal breakthrough in SK-2D was likewise observed when a survey was conducted on a similar period. However, thermal recovery is noted by 2000 (Fig. 7). The field enthalpy at this period stabilized at 1150-1200 kJ/kg. This is attributed to constant rates of mass extraction and injection between M1GPF and M2GPF. Moreover, a stable steam field supply was sustained when an anti-scalant injection system was installed in APO-1D.

Resembled by the field geochemical indicators were the increase in Cl in the brine and decrease in the ratio of Cl to Ca. The latter invariably changed when mass and injection rates stabilized (Fig. 8). The increase in the salinity of the confluent brine, however, did not adversely affect the silica saturation index of the first flashed brine. It maintained below saturation level (Fig. 8). The changes in the individual discharge chemistry were noted in wells APO-1D, APO-3D, SP-4D, SK-2D and SK-4B. Relative to the initial chemistry of these wells, reservoir Cl and $CO_2$ have increased and decreased, respectively (Figs. 9 and 10).

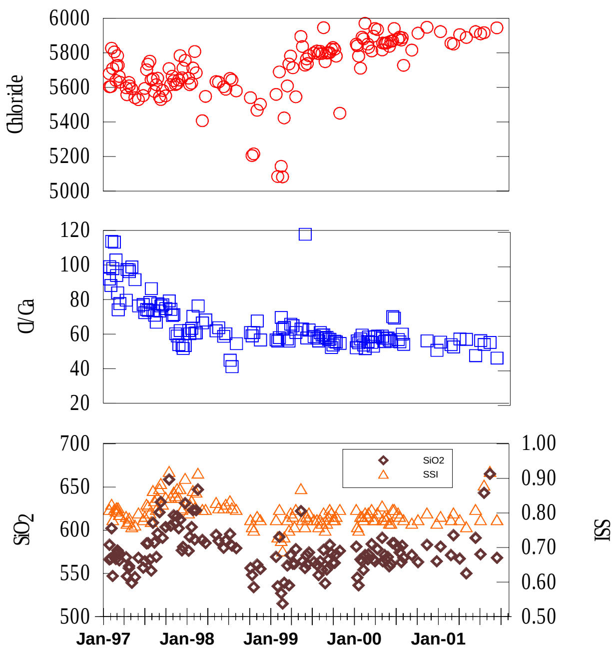


*Figure 8. Trends of Cl, Cl/Ca, $SiO_2$ and SSI in the brine of M1GPF*

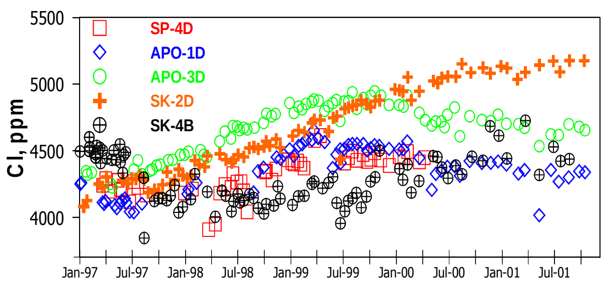


*Figure 9. Trends of $Cl_{res}$ of M1GPF wells affected by injection fluids*

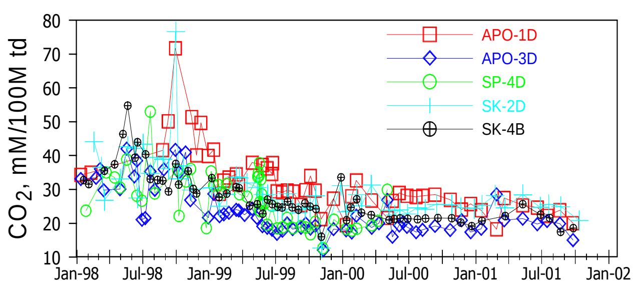


*Figure 10. $CO_2$ Trends of APO-1D, APO-3D, SP-4D and SK-4B*

The Tambaan Faults (West and Central) and Mook East C would be the possible conduits of the injection fluid return from MT-2RD via Mook faults going to well SK-2D. Reinjection fluids further NW of the field may channel from faults Kullay and Matingao Central (MT-1RD), Kullay A and Sisiman (KL-2RD), Sisiman, NNW Sisiman and Sisiman Sp B (KL-1RD), and Adtapan and Mandarangan S (KL-3RD), via Matingao Collapse, Sabpangon North and Marbel Fault zones.

There is an increasing massflows of Sandawa wells TM-1D, TM-2D, KN-2D and KN-3B. A proportional increase in waterflow and steaflow is depicted by these wells maintaining the field enthalpy at 1800-1900 kJ/kg (Fig. 11). The initial suspect pertaining to this change is the recharge of deep and hot upflowing fluids.

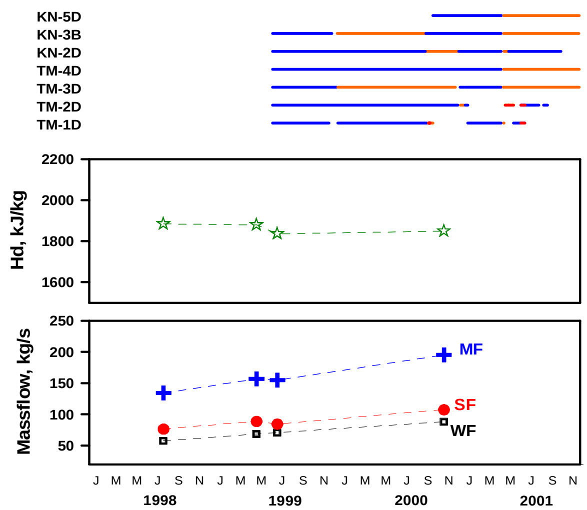


*Figure 11. M2GPG field trends*

## CHEMICAL SCALING

Figure 13 shows calculated calcite saturation indices at different boiling temperatures of the discharge fluids of Marbel. Even at reservoir temperature of 240-250°C, the fluid is already saturated with respect to calcite.

Calcite deposition was particularly active in wells SP-4D, APO-1D, APO-3D, SK-5D and MD-1D. Other wells, i.e. SK-2D and SK-4B, calcite deposits were not detected. SP-4D and APO-1D already underwent two mechanical work-overs, and CIS in the latter. These could be utilized within less than a year before they ceased to flow without inhibition. MD-1D underwent only one mechanical work-over and could be used for two years without chemical anti-scalant. APO-3D displays stable output (Fig. 12), however, calcite deposits were collected during the scraper survey on June 1998. SK-5D initially produced 53 kg/s of mass flow and then a steady output is observed for almost one-and-a-half year producing at 33 kg/s (Fig. 13).

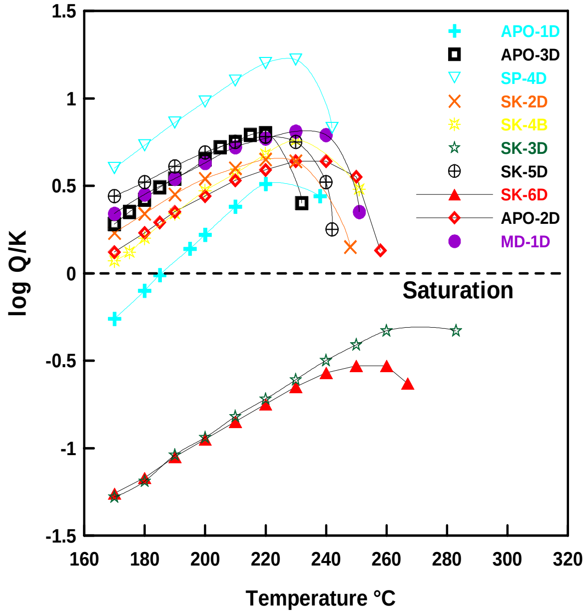


*Figure 12. Calcite saturation indices (CSI) of MGPF wells at multiple boiling steps*

The success of CIS is exemplified by APO-1D. As production started in M1GP, output decline was observed in from the well. This was attributed to calcite deposition in the well bore. Soon enough a calcite inhibition was installed in the well resulting to sustained production. Figure 14 compares the massflows when CIS was not installed in APO-1D.

Currently, the output is frequently monitored by tracking down the waterflow trend using NaBz tracer dilution method. So far, the trend shows a stable waterflow which would correlate to a steady output trend (Fig. 14).

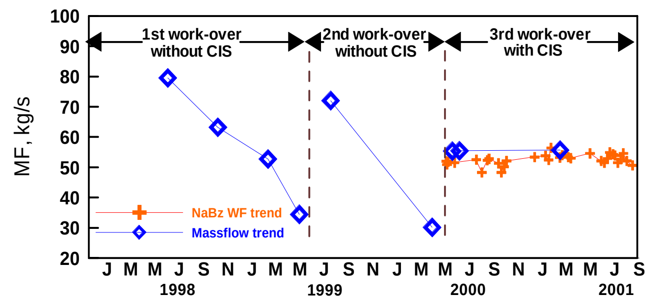


*Figure 14. Massflow trend of APO-1D with and without a calcite inhibition system. Waterflow trend by NaBz method shows a steady output*

The Silica Saturation Index (SSI) of M1GPF neutral-pH separated brine at its first flash is 0.8 at 165°C. When the second flash system became operational on 1999 in M2GPF, final SSI of confluent fluid at 142°C has been at the saturation level (Fig. 15). On the other hand, the SSI of separated brine of M2GPF at 170°C ranges from 1.4-1.5. Induction experiment proved that the silica induction time was about 180 minutes owing to the inhibiting property of the fluid due to its slightly acidic nature (pH 4-5). The induction time is also sufficient enough for the fluid to be heated since it requires 23 minutes when the brine is dispersed to the formation. Brineline inspection during power plant shutdowns in M1GP and M2GP showed thickness of silica deposit at less than one millimeter.

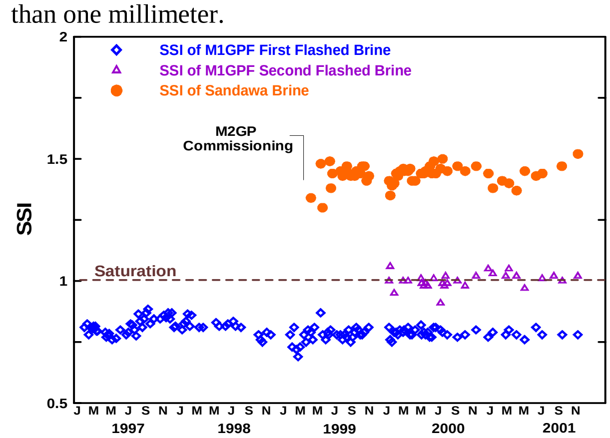


*Figure 15. SSI trends of MGPF brines*

## CONCLUSION AND RECOMMENDATION

The commercial operation of MGPF started with 1 x 52 MWe power plant (M1GP). Injection breakthrough was indicated in Marbel wells, which was detected on 1998. The initial field enthalpy in

M1GPF dropped from 1250-1300 kJ/kg to 1150-1200 kJ/kg, then stabilized with the current production and injection strategy. With the reservoir response in M1GPF, the steam availability was influenced by wells affected by calcite. However, a steady steam supply was sustained since June 2000 upon the installation of anti-scalant in APO-1D. The operation of the 1 x 52 MWe double flash power plant system in M2GP on 1999 required the additional extraction in Sandawa sector. Production wells in Sandawa showed increasing massflows as initial response, however, the field enthalpy remained stable at 1800-1900 kJ/kg. The steam availability increased with time despite MD-1D was affected by calcite deposition.

Although no further thermal breakdown was observed with the current field extraction in M1GPF production wells, it is suggested that portion of the separated brine be dispersed further to Sudsuwayan, north of Kullay. On the other hand, the reservoir process in M2GPF provided higher steam availability in the field, but injection requirement elevated and necessitated the drilling of an additional infield injection well.

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