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# THE PERPLEXING PROBLEM OF INJECTED FLUIDS AND GROUNDWATER INFLOW IN MAHANAGDONG GEOTHERMAL FIELD, LEYTE, PHILIPPINES

Edwin B. Herras and F. L. Siega

PNOC Energy Development Corporation, Merritt Road, Fort Bonifacio, Taguig City, Philippines

## ABSTRACT

*In about a year after the Mahanagdong Geothermal Field went into commercial operations in July 1997, the Mahanagdong reservoir was faced with problems such as calcite scaling and the natural inflow of groundwater coming from the northwest part of the field. The entry of groundwater as in the case of well MG-23D was marked by a decline in reservoir chloride concentration, silica (quartz) geothermometer and a corresponding increase in reservoir calcium concentration. Its output decline of 10 MWe, however, was recovered by cement plugging the identified cold-water conduit. Meanwhile, wells with calcite scaling problems were revived through mechanical clearing operations and the installation of a calcite inhibition system.*

*In the last quarter of 1999, wells MG-3D, MG-14D, MG-30D and MG-31D, located in the northeast part of the field, showed indications of the incursion of injection returns. The transfer of brine injection from well MG-21D, to an off-field reinjection pad, MN-2RD, in the north was implemented as a countermeasure to reduce the impact of injection returns in the production wells. The countermeasure implemented, however, proved to be more detrimental to production as inflow of groundwater as a consequence of pressure drawdown became the dominant reservoir process. The incursion of groundwater into the production sector has been a major contributory factor to the significant decline in the in-situ steam supply in Mahanagdong, which declined to its current level of 135 MWe from a high of 192 MWe in March 1998.*

*The reservoir management strategy to sustain steam production in Mahanagdong involved the shift of brine injection back to well MG-21D. Simulation runs conducted show that in-field hot brine injection could significantly reduce pressure drawdown in the center of the field consequently suppressing the entry of groundwater. Moreover, condensate injection was also moved to an off-field injection pad, southeast of the production field. The construction of a 14-kilometer steamline was also implemented to divert excess steam from Tongonan to Mahanagdong to sustain the 180 MWe production steam requirement. As a long-term strategy, the eastern sector beyond the current production block will be developed for additional steam production requirements.*

## 1.0 INTRODUCTION

The Mahanagdong geothermal field is located 8 km south of the Tongonan field. Its major upflow zone is located near MG-3D (Fig. 1) characterized by fluid temperature as high as 300°C and a reservoir chloride concentration of 4000 mg/kg. Reservoir permeability is provided largely by steeply dipping fractures related to the

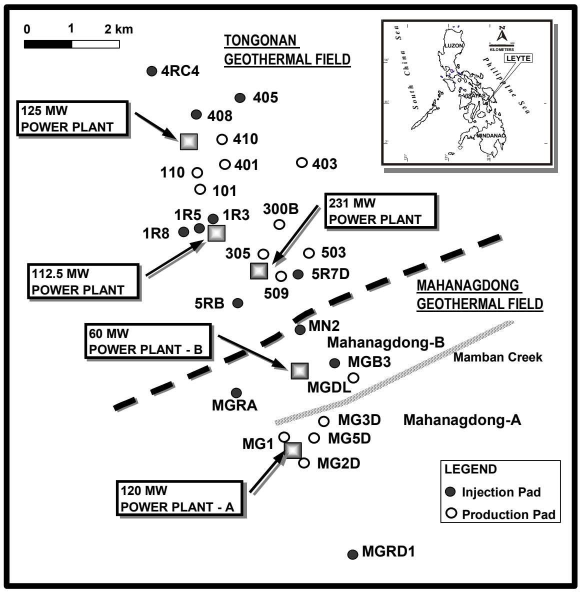

Figure 1. Map of the Greater Tongonan geothermal field.

left-lateral Philippine Fault, a major NW-trending transcurrent fault that cuts across Leyte Island. The deep reservoir fluid outflows to the south with temperature of 250°C as intersected by injection wells in MG-RD1 pad. Northwest of the field's hottest sector, an acid reservoir with temperature >290°C has been penetrated by wells MG-9D, MG-20D, and MG-21D. In the field's western margin, on the other hand, dilute and relatively cold fluids with temperature of 170°C were encountered by wells MG-4DA and MG-17D. The entry of cold fluids in these boreholes is marked by: 1) abrupt temperature reversals from 230 to 170°C, 2) presence of low-temperature Mg-rich alteration minerals, 3) presence of goethite and hematite veins, and 4) fluid inclusion homogenization temperature (Th) values of about 170°C. The natural downflow of cold fluids in these wells results to discharge fluid chemistry characterized by Cl reservoir content of 2,000 ppm, Although far from being typical groundwater, the dilute and cold fluids downflowing in MG-4DA and MG-17D has been dubbed the *"Paril groundwate*r**"**.

Potential problems prior to commercial operations were already predicted from the natural state of Mahanagdong geothermal system, which include (1) formation of calcite blockages in the southern wells; (2) inflow of cooler fluids from the west; (3) inflow of injected waste brine passing through the permeable structures; (4) inflow of acidic fluids from the north; and (5) persistence of high-gas fluids in the east.

The exploitation of the Mahanagdong reservoir was divided into two sectors: "MG-A" and "MG-B". A 120 MWe main plant and a 12 MWe topping cycle plant constitute MG-A. The main plant is supplied by steam from 14 production wells drilled in the central and southern parts of the steamfield; separated brine is injected into 5 wells in MG-RD1 pad to the southeast (Fig. 1). Well MG-4DA and MG-17D was utilized for power plant condensate injection which was later transferred in well MG-9D (August 1998) to preclude inflow to the production sector. MG-B production wells, drilled into the reservoir's high-temperature and high-gas region to the north, feed a 60 MWe main plant and a 6 MWe topping cycle plant. Injection is through pads north of the area, MN-1 and MG-B3 where MG-21D is located.

MG-A's commercial operation began in August 1997 with >270 kg/s of steam available at the wellheads, more than enough to supply the 120 MWe main plant. With time, however, steam availability continuously declined reaching an equivalent of 80 MWe by mid-1999. Although many factors were cited for the steam decline, geochemical monitoring suggested that cold-water influx into the production sectors was a significant contributory process.

## 2.0 MAJOR RESERVOIR PROBLEMS IN EARLY STAGE OF PRODUCTION

### 2.1 Inflow of Groundwater

Inflow of groundwater from the Paril area became more evident in the southwest quadrant of the Mahanagdong field. The effect of this reservoir process is more pronounced in well MG-23D, which exhibited a significant decline in output from 18 to 8 MWe. Fluid chemistry likewise indicated dilution in Cl from 2700 mg/kg to 2530 mg/kg with slight increases in Ca and $SO_4$ levels (Fig. 2). The quartz geothermometer ($TSiO_2$) also showed decline in temperature from 271°C to 255°C. These trends in fluid chemistry suggested the intrusion of a different type of fluid characterized by high SO4 and Ca level but low in Cl and TQtz, which dominated the discharge of MG-23D when its bottom permeable zone was isolated by calcite blockage. The well was cut-out due to the unscheduled shutdown of the

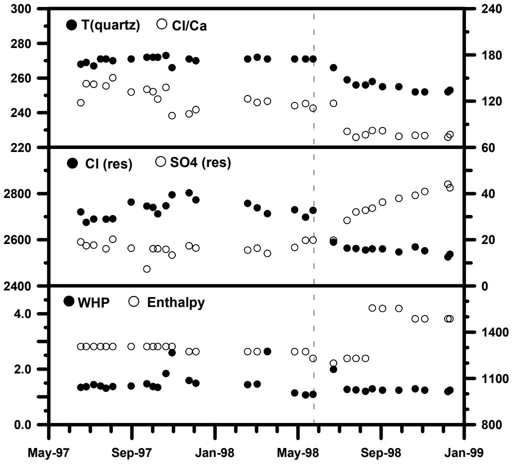

Figure 2. Geochemical trends of well MG-23D showing the predominance of cooler waters from the upper feed zone starting June 1998 as the hot bottom feed was isolated by calcite blockage.

FCDS in January 1999. Since then, the well did not sustain discharge due to the blockage and further thermal deterioration was observed just below the Production Casing Shoe (PCS). The downhole samples collected at the depth where cooling was observed revealed fluids having very low chloride with high calcium and sulfate content, which is similar to the steam-heated groundwaters of Paril hot springs. This suggests that the cold, diluting fluids originate either from the top of the reservoir or from the northwestern periphery of the field.

The isotopic data showed evidence of cooler water intrusion as indicated by depletion of $\delta^{18}O$ from -2.0 ‰ (18 June 1997) to -2.6 ‰ (27July 1998). The shift in the data point of MG23D (Fig. 3) showed that the chemistry of the well shifted towards the isotopic composition of MG17D type of fluids in the west. It ruled out the predominant ingress of plant condensate as the present data points shifted away from the isotopic signature of the plant condensates.

Well MG-23D underwent rig workover in June and August 1999. The first workover cleared out calcite scales at 1462-1552m and at 1100-1150m and 1552-1675m. The second workover involved squeeze cementing which sealed off the identified cooler fluid entry at 650m and 1300m. The well sustained discharge after its workover and its present chemistry suggests recovery from the inflow of cooler fluids and greater contribution from the bottom feed with its quartz geothermometer already at 265°C (November 1999).

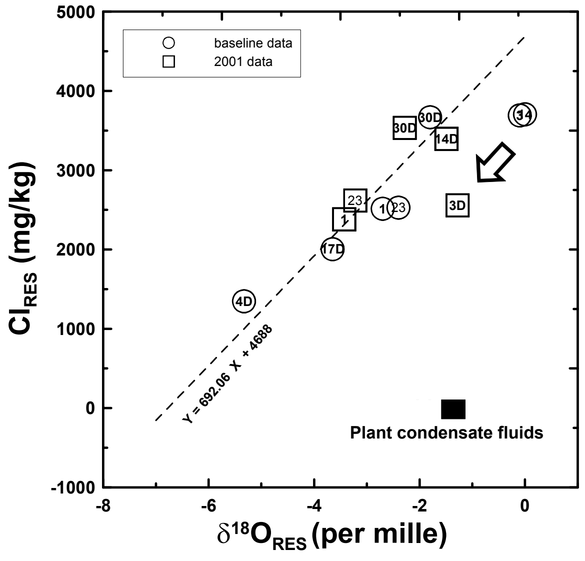

Figure 3. Cross plot of $\delta^{18}O$ vs. $Cl_{res}$ of selected Mahanagdong wells showing the shift of well MG-3D towards the isotopic composition of power plant condensates.

Other wells affected by the inflow of groundwaters are wells MG-1, MG-27D and MG-29D. Well MG-1 similarly exhibited a decline in its $TSiO_2$ and reservoir chloride in May to June 1999 while well MG-27D showed a marked drop of 7°C in December 1999 from its baseline values. Meanwhile well MG-29D also exhibited a 10°C drop in $TSiO_2$ and 700-mg/kg reduction in reservoir chloride from its baseline values in the first quarter of 2000 due to the effect of groundwater inflow.

Radioisotope ($^{125}I$) tracer tests conducted in well MG-4DA in October 1999 showed positive tracer returns in wells MG-27D, 29D, 28D, 26D, 31D and 30D (Delfin et al., 2001). The preferential flow of Paril groundwater towards the northeast supports the chemical trends exhibited by these affected wells. Previous sodium fluorescein tracer tests conducted in April 1999 also established a hydrological connection between MG-17D and well MG-23D and MG-25D through the Lower Mahanagdong fault.

### 2.2 Injection Returns

Inflow of injection returns in the production sector of MG-A and MG-B were observed in 1999, two years after the start of commercial production in Mahanagdong. The two major sources of injection returns are pad MG-RD1B injection wells, located southeast of the production area and pad MG-B3 injection wells located northwest of the production area (Fig. 1).

The MG-A wells affected by injection returns are MG-7D, MG-16D and MG-22D. High chloride, low gas fluids were noted in MG-7D, MG-16D and MG-22D. Injected brine in MG-7D has been manifested by the steep increase in field chloride from 3000 mg/kg in the first half of 1999 to 3200 mg/kg in year 2000. This was coupled by the decline in total discharge $CO_2$ from 200 to 130 millimoles/100 moles water.

MG-22D likewise showed the same trends based on the increase in chloride from 2800 to 3000 mg/kg while its total discharge $CO_2$ decreased from 120-130 to 90-120 millimoles/100 moles water. No significant thermal deterioration was observed in this well.

Its Quartz geothermometer remained relatively stable at 267 to 270°C.

The field chloride of MG-16D rose from 3000 mg/kg to 3200 mg/kg. Total discharge $CO_2$ declined from 110-120 to 80-100 millimoles/100 moles water during the same period. Among the three, this was the only well that showed thermal degradation from 273-277°C to 269-273°C based on quartz geothermometer.

Based on chemical and structural examination, it was postulated that the injected fluids is coming from the southern injection sink. The fluids are passing through a highly permeable northwest-trending structure that have intersected three injection wells (MG-5RD, MG-6RD and MG-9RD) in pad MG-RD1. The brine then traverses to interconnected fault, i.e. Mahanagdong fault, which is a common structure of the three wells exhibiting injection returns.

In Mahanagdong-B sector, signs of brine injection returns were noted in wells MG-26D, 28D, 30D and 31D. These wells showed an increase in field chloride and decline in total discharge $CO_2$. A decline in quartz geothermometer was observed in some of these wells. The general increase in field chloride concentration, as represented by deep wells MG-30D and MG-31D, is from 3600-3900 mg/kg to 4100-4500 mg/kg. Such increase in chloride level is the effect of the brine injected at the northern injection sink having a chloride content of about 4700 mg/kg.

The same fluids invading the Mahanagdong-B wells also affected the neighboring wells in Mahanagdong-A, namely MG-3D and MG-14D. Quartz geothermometer of MG-3D decreased from a stable level of 298°C in November 1999 to 280°C in August 2000. Total discharge $CO_2$ also declined from 360 to 250 millimoles/100 moles water. Its reservoir chloride, being initially high because of boiling process, declined from around 4700 mg/kg to a stable level of 4200 mg/kg. This final concentration is similar to that of MG-30D and MG-31D, which are also affected by injection returns. On the other hand, the discharge enthalpy of MG-14D declined from 2400 kJ/kg in October 1999 to 1440 kJ/kg in September 2000. Its resulting deep fluids have higher chloride and about 20°C cooler (based on quartz geothermometer) than its 3900 mg/kg Cl and 295°C baseline levels.

## 3.0 MEASURES TAKEN TO SUSTAIN PRODUCTION

### 3.1 Optimization of Injection Scheme

To arrest the inflow of injected brine, the brine load of about 100-120 kg/s from the nearby injection well, MG-21D was transferred to the off-field Mamban-1 injection wells in August-September 2000. Furthermore, the injection of 120-150 kg/s of brine from the thermal pond that was partly being disposed into well MG-9D since the start of 1999 was also transferred to MG-RD1B. MG-9D was instead utilized solely as injection well for the condensate (est. 30-90 kg/s) from Mahanagdong-A main power plant.

During the first quarter of 2001, MG-3D, MG-14D, 30D and 31D showed slight recoveries from the mixing of injected brine based on their stabilized chemical trends. Well MG-3D temporarily showed stabilized trends in its quartz geothermometer of 270°C from its previously declining trend. MG-30D and MG-31D also displayed recovery after its $Cl_{RES}$ levels dropped back to its original level of 3600 mg/kg. However, the recoveries were short-lived as the chemical trends continued to decline the succeeding months.

MG-3D's reservoir chloride continued to decline and stabilize at 2500 mg/kg in 2001 compared to its 4500 mg/kg level in 1999. Significant declines were also observed in its quartz geothermometer that dropped from a high of 290°C in 1999 down to 245°C (Oct 2001). Bore output data further show the decline in discharge enthalpy of MG-3D from 1500 kJ/kg in Mar-2001 to 1420 kJ/kg in June-2001and the significant increase in waterflow from 49 kg/s to 54 kg/s.

Well MG-14D showed the same effects as in well MG-3D as indicated by its continuing decline in chloride concentration from 4700 mg/kg in Oct-2000 to 3400 mg/kg in Oct-2001. However, its quartz geothermometer has remained stable at 275°C implying that the fluids are sufficiently reheated upon reaching the well. Bore output data also showed the continuous decline in enthalpy from 2400 kJ/kg (Oct 1999) to 1800 kJ/kg in June 2001 and its increase in waterflow.

MG-30D and MG-31D exhibited similar declining trends in its reservoir chloride, quartz geothermometer, gas in total discharge and enthalpy that suggest the continuous inflow of liquid recharge into the well. Isotopic data provide evidence of the inflow of cooler water on these wells based on the depletion of $\delta^{18}O$ by -0.14 to -1.5 ‰ (July 2001) compared to their baseline levels in 1992-1998. The cross plot of $\delta^{18}O$ versus $\delta^{2}H$ show the data points of well MG-3D, 14D, 30D and 31D shifting towards MG-4DA and MG-17D data points, which implies that these wells may be also affected by the type of waters downflowing in wells MG-4DA and MG-17D.

The cross plot of $\delta^{18}O$ vs. $Cl_{RES}$ (Fig. 4) likewise show a shift of well MG-3D's present data points towards the power plant condensate data point. The deviation suggests that the discharge fluids of MG-3D may consist of power plant condensate type of fluids with a mixture of reservoir fluids. This is possible since MG-3D lies nearest to the condensate injection well, MG-9D. However, the general shift of data points towards MG-4DA and MG-17D is an indication that dilute and isotopically depleted waters akin to the waters from the northwest sector are affecting wells MG-3D, MG-14D, MG-30D and MG-31D.

Reservoir modeling and simulation studies of Mahanagdong reservoir using Tetrad simulator (Saw, et.al., 2002) were conducted in April 2002 which successfully replicated the conceptual model and the hydrological flow trends of the Mahanagdong field. Results indicate that extensive drawdown in the MG-DL area from 1998 has drawn-in cold fluids from the MG-B3, MG-9D and the Paril area. This is supported by downhole surveys that indicated a decline of 5 MPa in the central part of the production field after four years of production. Different simulation scenarios were conducted to predict the hydrological flow patterns. The scenario where hot brine injection was done in pad MG-B3 (MG-21D) while condensate injection was done in pad MG-RD1B showed the best results. In this scenario, most of the wells were projected to have increase in steamflow and enthalpy values. It was maintained that the recharge of hot injection in MG-21D would stabilize the pressure at the MG-DL area and suppress the entry of cool fluids from the northwest towards the production area.

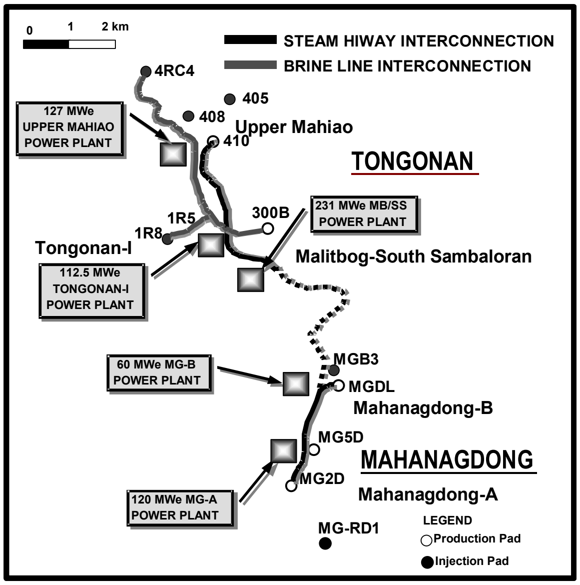

Figure 4. Map showing the trace of the Steamline Interconnection (SLI) connecting the FCDS of the Tongonan and Mahanagdong fields.

Following these recommendations, the injected brine was transferred from MN-1 pad back to MG-21D last June 2002 while the condensate being injected in well MG-9D was transferred to well MG-8RD (MG-RD1B pad) last July 2002.

At present, the affected wells showed recovery based initially on the increases in chloride levels. Wells MG-3D, MG-30D and MG-31D showed an increase in chloride from 3500 mg/kg to 3700-3800 mg/kg while MG-14D increased from 3700 mg/kg to 3900 mg/kg. Fluid temperatures of these wells from quartz geothermometer have begun to stabilize as well as their gas levels. The long-term effect of the injection strategy however still remains to be seen. The increases in the chloride levels of these wells could only mean either, *a)* renewed hot reservoir recharge from the wells bottom feed zone or *b)* recurring inflow of injected brine into the wells. Previous experience in the year 2000 has already shown inflow of injection returns in MG-DL wells while injecting in well MG-21D, MG-20D and MG-15D. In spite of the anticipated possible inflow of injected brine in the production sector, management has opted for this strategy because of its less damaging effects on the production wells, having higher temperatures than the Paril groundwaters. Furthermore, the inflow of brine into the production wells could be controlled to its optimum level by reducing the volume of disposed brine.

### 3.2 Steamline Interconnection

To augment the steam supply of the Mahanagdong production field, it was decided to tap the excess steam from Tongonan geothermal field, which lies about 2-3 km north of the Mahanagdong power plants. Excess steam from Tongonan was transported to the Mahanagdong sector through a 14-km long 36" main steam line called the Steamline Interconnection (SLI), which connected the existing Fluid Collection and Disposal System (FCDS) of both fields. In the latter part of year 2001, the SLI was commissioned and delivered 40 MW of steam to both Mahanagdong-A and B, thus maintaining the full load of 180 and 60 MW, respectively into the power plants. Presently, it has been the major solution to the decline in steam supply of Mahanagdong.

### 3.3 Development Expansion to the East

The long-term goal of sustaining the steam supply of the Mahanagdong reservoir involves the development of pad MG-F. Pad MG-F aims to tap the potential resource located further east of the present production block. The potential resource was delineated by magnetotellurics survey and well bore data indicated increasing temperatures and pressures towards the east. Production well drilling will commence in 2004 to probe the area and possibly delineate the eastern boundary of the Mahanagdong resource.

## 4.0 CONCLUSIONS

The exploitation of the Mahanagdong geothermal field since 1997 has incurred pressure decline in the central part of the reservoir. This has induced the inflow of cooler peripheral waters that has presently swamped the reservoir. Several solutions have been implemented to address the declining steam supply. A major solution to the persistent cool peripheral water inflow is through the eastern expansion of the Mahanagdong production block to reduce field pressure drawdown and minimize the inflow of groundwaters from the western sector.

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