# SUSTAINING AND OPTIMIZING STEAM PRODUCTION IN THE SOUTHERN NEGROS GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

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ABSTRACT

The Southern Negros Geothermal Production Field (SNGPF) in Central Philippines, has been supplying steam to the 3 x 37.5MW power plant in Palinpinon-1 and 4 x 20MW modular plants in Palinpinon 2 in the last 25 and 15 years, respectively. Field exploitation has induced field wide reservoir changes that constantly affected the capability to sustain steam supply to the power plants. Pressure drawdown and massive returns of injected separated brine are two major reservoir processes affecting steam production. Secondary processes, such as mineral deposition, cool and acidic fluid inflow also affected steam supply.

Extensive monitoring of the physical and chemical changes in reservoir fluid properties facilitated the careful understanding of reservoir response to exploitation. This also led to the timely formulation and implementation of reservoir management strategies that effectively addressed the various problems affecting steam supply. Foremost was the shifting of the bulk of injection load away from Puhagan to the Ticala and Malaunay areas in 1991. Drilling and priority utilization of high enthalpy wells were also implemented to increase steam supply and at the same time reduce brine load. Later, the strategy of deep injection to promote sufficient reheating of injected brine before reaching the production sector was pursued. Well intervention techniques such as mechanical workover and acid treatment also became very effective in restoring capacities of wells with mineral deposits (along the wellbore and in the formation) and thus, augment steam supply and injection capacity.

While reservoir management strategies were mainly aimed at addressing the effects of injected brine returns, these strategies have at the same time promoted boiling of the reservoir fluid at shallow levels and permitted the expansion of the two-phase zone. More recently, additional steam production from the two-phase zone was proven feasible after the successful restoration of two (2) non-productive wells and the conversion of some Puhagan injection wells into producers.

Additional steam production in SNGPF was also optimized after the Palinpinon reservoir has reached equilibrium to date as manifested by the relatively stable reservoir pressures recorded. An additional 20MW generating capacity was established by the optimization study in Palinpinon 2 that would induce a conservative reservoir pressure drawdown of about 1.0MPa. An economically targeted additional generation of 35MW in the area would produce a much higher reservoir pressure drawdown of around 1.7MPa that could hasten influx of injection returns to the production sector.

## 1.0 INTRODUCTION

The Southern Negros Geothermal Production Field (SNGPF) is situated in the interior municipality of Valencia in the southern tip of the peninsular arm of the Negros island in Central Philippines (Figure 1). The field is divided into two areas, namely, Palinpinon-1 and Palinpinon 2 production fields. The development of the Palinpinon 1 field began in 1981 after exploration drilling confirmed the existence of an exploitable geothermal resource. A 1.5MW pilot plant that was installed and operated in September 1980, proved the viability of a commercial geothermal production in the area. The power plant then supplied electricity to the city of Dumaguete, the capital of Negros Oriental. On May 1983, the Palinpinon reservoir started supplying steam to the 112.5MW Palinpinon 1 geothermal power plant operated by the National Power Corporation (NPC). Ten years later, the 80MW Palinpinon 2 geothermal modular plants were installed after establishing the Palinpinon resource can still support additional capacity. Four 20MW modular units (one each in Balasbalas and Nasuji areas, and two in Sogongon sector) were commissioned between December 1993 and January 1995. To this day, the field has a total installed geothermal capacity of 192.5MW.

After 25 years of continuous exploitation, the rated installed capacity of Palinpinon 1 power plant can no longer be attained due to the increased inefficiencies of the power plant coupled with the declining steam supply. The need therefore to optimize steam production has become crucial; more so as the demand for additional power has been seen to increase each passing year. It was also with this situation that the Nasulo power plant was proposed to be installed in Palinpinon 2 area and being pursued to be commissioned in 2012. The numerical simulation conducted by Amistoso, et al. (1988) initially proved that the resource could sustain an 80-MW plant in Palinpinon 2, however, the updated volumetric reserve estimation and lump parameter modelling conducted by Amistoso, et al. in 2002 showed that this sector could still support an additional 20MW power plant.

## 2.0 SOUTHERN NEGROS GEOTHERMAL FIELD CONCEPTUAL MODEL

The initial conceptual model of the field developed, was based on pre-exploitation pressure and temperature data, well discharge data, geochemical and geological data (Urbino et al, 1988). The reservoir model indicated that a cooling intrusive rock beneath a dormant Cuernos de Negros volcano heats-up fluids at depths to temperatures >320°C, and recharge the reservoir in two upflow areas. The major upflow is located south-southwest of Puhagan area while the minor one occurs in the Sogongon area. The reservoir was initially liquid-dominated with localized two-phase zones at the shallow levels. These were detected in exploratory wells drilled in the Puhagan, Ticala, and Nasuji-Sogongon areas. The existence of these two-phase zones was manifested by the excess enthalpies of the discharge fluids. Shallow production well OK-2 in central Puhagan, for instance, produced fluids with a maximum enthalpy of 1819 kJ/kg during discharge testing in 1978.

The present hydrological model of the Southern Negros geothermal system shown in Figure 2 indicates two outflow zones (Pamatian et al, 2003). One occurs towards the northeastern sector through a narrow conduit into the outflow area in the lower elevations of the Okoy Valley and the other towards the western sector to the Nasuji-Sogongon area through a much broader channel. Fluid flow in the system is mainly controlled by geologic structures such as faults, contact zones between lithologic units and sedimentary formations. However, major permeability is provided by faults mapped in the area, namely the NE trending Nasuwa, Ticala, Puhagan, and Odlumon Faults and the NW trending Nasuji and Sogongon Faults. These structural faults and their splays, while playing major role in the hydrological flow of the system, also provided good communication channels between the production and injection sectors.

## 3.0 FIELD EXPLOITATION AND RESERVOIR RESPONSE

Pressure drawdown and injection returns have been the two major processes dictating the reservoir condition with exploitation of the Palinpinon geothermal field. However, reservoir response in Palinpinon 1 varies with that in Palinpinon 2 with regards to these two processes. Field management interventions, i.e. well utilization and brine disposal strategies, well workovers and acid treatment, maintenance and replacement (M&R) drilling and expansion programs, among others designed to sustain steam supply and optimize operations have been observed to influence pressure drawdown and injection returns more than any other reservoir processes in shaping the prevailing reservoir conditions.

### 3.1 Pressure Drawdown

Pressure drawdown is a natural consequence to fluid extraction. Figure 3 depicted the average reservoir pressure trend in Palinpinon 1 showing the baseline pressure of around 12MPag reckoned at 1000 m below sea level, gradually declining during the early stages of commercial operation from 1983 to 1989. However, a sharp decline in reservoir pressure was observed from 1990 to 1992 after the bulk of brine injection was shifted away from the Puhagan production sector in 1989 and the full load operation of the power plant in 1991 with the interconnection of the Panay island power grid system. The full load operation induced as much as 3.0MPa reservoir pressure drawdown.

Mass withdrawn had reached about 730 kg/s with 440 kg/s injected back to the reservoir. Lower mass extraction during the prolonged 2-unit operations of the power plant in 1997 to 1999 and in 2003 to 2004 due to PMS of turbine units allowed the reservoir pressure to recover briefly from 5.5MPag to 6.0MPag, and from 5.0MPag to 5.5MPag, respectively inducing marginal (low WHP) production wells, e.g. PN33, PN29D and PN13D to contribute back to the Fluid Collection and Recycling System (FCRS). Stable reservoir pressure was attained since 1996 and has been maintained up to the present with the implementation of appropriate field management strategies. The current reservoir pressure averaged about 5.0MPag.

The effect of pressure drawdown and boiling in the wells is manifested by increases in discharge enthalpy coupled with a decline in mass flow. In many cases, these changes resulted to net increase in steam flows (Table 1). However, output in some affected wells declined, e.g. PN13D and PN25D.

Even before the commissioning of the 80-MW Palinpinon 2 modular plants, the average reservoir pressure in this sector declined from a baseline value of around 9.0MPag starting in 1990 and began to level off in 2000 to approximately 6.0MPag gradually moving towards the current Palinpinon 1 reservoir pressure (Figure 3). The pressure decline occurred at the same time the reservoir pressure in Palinpinon-1 started to drop in 1990, confirming that both sectors share the same reservoir source. The rate of pressure drawdown increased further albeit slightly with increasing mass extraction from about 150 kg/s when the Nasuji module was commissioned towards the end of 1993 to a high of 459 kg/s when the Balasbalas plant module was put online in April 1995.

Since commissioning, the modular plants in Palinpinon 2 have been operating at full load except in the Balasbalas module where recently the plant load has been below the rated capacity of 20MW due to steam supply shortfall. Pressure drawdown in Palinpinon 2 has affected steam production in production wells SG2, and SG3D in the Sogongon sector which tapped the shallow two-phase zone causing declines in their outputs. Outputs in production wells NJ9D and NJ10D drilled in central Nasuji sector however, remained unchanged notwithstanding the increased boiling of fluids. At present, the reservoir pressure in this sector averaged slightly below 6.0MPag with mass extraction ranging between 300 kg/s to 360 kg/s.

The Palinpinon-1 plant on the other hand, has been operated at variable loads in favour of the Independent Power Producers (IPPs), designated as the 'frequency marshall' which absorbs sudden load swings in the Visayas grid. In addition, the aging turbine units require frequent and longer PMS to keep them in shape. As a result of the reduced mass extraction during these periods, drawdown had been slowed down as the reservoir pressure recovered seen as "swells or humps" in the plots.

### 3.2 Injection Returns

As the Palinpinon reservoir is exploited, the pressure differential between the production and injection sectors increased and in turn drives the injected brine (~160°C) back to the production area. The breakthrough times of the injected fluids to the production sector vary considerably from injection well to injection well. Experience showed that injection flow rates and the permeability of the structural faults that convey this fluid are the two major factors that significantly influence the arrival time of the injection fluids to the production sector. In Palinpinon 1 for example, the Puhagan, Ticala and Odlumon faults have been identified to channel injection fluids back to the production sector.

Tracer tests conducted both in Palinpinon 1 and Palinpinon 2 confirmed the interconnection between the production and injection sectors. Hermoso and Mejorada in 1997 gave details of the results and established the following direct communication of a certain injection well to usually multiple production wells, to wit: PN-1RD to PN-26, PN-28, OK-7 and OK-2; OK-12RD to PN-15D, PN-21D, OK-10D, OK-7, PN-28 and PN-26; and PN-9RD to OK-7, PN-29D, PN-26, PN-28, PN-18D, PN-30D, PN-23D and PN-31D. Monitoring of the chemical parameters of the injected brine, i.e. injection line chloride, reservoir chloride and carbon dioxide confirmed the positive effects of shifting the bulk of injection away from the Puhagan production sector. Pamatian, et al. (2003) also showed that injection line chloride dropped from 11,000 ppm to an average of 9,000 ppm when injection load in the Puhagan injection sector was reduced.

Injection mass front, which if left unchecked, could progress into thermal front that cools the feed zones of the affected wells. Thermal declines among affected Puhagan wells range from 5°C to 30°C based on $TSiO_2$ (Hermoso and Mejorada, 1997) and actual downhole measurements. By experience, thermal fronts as a result of injection load of over 50 kg/s into PN5RD could reach the south western Puhagan production sector in about two weeks causing drops in outputs. Similarly, albeit on a longer period, injection load of over 130 kg/s into TC3RD could cause thermal fronts to reach the south-eastern Puhagan production sector in about three months.

In the case of Palinpinon 2, communication from injection wells, NJ2RD and SG2RD to some production wells have been properly documented by separate tracer tests as summarized in PNOC EDC (1995) and recently reported by Maturgo, et al. (2006). Mass fronts have reached as far as well NJ3D to the North, in OK5 farther to the West and in well NJ5D to the Northeast. Wells NJ-3D and NJ-5D manifested temperature and output declines including NJ8D in central Nasuji. The tracer test conducted in the Palinpinon 2 area in 2005 revealed that as much as 25% of the injected brine in NJ-2RD and SG-2RD return to nearby production wells through NW-SE and NE-SW trending faults within a year. This was also confirmed in a thermal breakthrough simulation study conducted by Esberto in 2003.

Injection breakthrough causes decline in the discharge enthalpy with corresponding increase in mass flow, resulting to a net decline in steam flow and hence, the output. In worst cases, it induces downflow from the upper permeable zone that suppresses feed from the deeper zones. In such cases, both mass flow and enthalpy deteriorate as in well OK-7 whose output dropped from 7.0MW to only 1.3MW after its mass flow declined to 42.9 kg/s and enthalpy to 236 kJ/kg. In 1989, well PN-26 ceased to produce commercially and was cut-out from the system. Production wells PN-17D and PN-21D also became non-commercial and were decommissioned in 1993 and 1996, respectively. By 1997, six of the 25 producers in Palinpinon-1 became non-productive and the field lost about 39MW of steam capability (Figure 3). In Palinpinon 2, wells NJ5D and NJ8D in central Nasuji and NJ3D in northern Nasuji manifested similar trend. Discharge enthalpies declined from about 1400 kJ/kg to slightly over 1200 kJ/kg in 2000 to 2001, just six years after commercial operation of the power plants. A combined steam flow of around 50 tons per hour (tph) had been lost from these wells, which is equivalent to about 6 MW.

## 4.0 RESERVOIR MANAGEMENT STRATEGIES

### 4.1 Shifting Injection Away from the Production Area

Massive injection breakthrough from infield injection wells in Palinpinon 1 aggravated by the increased mass extraction brought about by the Negros-Panay interconnection prompted the shift in the bulk of injection farther away towards the Ticala and Malaunay sectors starting in 1989 (Figure 4). The reduced injection load in Puhagan from ~300 kg/s to 100 kg/s induced recoveries in a number of wells. Field-wide response was manifested by the decline in the injection line chloride. Subsequently, the two-phase condition at the upper permeable zones of some production wells expanded as pressure drawdown intensified inducing production from the deeper zones. The mass flow of well PN-29D recovered from 27.6 to 66.3 kg/s while its enthalpy increased from 1058 to 1408 kJ/kg resulting to an increase in steam flow from 17.6 to 82.5 tph. Similar improvement was observed in well PN-19D when its lower zones contributed to the discharge. Over-all, steam supply to the power plant had improved.

Despite the transfer of the bulk of injection, thermal breakthroughs were still observed in several wells which are hydrologically connected to injection wells N3R and TC3R through Ticala Fault. These injection wells were later decommissioned and re-drilled as in the case of the latter. By the middle of 1997, injection at the Puhagan area was totally eliminated. This induced excessive pressure drawdown in the southern and south western sector of the production area. Although the enthalpies of the wells increased, their mass flows significantly declined resulting to decline in steam outputs. The total transfer of injection away from Puhagan area therefore, was not entirely beneficial to the system.

### 4.2 Deep Injection to Promote Sufficient Reheating

In 1992, injection into well TC-2RD that intersected Odlumon Fault at deeper levels was found to provide pressure support to the south eastern sector of the Palinpinon 1 production field. Sufficiently reheated injection fluids coming from this well found their way to OK-10D and PN-13D. Also injection of brine into this well has improved the pH of PN20D as a result of the dilution of acidic fluids in this well with the returning injection fluids. Consequently, injection of brine towards Odlumon fault was maximized with the drilling of TC-4RD in 1995 and re-drilling of TC3R deviated towards this fault in early 1997.

Cement plugging of top zones in highly communicative injection wells was also applied to facilitate deep injection. PN-2RD and PN-3RD were the first wells to be plugged but with continuous injection, the cement plugs collapsed. (Pamatian, et al., 2003).

### 4.3 Drilling and Utilization of High Enthalpy Wells

This strategy was adopted in Palinpinon 1 to improve steam production without increasing the volume of separated brine. Wells with high discharge enthalpies were given priority in utilization over watery wells during low plant loads. OK-2, PN-30D and PN-32D are such wells. Although the steam capability of the field was improved, it was not enough to sustain full load operation. Thus, PN-33 was drilled in 1993 to tap the shallow two-phase zone. Interconnection of LG-2D to the Palinpinon 1 FCRS was also proposed. Drilled within the upflow area, LG-2D with an output of around 9.5MW and water flow of only 4 kg/s could have replaced at least four low enthalpy wells and thus, reduce separated brine load by about 84 kg/s (Amistoso, 1993). Unfortunately, the well was lost during a work-over in 1995 and was cement plugged. Production wells LG-3D and LG-4D were later drilled as replacements and were put on-line to the system before the end of 1996.

Prioritization of high enthalpy wells had been effective at the time when effects of injection breakthrough were prevalent in the production sector however, with the 3-unit operation of the power plant; discharge of all production wells into the FCRS cannot be avoided. Injection breakthroughs associated with the increased mass extraction during full load had been controlled with the commissioning of TC3RD and TC4RD into the system. Maximum utilization of all production wells in Palinpinon-1 has since been continued to the present.

### 4.4 Controlled Injection

Balancing the effects of pressure support versus pressure drawdown as a strategy to sustain steam production requires the controlled injection of waste brine in some injection wells in Palinpinon 1 as well as in Palipinon 2. This involved a complex process of determining the optimum or preferred injection load that took into consideration the selection of the injection wells to be used and the mechanism of how injection fluids from this well can affect steam production.

In Palinpinon 1, it has been established that a load of about 50 kg/s and not more than 130 kg/s in PN5RD and TC3RD, respectively could provide pressure support to the wells in the southern and south western sectors of the field without adverse effects to the production zones (Figure 4). Knowing the injection breakthrough times and identifying the specific production wells that will be affected enabled the implementation of short-term interventions to address operational constraints, thus providing operational flexibility. Excessive load in PN5RD for example would drastically affect the outputs of wells PN24D, PN30D and PN23D in south western Puhagan in just two weeks while higher loads in TC3RD would affect PN22D, OK9D and PN20D at the opposite side of the production field albeit at a longer period of time of at least three months. Cold brine injection at SG3RD in Palinpinon 2 has been limited to 50 kg/s to minimize effects of injection returns to the production sector. This injection strategy has been implemented up to the present.

## 5.0 STEAM CAPABILITY OF THE PALINPINON GEOTHERMAL FIELD

### 5.1 Palinpinon-1 Steam Supply Trend

The maximum available steam (Figure 3) measured prior to the commissioning of the 112.5MW Palinpinon 1 plant was about 1400 tph equivalent to around 150MW based on the NPC contracted steam rate of 9.2 tph/MW. The 2.0MPa drawdown early in the commercial operation of the Palinpinon 1 plant from 1983 to 1989, aggravated by the effects of injection returns from the infield injection wells in Puhagan, caused the sharp drop in the total steam flow to about 1,050 tph in 1990. The shift in the bulk of injection from the production sector starting in 1989 raised the steam flow back to the 1,200 tph level however, the rapid injection returns from TC3R conveyed back to the production sector via Ticala fault and bolstered by the high pressure difference, reduced it back to 1,000 tph in 1993. Deviating TC3R towards the Odlumon fault and the subsequent controlled injection in PN5RD and TC3RD had sustained steam production at this level until 2006 keeping a balance between pressure support in the form of sufficiently reheated injection fluids and pressure drawdown in the reservoir.

Towards the end of 2006, steam supply declined again to around 900 tph. Effects of pressure recovery that induced an increase in the liquid saturation of the geothermal fluid during the month long PMS of a turbine unit, and the cooling effects of the drilling fluids injected for almost three months at the height of PN21D and PN17D workover and acidizing, conducted during this period partly contributed to the steam flow decline. Neighbouring wells, e.g. PN15D drilled in the eastern sector close to PN21D and those drilled along the path of the Ticala fault, e.g. PN32D, PN24D among others manifested drops in outputs. Such effects on the steam supply however, would wane after a month or two after the plant resumed full load operations.

The persistent decline in the steam supply in this period was largely attributed to pressure drawdown that had intensified since 2004 which was manifested by an increase in the average field utilization enthalpy from 1400 kJ/kg to 1600 kJ/kg coupled with a corresponding decrease in the total brine flow from 330 kg/s to 290 kg/s. This prompted the revision of the injection strategy, where brine injection in the Malaunay sector was reduced from 90-100 kg/s to just 50 kg/s to maximize the injection load in the Ticala sector, at the same time maintaining the injection load in PN5RD at 50 kg/s to increase pressure support in the south-eastern and south western Puhagan production sectors.

Exacerbating the steam decline is the increase in steam consumption of the power plant during this period. Actual steam rate increased from 9.6 tph/MW to over 10 tph/MW. As a result, the power plant can barely sustain a plant load above 90MW.

The steam augmentation strategies implemented in the last two years of the Palinpinon-1 operation have increased the steam supply to about 960 tph enough to support a plant load of over 95MW. These strategies are discussed in the next section of this paper.

### 5.2 Palinpinon 2 Production Field

The combined steam supply of the 80MW Palinpinon 2 modular plants totalled 985 tph at the start of its operation distributed as follows: ~175 tph in Balasbalas module, 303 tph in Nasuji module and about 500 tph in Sogongon module (Figure 5). Immediately as the modular plants were commissioned, the total steam supply had declined to around 750 tph by year 2000 at a rate of around 40 tph per year. The decline is attributed to reduction in the steam flow in the Sogongon sector by as much as 150 tph largely from SG2 and SG3D due to pressure drawdown and about 90 tph in Nasuji sector mainly from NJ5D and NJ8D due to injection returns. Formation of a mineral blockage in NJ7D in 1999 also contributed as much as 21 tph to this steam flow reduction. Commissioning of well BL3D, with steam flow of about 100 tph, in 2001 for the Balasbalas module increased the steam field capability to ~860 tph but was later reduced to ~770 tph when BL1D was decommissioned seven months later due to thinning of the 9-5/8" production casing. Moreover, the combined steam flow of ~120 tph gained from the restoration of the output of NJ7D after its acid stimulation to remove the mineral blockage and the utilization of the once-acidic well NJ6D to the Nasuji module in early 2004 further increased the total steam capability to about 900 tph. Henceforth, the total steam capability of Palinpinon 2 had stabilized declining only around 40 tph to around 860 tph at present, capable of supporting a load of at least 100MW.

Individually, steam supply in the Nasuji and Sogongon sectors had remained stable for the past four years meeting the requirement of the respective power plant despite the effects of pressure drawdown, injection returns and mineral blockage. Steam supply in the Balasbalas sector however, had declined steadily from 192 tph in 2004 to 150 tph at a rate of 17 tph/yr based on metered steam flow. At present, steam supply in this sector can only support a maximum load of about 17.5 MW incurring a 2.5 MW shortfall. Plans to restore steam production in BL1D is being undertaken to augment steam supply in this sector. The Nasuji sector on the other hand, still has an excess of about 165 tph capable to support an additional 20 MW plant which is being pursued to optimize steam production. These optimization plans will be discussed in the next section of this paper.

## 6.0 STEAM AUGMENTATION AND OPTIMIZATION OPTIONS

The two-phase condition at the shallow levels of the reservoir identified in the conceptual model of the Palinpinon geothermal field had expanded considerably after 25 years of exploitation in Palinpinon 1 and 15 years in Palinpinon 2. The vertical expansion of the steam or two-phase cap is reflected by the change in the water levels of the Palinpinon wells (Figure 6). Water levels had dropped from a baseline data of 200 mMSL to -600 mMSL and -700 mMSL in central Puhagan, and in Nasuji - Sogongon areas, respectively. This is also manifested as a shift in the hydrostatic lines representing the wellbore pressures at the control points measured at different stages of exploitation (Figure 7). The extent of the lateral expansion of the two-phase horizon of the Palinpinon-1 field was estimated based on volumetric calculation by Amistoso, et al. in 1993. From localized areas, it has widened encompassing almost the entire Palinpinon-1 field, taking the form of the north-easterly outflow tongue of the system estimated to cover an area of 4.93 $km^2$ with a power potential of 35.5 MW-years. In the case of Palinpinon 2, the extent of the lateral expansion can be only be surmised from the recent simulation data (Figure 8) presented by Amistoso (2004). Production from this two-phase zone has been proven by shallow wells OK-2 and PN-33 in central Puhagan, and by SG2 in Sogongon sector, and recently by well NJ6D which had become commercial in 2004.

Recognizing the potential of this expanding relatively dry component of the geothermal resource, the following optimization strategies had been proposed and pursued to sustain and augment steam supply to the power plants. Excess steam flow in Palinpinon 2 as a result of the additional steam production from this two-phase zone has been estimated to support additional plant capacity.

Optimization options other than those that are related with the expanding two-phase zone are also presented below. These include workover and acid treatment method of restoring the outputs of production wells and proposals to revise the present power plant design, in order to sustain and optimize steam production.

### 6.1 Revival of Pre-maturely Decommissioned Wells PN-21D, PN-17D and PN-26

The massive injection breakthroughs affecting the early stage of the commercial operation of the Palinpinon-1 geothermal plant caused the pre-mature decommissioning of PN21D, PN17D, PN26 and OK7 in 1989 to 1996. Over 10 years after their shutdown, these wells were recommended by Aqui, et al. in 2005 for re-utilization to augment steam supply in Palinpinon-1. The significant drawdown and the reduced effects of injection returns in the production sector had justified their workover and acid treatment. The remedial jobs were carried out and were completed respectively in November 2006 and July 2007.

Post workover shut surveys in PN-21D confirmed the presence of a two-phase feed at the upper zone at 1250-1400 mMD which is evident by the decline in its water level by about 600m to 800 m below sea level. Also, the temperatures at the deeper zones are higher compared to the 1985 values indicating recovery from the effects of injection returns. The output of the well was regained (Table 2) despite the no significant change in the current mass flow compared to the baseline value in 1988; the corresponding enthalpy is higher indicative of a two-phase contribution.

Aside from the workover and acidizing of PN-17D, the hot zone at the cased-off section just above the production casing shoe was perforated. Shut surveys corroborated by circulation losses during drilling warranted the opening of this section. Like well PN21D, post workover shut surveys indicated that the water level had dropped to ~600 m below sea level and the temperature profile showed two-phase fluids entering the well at the perforated section. The relatively strong downflow from 2100 mMD noted during the 1989 survey has apparently disappeared as temperatures at 2400-2800 mMD recovered signifying recovery from injection breakthrough. PN-17D yielded a commercial output of 4MW (Table 3) after its revival.

PN-21D and PN-17D were put on-line to the system on December 2006 and August 2007, respectively. The successful revival of these wells increased the field steam capability by about 8MW. The wells have since been utilized without significant deterioration in output to date.

Just recently, PN26 was worked over and acid stimulated to restore its productivity. However, the well was not able to regain its commercial output most likely due to a casing problem encountered towards the end of the workover. Restoration of the productivity in OK7 was not pursued as the well was significantly damaged during its last workover.

### 6.2 Conversion of Puhagan Injection Wells Into Producers

The positive results of the workover and acidizing jobs in PN21D and PN-17D strengthened the earlier recommendation to convert selected Puhagan injection wells into production wells (Aqui, et al, 2005) to further augment the steam supply for Palinpinon-1 plant.

Well PN-6RD, drilled towards the north-eastern part of the Puhagan field just as PN17D was tested first in July 2007. The well discharged relatively dry steam of about 6.7MW. This output was confirmed and sustained during the extended discharge test conducted from December 2007 to January 2008.

The Puhagan injection wells PN-7RD, PN-8RD and PN-9RD drilled in the northwest flank of the field, are closest to the production area with established good communication to producers through common geological structures intersected. The three wells have high shut-in pressures of 2.16 MPag, 1.51 MPag and 2.68 MPag, respectively and still have exploitable temperatures at depths ranging from 210°C to 260°C. PN8RD did not sustain discharge due to a blockage just below its PCS. PN-7RD on the other hand sustained discharge when flowed but the output was non-commercial as discharge cycled likely due to the mineral blockage within the production liner. PN-9RD sustained discharge when tested producing at least 3 MW at the wellhead. As expected, the well's discharge was liquid dominated confirming that the two-phase condition at this part of the reservoir had not expanded significantly.

With the proven combined commercial outputs of PN6RD and PN9RD of about 8.0MW, steam lines and other surface equipment which will convey the steam to the power plant were already installed in May 2008. Commissioning of these wells to the system however, are still being put on hold pending finalization of the steam supply contract between EDC and NPC.

### 6.3 Additional 20 MW Nasulo Power Plant in Palinpinon 2

Lumped parameter modelling and numerical simulation conducted by Amistoso, et.al. (1988) as part of the Palinpinon 2 Resource Assessment and Development Strategy showed that an 80MW power plant could be sustained in this sector for 25 years. The stable reservoir pressure attained 4.5 years after the commissioning of the modular plants of about 6.0MPag and the excess steam equivalent to 11MW from the Nasuji-Sogongon production sector, prompted Amistoso et al. (2002) to assess the viability of an additional production in the Nasuji area. The pressure decline curve analysis used in the Lumped Parameter Modelling, and the Volumetric Stored Heat Estimate both projected a 1.0MPa pressure drawdown albeit at higher recovery factors of 30 to 40% for the latter, signifying that an additional 20MW in this sector is technically and commercially feasible (Figure 9).

The initial development strategy requires drilling of a new production well at start up operation but the unexpected revival of well NJ6D drilled within the acidic block with a stable output of 10MW made it unnecessary. However, the new production well, NJ11D will be drilled by 2014 to sustain steam supply up to end of the steam sales contract in 2031. Also the relatively dry discharge of NJ6D, reminiscent of the expanding two-phase condition in this part of the Palinpinon 2 production sector, defers drilling of a new injection well, NJ3RD four years after commissioning of the plant. Steam projections made by EDC using the pressure-enthalpy correlation indicated that workover of BL1D in the Balasbalas sector and SG2 in the Sogongon sector must be conducted in 2008 and 2010, respectively to augment and sustain steam supply to the power plants.

A similar study was recently conducted to evaluate the viability of a higher plant capacity of 35MW in view of a more cost effective turbine (Aqui and Austria, 2008). The lumped parameter model yielded an almost 2.0MPa pressure drawdown that would bring down the average reservoir pressure from a current of about 5.6MPag to 3.7 MPag as a result of additional extraction of geothermal fluids. Additional wells, i.e. three production wells and two injection wells must be drilled before start-up operation to meet the additional steam and injection capacity requirements. The higher pressure drawdown would induce faster mass and hence, steam flow decline and therefore would necessitate drilling of M&R wells not only in the Nasuji sector but also in the Balasbalas and Sogongon sectors spread over a period of three years after commissioning of the plant. Also, the bigger pressure differential would hasten breakthrough of injection fluids to the production sector.

Finally, the recalculated volumetric stored heat estimates indicated that the present Palinpinon 2 resource area cannot support the steam flow requirement of a 35 MW plant notwithstanding the inclusion of the acid region covered by Block C. More so, as results of the re-testing of the production wells i.e. NJ1D and OK11D drilled inside this acid block proved the impracticable use of these wells at present due to the acidic nature of the discharging fluids.

### 6.4 Well Workover and Acidizing

The formation of mineral deposits or scales within the wellbore and immediate surrounding of the feed zones reduce the steam generating capacity of the producing wells by restricting feed contribution from the lower feed zones. The effect of this mineral blockage is manifested by the decline in mass flow accompanied with an increase in the discharge enthalpy. But unlike the effect of pressure drawdown, the output of the affected well decreases with the mass flow. Calcite (PN21, PN15D, and PN13D) and anhydrite (PN20D, PN22D, NJ4D and NJ8D) deposition usually occur at the flashpoint in the well. Well output have been observed to decrease drastically by as much as 30 to 40% which could go higher if left unchecked.

Immediate mechanical workover were conducted once the output of the well had been reduced by 50%. Technological breakthrough in the field of well stimulation by acid injection in conjunction with mechanical workover has been successful in restoring the generating capacity of damaged wells. However, the susceptibility of recurrence of the mineral deposition made this a short term or stop gap option of sustaining steam supply. Well PN30D in Palinpinon 1 and SG2 in Palinpinon 2 are candidate wells for workover and acid stimulation due to mineral blockage at the cased-off section of the respective wellbore. The current 8.0MW output of SG2 however, is still above 50% of its original value hence, its priority for workover and acidizing is still low.

### 6.5 Integration of a Second Flash, Low Pressure Turbine for Palinpinon 1

The exergy analysis performed by Aqui, et.al. in 2004 showed that steam production in Palinpinon 1 can be optimized by harnessing the useful energy of the separated brine before injecting it back to the reservoir (Figure 10). The results of the exergy analysis and the sensitivity study indicated that a secondary flash, low pressure plant would yield an additional generating capacity of about 18MW increasing the over-all utilization efficiency of the plant from 40% to 45.6%. It further showed that maximum improvement occurs at a flash temperature of 115C higher than the flash temperature of the Ormat System of 90C.

The integration of a second flash system on top of the existing 112.5MW plant allows direct connection of the marginal wells (low WHP wells), e.g. PN14, PN13D and PN25D to the low pressure turbine. At present, these wells will cease production with continuous discharge to the system due to low wellhead pressure (WHP). Operating them at a lower pressure allow these wells to continuously contribute to the FCRS.

The lower injection temperature of the waste brine from the secondary plant poses a concern with regards to silica deposition but this can be mitigated with the inhibition system to control mineralization along the RI line and within the wellbore.

**7.0 CONCLUSION**

The Palinpinon Geothermal field experience has demonstrated that timely implementation of appropriate and effective resource management interventions to address effects of pressure drawdown and injection breakthroughs can be done to sustain and optimize steam production. Understanding the mechanisms how these two major reservoir processes interacts with each other, on steam production in particular and the reservoir in general, in response to the continued exploitation of the field have helped in finding and devising ways to utilize the expanding two-phase region at the shallow levels of the resource for steam production.

The current Palinpinon field management strategy has been geared towards tapping this two-phase fluid to sustain and optimize operations of the power plant. The successful re-utilization of pre-maturely decommissioned wells after more than ten years of shutdown and conversion of some infield injection wells in Puhagan into producers had proven the merits of this strategy. The steam capability of the field has been consequently improved. The plan to construct an additional 20MW Nasulo power plant in Palinpinon 2 has been the result of a careful re-assessment of the resource that also takes into consideration the major contribution from the two-phase region. The simple yet effective lumped parameter modelling and volumetric stored heat calculation have been instrumental in predicting the Palinpinon field response to changes in the reservoir condition as a result of exploitation. Moreover, the pressure-enthalpy correlation has provided a simple means of projecting well flows necessary in determining the drilling of M&R wells and workover jobs.

Integration of a secondary flash, low pressure plant proposed as a result of the exergy analysis promised a long-term option to optimize the operation of the plant and maximize utilization of low pressure production wells. However, workover and acid stimulation of wells with mineral blockage had been proven successful to sustain steam supply in the short-term.

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**FIGURES AND TABLES**

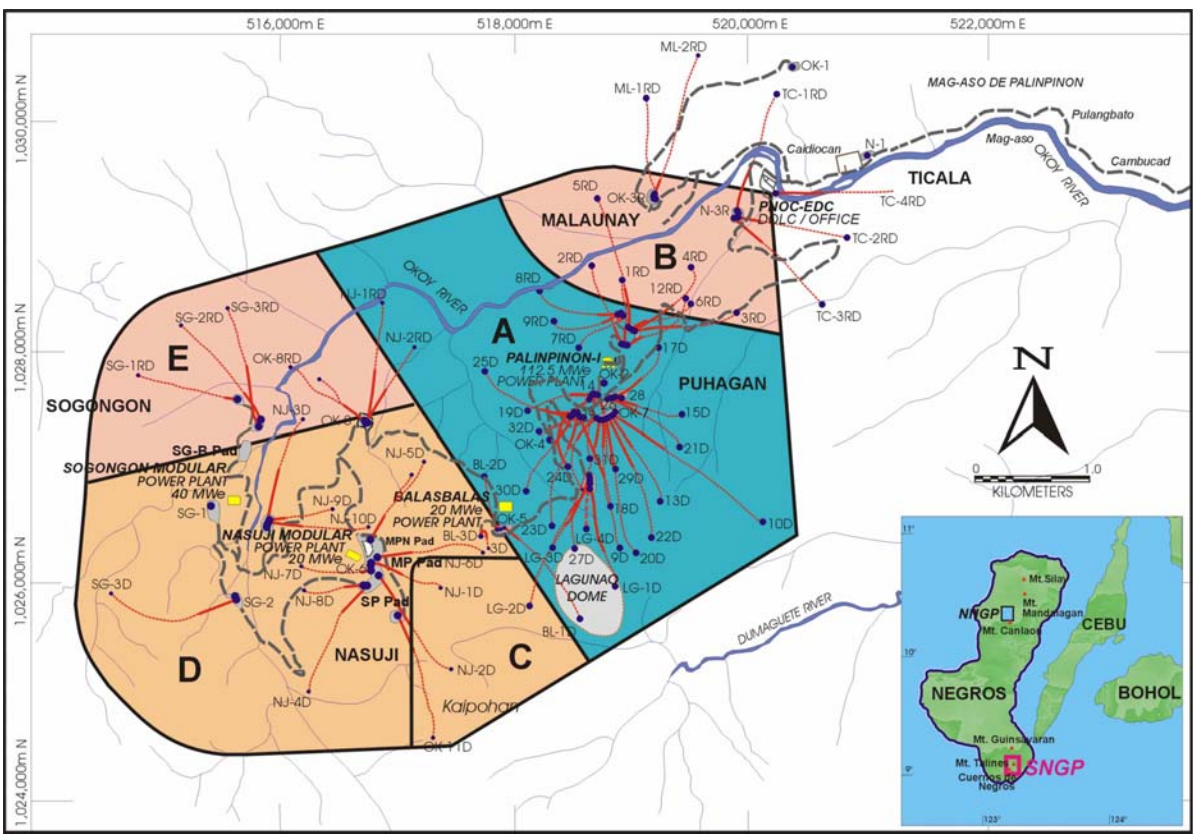


Figure 1. Location map of SNGPF showing the Resource Boundaries

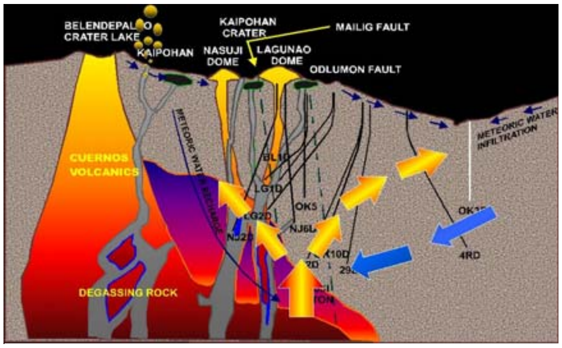


Figure 2. Conceptual model of the SNGPF reservoir (After Pamatian, et al., 2003).

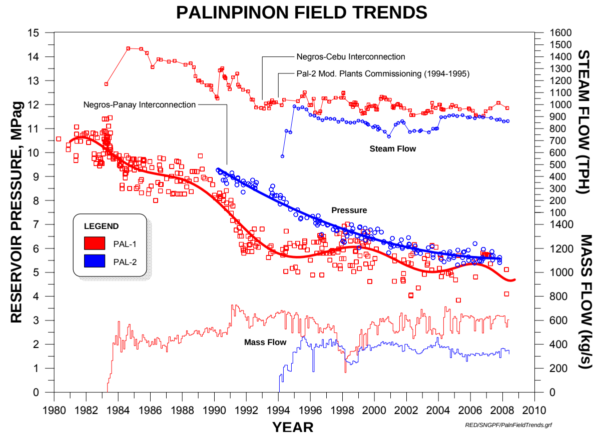


Figure 3. Palinpinon 1 and 2 Field Trends

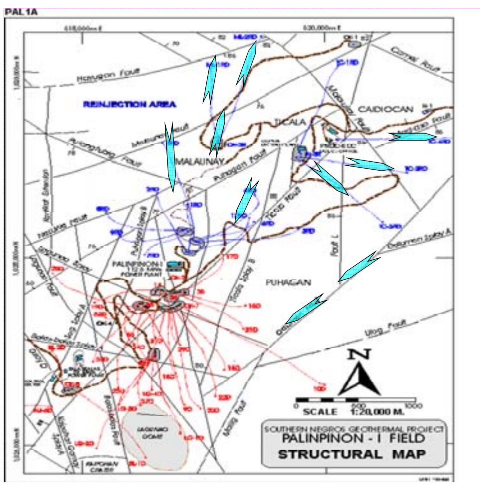


Figure 4. Shift of the Bulk of Injection from Puhagan Injection sector to Malaunay-Ticala Injection

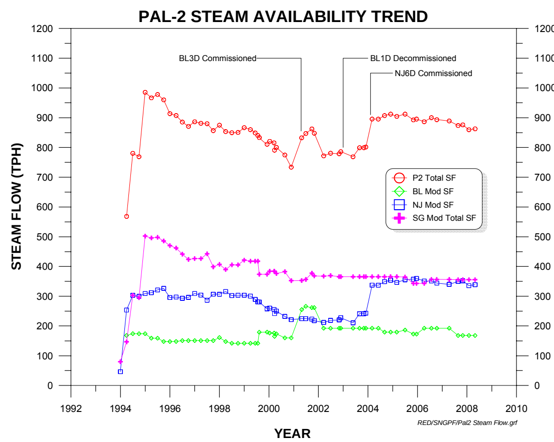


Figure 5. Palinpinon 2 Steam Capability

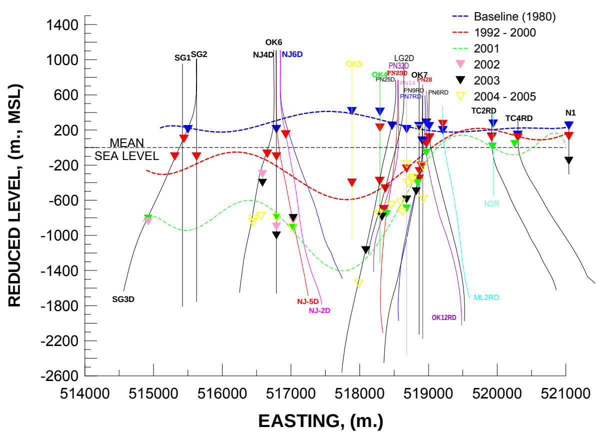


Figure 6. Progressive decline of water levels in Palinpinon wells due to reservoir pressure drawdown.

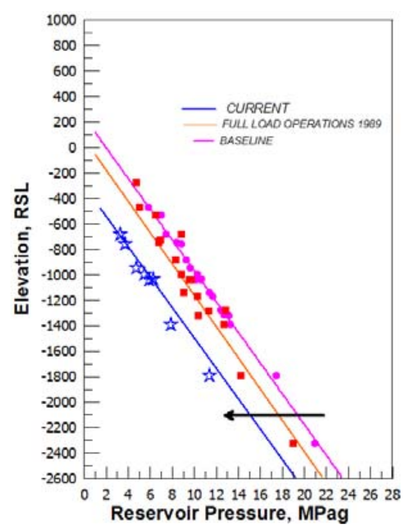


Figure 7. Shift of hydrostatic lines due to pressure drawdown

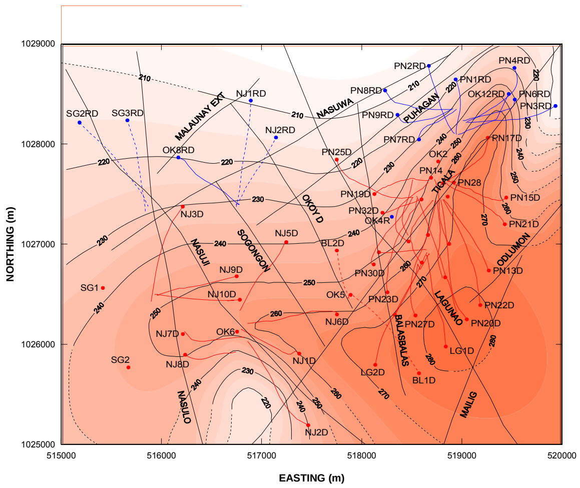


Figure 8. Estimated aerial expansion of the steam/two-phase cap of the Palinpinon field based on the simulated temperatures.

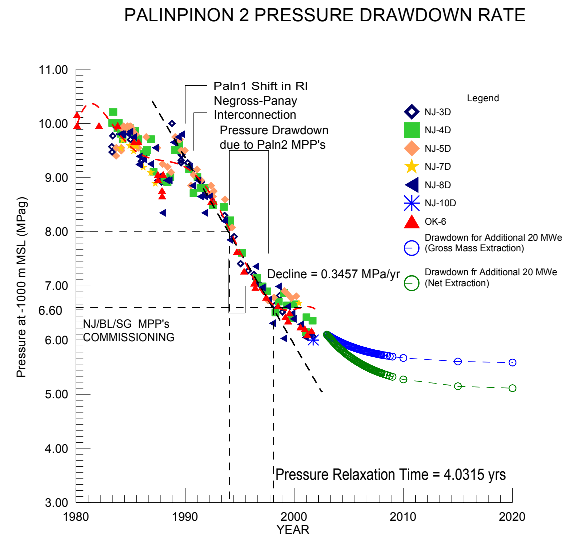


Figure 9. Palinpinon 2 Pressure Decline Curve

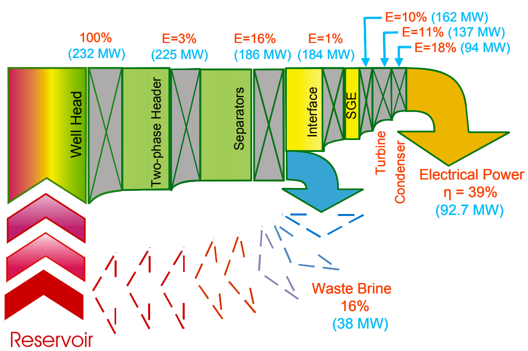


Figure 10. Palinpinon 1 Exergy Analysis

Table 1. Palinpinon-1 Wells Affected By Pressure Drawdown

| WELL NAME | Δ MASS FLOW (kg/s) | Δ ENTHALPY (kJ/kg) | Δ WATER FLOW (kg/s) | Δ STEAM FLOW (TPH) |
|---|---|---|---|---|
| PN-22D | -30 | +1200 | -20.3 | -35 |
| PN-27D | -23.9 | +353 | -21.2 | -9.6 |
| PN-23D | -12.1 | +153 | -7.6 | -16.2 |
| PN-15D | -21.4 | +553 | -17.1 | 15.5 |

Table 2. Bore Outputs of PN21D and PN17D after Re-commissioning

| | WHP *(MPag)* | H *(kJ/kg)* | MF *(kg/s)* | WF *(kg/s)* | SF *(TPH)* | MW | Date Tested |
|---|---|---|---|---|---|---|---|
| **PN21D** | 0.76 | 1105 | 42.5 | 29.5 | 30.4 | 3 | 7-Dec-06 |
| | 0.71 | 1625 | 21.7 | 10.1 | 35.2 | 3.5 | 27-Mar-07 |
| | 0.69 | 1511 | 34.2 | 17.7 | 48.7 | 4.8 | 28-Sep-07 |
| **PN17D** | 0.64 | 1395 | 27 | 15.3 | 32.9 | 3.3 | 17-Aug-07 |
| | 0.65 | 1441 | 27.1 | 14.8 | 35.2 | 3.5 | 28-Sep-07 |

Table 3. Bore Outputs of Puhagan Injection Wells after Conversion to Production Well

| | WHP *(MPag)* | H *(kJ/kg)* | MF *(kg/s)* | WF *(kg/s)* | SF *(TPH)* | MW | Date Tested |
|---|---|---|---|---|---|---|---|
| **PN6RD** | 0.66 | 2726 | 16.4 | 0.3 | 57.7 | 5.7 | 27-Dec-07 |
| | 1.59 | 2703 | 10.0 | 0.3 | 35.0 | 3.5 | 1-Jan-08 |
| | 1.03 | 2722 | 15.8 | 0.4 | 55.6 | 5.5 | 23-Jan-08 |
| **PN9RD** | 1.14 | 1208 | 18.4 | 11.9 | 15.6 | 1.5 | 14-Feb-08 |
| | 0.79 | 1280 | 36.8 | 22.6 | 35.8 | 3.5 | 10-Mar-08 |