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RESERVOIR MANAGEMENT DURING 15 YEARS OF EXPLOITATION: SOUTHERN NEGROS GEOTHERMAL PRODUCTION FIELD Valencia, Negros Oriental Philippines

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ABSTRACT

The Southern Negros Geothermal Production Field in the Philippines has been exploited for electrical energy production since 1983. Steam production has been affected by the problems encountered in the production and reinjection wells, namely, mineral deposition in the wellbore and in the formation, reinjection fluid returns, acidic fluid intrusions, and pressure drawdown.

PNOC-EDC, through intensive monitoring and thorough understanding of the field's behavior under exploitation, was able to formulate immediate and long-term reservoir management strategies for the sustainability of the resource. Foremost was the shifting of the bulk of injection away from the production area in 1989 to address the problem on reinjection fluid returns. PNOC-EDC proceeded to totally eliminate infield injection and permit the expansion of the shallow two-phase zone. Together with the strategy of prioritizing the utilization of high enthalpy wells, the reinjection load was reduced. Later on, the promotion of 'deep injection' was adopted which minimized drawdown rate by providing pressure support and reheated recharge to the production sector. In addition to work-overs and drilling of make-up and replacement wells, the steam productivity of the field for the last 15 years was also maintained through newer technologies such as acid stimulation.

1.0 INTRODUCTION

The Southern Negros Geothermal Production Field (SNGPF), also known as the Palinpinon Geothermal Field, is located in Valencia, Negros Oriental, central Philippines (Figure 1). The field is subdivided into two geographical areas, namely, the Palinpinon-1 (P1PF) and Palinpinon-2 (P2PF) Production Fields. Early exploratory activities in the area started in 1975 and to date, a total of 75 wells have been drilled. About five years later, a 112.5 MWe power station, called the Palinpinon-1 Geothermal Power Plant (PGPP1) was constructed in P1PF area and began commercial operation in May 1983.

Development of the Palinpinon Geothermal Production Field was suspended in 1986 due to political and economic instability of the country at that time but was later pursued when conditions stabilized. After the resource re-assessment of the P2PF area showed that the field could still support additional capacity (Urbino, et. al., 1988), further development resumed in late 1989. Numerical simulation studies conducted by Amistoso, et al. (1990), further proved that the resource could sustain steam production of at least 80 MWe in P2PF. Hence, from 1993 to 1995, PNOC-EDC commissioned four modular power plants in the area, namely, the 1x20 MWe Balasbalas, 1x20 MWe Nasuji and 2x20 MWe Sogongon modules. SNGPF supplies power to the whole island of Negros and to the neighboring islands of Panay and Cebu via sub-marine power cables.

2.0 RESERVOIR RESPONSE TO EXPLOITATION

Four major processes were identified during the 15 years of intensive field monitoring. (1) Pressure drawdown, (2) reinjection returns, (3) cold/acidic inflows, and (4) mineral depositions that occurred during exploitation and have constantly affected the sustenance of steam supply. Amistoso and Orizonte (1997) presented a detailed discussion on the reservoir response to exploitation.

2.1 Pressure Drawdown

Since the start of the commercial operation of PGPP-1 in 1983, the P1PF reservoir pressure had dropped by ~5.5 MPa. In P2PF, about 2.5 MPa has been drawn down since 1992, which is before the start of operations of the P2PF power plants. Figures 2 and 3 show the pressure trends for P1PF and P2PF, respectively. In the P1PF area, the hydrostatic level has lowered by about 500 m as intense boiling occurred at the upper zones. Consequently, there was expansion of the two-phase cap with an estimated in-place potential of 35.5 MWe-years based on volumetric stored heat calculations (Amistoso, 1993). This process was manifested as a substantial increase in enthalpy and decrease in mass flow of the production wells. In some wells, net output increases were observed while in others, particularly those severely drawn down, the effect of enthalpy increase was off-setted by the substantial decline in mass flow resulting to a net decline in steam flow.

2.2 Reinjection Returns

As a general rule, the saturation temperature of a fluid decreases with pressure. However, thermal decline in P1PF was not solely attributed to this process. The breakthrough of insufficiently reheated injected brine (due to massive and rapid returns) to the production sector also caused cooling of feed zones in the affected wells. As early as 1984, reinjection returns had already been detected in the Puhagan production area and temperature declines ranging from 5°C to 20°C were measured in wells experiencing this kind of intrusions. Driven by pressure differential between the production and reinjection sectors, these fluids were channelled through the Ticala, Puhagan and Odlumon faults and their splays, the major permeability connectors crossing the field. Also, the compact development of the field enhanced this fluid flow pattern in the reservoir.

The effect of reinjection returns is manifested as a reduction of enthalpy with corresponding increase of the mass discharged. Often times, the net result is a decline in steam flow, hence, output. The worst case was experienced in PN-26 and OK-7 where the main production zones were severely cooled (Figure 4). These two wells can no longer produce at commercial operating pressure. Meanwhile, the chemistry of the discharge reflected reinjection (RI) returns as increases in the reservoir chloride levels, decrease in discharge CO_2 and decrease in silica quartz temperature, $TSiO_2$. Hermozo and Mejorada (1996) have shown that almost all of the wells in Puhagan have RI fluid intrusions. Injecting in PN-2RD, for example, caused deteriorations in PN-29D, PN-28, PN-18D and PN-14. In the Palinpinon-2 area, reinjection well SG-3RD has been shut due to its strong connection with Nasuji production wells.

2.3 Strong Inflow and Downflow

Most of the wells in SNGPF have multiple feed zones. In a shut-in well, when the formation pressure exceeds the bore pressure in a feed zone, fluid enters the well at that zone. In some cases, the flow is strong enough to cause downflow that masks the true temperatures of the deeper zones. This is manifested as an almost isothermal profile of the temperature-depth plot (Figure 5). Strong fluid inflow-downflow suppresses the supposedly deeper hot recharge, thereby, lowering the output of production wells. At times, this causes difficulties in initiating discharge of wells.

2.5 Cool and Acidic Influx

Production wells with acidic discharge are found in SNGPF. PNOC-EDC internal standards sets pH 4.0 as a cut-off limit for fluid acidity. Less than this the corrosive effect on metallic surface equipment is deemed significant. Ten wells in Palinpinon were considered acidic. Five of these have natural acid zones while the rest had their initially neutral pH lowered when exploitation induced inflows of acidic waters. Seastres, et al. (1995) proposed that these acidic intrusions originated from perched aquifers at the shallow levels of the reservoir within the vicinity of the Lagunao and Nasuji domes. They postulated that the acid waters formed through the mixing of shallow groundwaters and the parent reservoir fluid upwelling south of Lagunao. The mixing caused oxidation of H_2S contained in the parent fluid and formed SO_4 rich waters.

2.4 Mineral Deposition

When the geothermal brine becomes oversaturated with respect to a component mineral, deposition often occurs. Minerals commonly deposited in the wellbore and formation are calcite ($CaCO_3$), anhydrite ($CaSO_4$) and silica (SiO_2). The first two usually form in production wells as bore blockages, while the third forms in RI wells. Mineral depositions, either in the formation or in the form of a bore blockage, directly affect the output or capacity of a well. The former causes permeability damage while the latter restricts the full flow of fluid during discharge.

<u>Silica</u>

The removal or separation of steam from the geothermal brine concentrates the silica quartz in the residual water. If the new silica concentration exceeds that of the amorphous silica saturation, scaling will occur (Truesdell, et al., 1984). The rate at which this mineral deposits is dictated by temperature, acidity and flow regime of the fluid.

In SNGPF, steam for power generation is separated at 0.68 MPaa leaving the residual water at 160°C and a silica saturation index (SSI) of about 1.10 at which silica is amorphous. Further cooling will cause precipitation, hence, deposition. As much as 50% decline in reinjection capacity has been monitored.

<u>Calcite</u>

Calcite or calcium carbonate ($CaCO_3$) is the reaction product of calcium and bicarbonates in geothermal fluids. Boiling or flashing concentrates the fluid causing calcite to deposit. This is why calcite blockages form within the vicinity of the flash point in the wellbore. However, calcite deposits do not form at higher temperatures.

<u>Anhydrite</u>

Anhydrite or calcium sulfate ($CaSO_4$) forms when calcium and sulfate waters in geothermal fluids mix. Wellbore blockages of this kind normally occur just below the points of acid-sulfate inflow.

3.0 RESERVOIR MANAGEMENT STRATEGIES

Reservoir management includes intensive monitoring of the chemical and physical changes in the reservoir as it undergoes exploitation through regular downhole surveys, well measurements and fluid sampling. Based on the interpretations of the results of field monitoring, long term, short term or strategies and policies were formulated for the optimized and sustained utilization of the resource.

3.1 Long Term

<u>Shift of Injection Farther Away From the Production Sector</u>

The initial RI wells in P1PF were drilled close to the production area (e.g., the nearest well, OK-12RD, is only ~300 m away from the production well PN-17D at the permeable zone). Also, geologic structures connect specific RI and production wells, thus providing channels for the reinjected fluids to return to the production sector and affect their steam production capacities. Utilization of these RI wells further risks other production wells. Thus in 1986, it was recognized that the bulk of RI load should be shifted farther away from Puhagan especially when the load increases. However, the implementation of such strategy was realized only in October 1989 after the completion of the RI lines to the Malaunay and Ticala areas. OK-3R in Malaunay and N-3R in Ticala were the wells initially utilized and additional wells were drilled later and utilized since then. The shift in RI load had temporarily relieved the production wells from RI fluid returns, thus improving the total field steam capability as observed starting 1991 (Figure 6). However, with the increase in production due to the increase in load after the Panay-Negros (inter-island) power grid interconnection, reinjection of waste brine also increased. Reinjection fluid continued to intrude back to the production sector since some RI wells, like TC-3R, had a strong permeability connection with some production wells through the Ticala Fault.

In 1996, it was decided to further intensify this strategy by totally eliminating injection into the Puhagan RI wells and allow further expansion of the shallow two-phase zone of the reservoir. In July 1997, PN-5RD, the last Puhagan RI well being utilized, was de-commissioned. The immediate reservoir response then was the field wide increase in enthalpy, indicating an affirmative response to the strategy. This however, was not fully realized, since, in August of that same year, PGPP1 reduced load, operating only two of the three 37.5 MWe turbine-generator units. The load reduction entailed significant reduction of mass extraction by ~250 kg/s and allowed reservoir pressure to stabilize, countering the desired two-phase expansion. This strategy will hopefully be pursued once PGPP1 will be back to three-unit operation.

Deep Injection and Top Zone Plugging

After the commissioning of TC-2RD in late 1991, it was observed that the pH of south-easterly wells PN-20D and PN-22D improved from 2-3 to near-neutral levels of 4-5. This indicated dilution of the acid feed by some recharge. Intensive monitoring showed that these wells received fluids coming from the Odlumon Fault, hence, from TC-2RD. Remarkably, there were no associated thermal deteriorations in the wells suggesting sufficient reheating of the returning fluids. Thus, PNOC-EDC pursued the strategy of promoting deep injection. In 1995, TC-4RD was commissioned to further inject into Odlumon. The results confirmed the positive effects of injecting into this structure. In 1997, TC-3R, which was previously draining into the Ticala Fault, was re-drilled and re-directed to intersect the Odlumon Fault.

Part of this major strategy was the plugging of the communicative shallow zones of carefully selected reinjection and production wells. Some reinjection and production wells in SNGPF have highly communicative zones at shallow levels through which reinjection fluids exit and enter. Sealing-off these zones, therefore, will cut-off this communication and promote deep channeling of fluids and thereby effecting sufficient reheating.

Reinjection wells PN-3RD and PN-2RD in Palinpinon-1 underwent top zone plugging operations using liquid loss circulation material (LCM) in 1994 and 1995, respectively. PN-3RD was evaluated to be successful (Hermozo, 1995), however, that of PN-2RD was not fully evaluated although its measured capacity has reduced by ~50%.

In June 1996, the first attempt to apply this technology to a production well, was conducted in OK-7. Unfortunately, the plugging operation failed and the commercial production of the well was not restored.

3.2 Short Term

Drilling and Prioritized Utilization of High Enthalpy Wells

The problem of reinjection fluid returns was partly addressed by reducing the waste brine through the utilization of high enthalpy production wells, especially those drilled near the upflow area southwest of Puhagan. This strategy improved the total steam supply for the power station but was not enough for sustained production at full-load operation. Thus, additional production wells were drilled to tap the shallow two-phase zone. This strategy improved the steam supply only slightly since the wells were relatively tight and were poor producers. Additional wells LG-3D and LG-4D at the Lagunao area were then drilled towards the postulated upflow to further improve the steam supply and at the same time reduce the waste brine flow. These two wells were able to produce from a highly two-phase zone.

3.3 Immediate

Mechanical Work-over and Acidizing

For wells with blockages in their wellbores (calcite or anhydrite), the immediate action would be to drill-out or clear the obstructions using a drilling rig. In case of casing breaks and collapse, milling operations are conducted and the damaged casing is relined with a smaller diameter one. However, relining reduces the capacity of the wells.

Whenever deposition extends to the surrounding formation, acidizing becomes necessary to dissolve the formation deposits. This relatively recent technology was proven successful in RI wells, and to a lesser degree in production wells. Acid stimulation or acidizing was adopted by PNOC-EDC starting 1993. This technology is being applied to wells with formation permeability damaged either by drilling mud (skin) or by mineral deposition, usually silica in reinjection wells. Most of the wells that have been selected for acidizing were reinjection wells (Malate, 1997).

Acid stimulation jobs are normally conducted using a drilling rig where the acid solutions are injected through open-ended drill pipes. Without the drilling rig, the acid solutions could also be injected using a high delivery pressure pump and coiled tubing unit combination such. Malate, et al. (1997), reported the improvements in wells after acidizing.

4.0 THE EXPERIENCE AS APPLIED TO P2PF

PNOC-EDC's 15-year experience of continuous exploitation in P1PF, particularly in the area of near-field injection, greatly influenced the siting of RI wells in P2PF. RI wells in Nasuji and Sogongon sectors were, therefore, drilled to the north as far away as possible to minimize returns and attain reheating of the reinjected fluid. Pressure drawdown and RI breakthrough were the major reservoir processes affecting steam production during the first 5 years of operation in the P2PF area. The pre-exploitation reservoir pressure was already drawn down by 1.5 MPag as a result of P1PF exploitation, evident in OK-6 drilled at the inferred upflow region. With the commissioning of the P2PF power plants, this was further drawn down towards the stabilized P1PF level at the end of 1998. The pressure has apparently stabilized at about 6.5 MPag since 1998.

Consequently, reservoir temperatures at the upflow region declined by as much as 10°C, as evidenced in OK-6 and SG-2, but remained almost unchanged elsewhere in the production sector, implying that temperatures in this part of the of the reservoir were not yet affected by pressure drawdown. The overall steam supply declined due to pressure drawdown with Sogongon module registering the highest decline rate of ~14 TPH/year. The steam short-fall in the

Balasbalas module also imposed operational constraints. Drilling of additional wells in the sector has already been planned.

Reinjection mass front indicated by the progressive increase in reservoir chloride concentrations, along with the decrease in total CO_2 discharged, was observed in the wells that intersect the communicative fault structures, namely, Nasuji, Nasulo and Sogongon. These faults channel the RI fluids coming mostly from SG-1RD, SG-2RD and SG-3RD and, to a lesser extent, from NJ-1RD, back to the production sector. No thermal declines were observed based on the relatively stable silica temperatures. Slight output declines, however, were noted in the affected wells as a result of decreased discharge enthalpy caused by the increase in the reservoir's liquid saturation. Intrusions of cooler fluids at the shallow zones, inherent in most Nasuji wells, also aggravated the problem. Drilling and utilization of NJ-2RD since March 1997 has enabled the reduction of RI load in the Sogongon RI sector particularly in SG-3RD which has been shut since August 1997.

With this situation in P2PF, appropriate reservoir management interventions, reminiscent of P1PF, were carried out to ensure adequate steam supply to the plants. Optimized production through the utilization of high enthalpy wells did not only address pressure drawdown but also effectively reduced the brine loads to Nasuji and Sogongon sectors. The subsequent shifting of the brine load from SG-3RD to NJ-2RD effectively minimized the return of reinjected fluids. Moreover, discharge settings of the Nasuji production wells were fine-tuned to control fluid intrusions that may otherwise pose operational limitations.

Similar strategies of high enthalpy well utilization were adopted to address pressure drawdown and reduce brine loading (i.e. RI returns) to the Nasuji and Sogongon RI sectors.

5.0 SUMMARY AND CONCLUSIONS

The intensive monitoring of the P1PF reservoir response over the first 15 years of exploitation, was able to identify four major processes, namely, pressure drawdown, rapid reinjection fluid returns, cool, acidic fluid intrusions and mineral depositions. These reservoir processes which have an adverse impact on the aim of sustaining adequate supply of steam to the power plant, were addressed by shifting injection away from the production area, deep injection and drilling/prioritizing utilization of high enthalpy wells. Other mitigating measures such as, mechanical work-over, acid stimulation of carefully selected RI and production wells and controlling the operating conditions of wells with intrusions. These have greatly improved steam production from the field.

Undoubtedly, PNOC-EDC's success in formulating and implementing reservoir management strategies has effectively sustained the use of the Palinpinon geothermal resource for steam production to the power plants.

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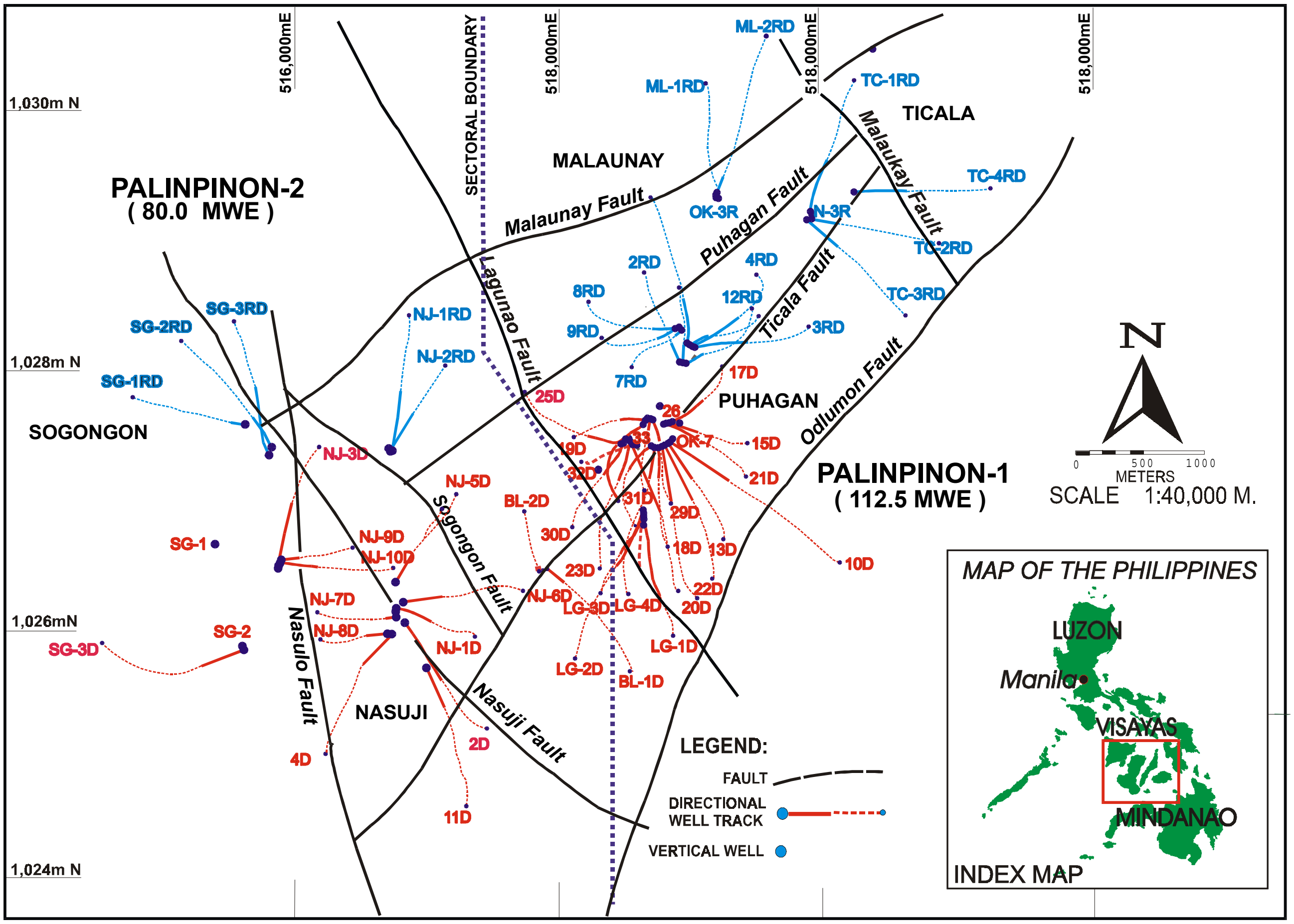

Figure 1. Location and structural maps of the Southern Negros Geothermal Production Field.

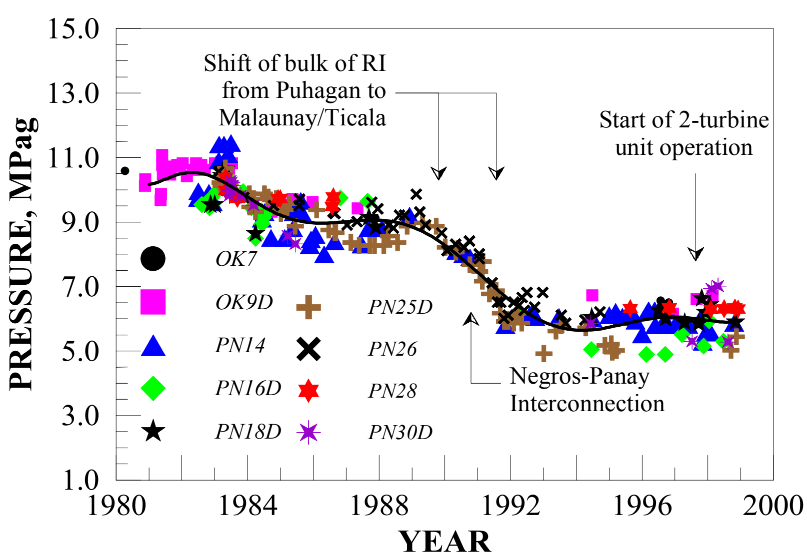

Figure 2. P1PF pressure trend reckoned at 1000 m below mean sea level.

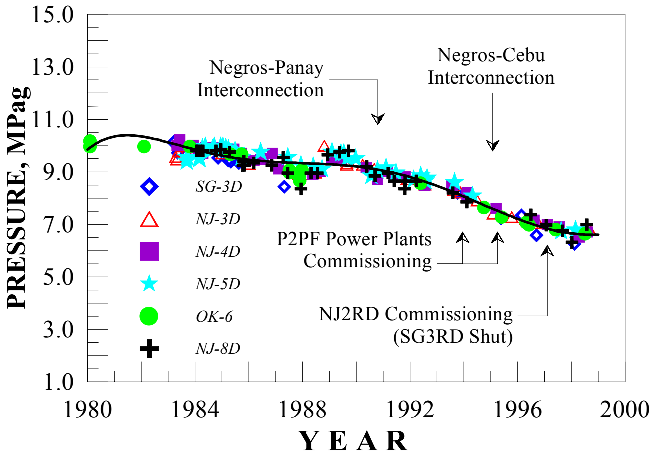

Figure 3. P2PF Pressure trend reckoned at 1000 m below mean sea level.

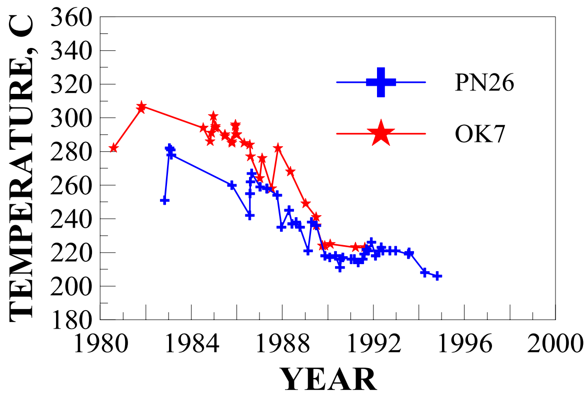

Figure 4. Temperatures of P1PF wells severely affected by reinjection returns. Depth: 844 m below sea level.

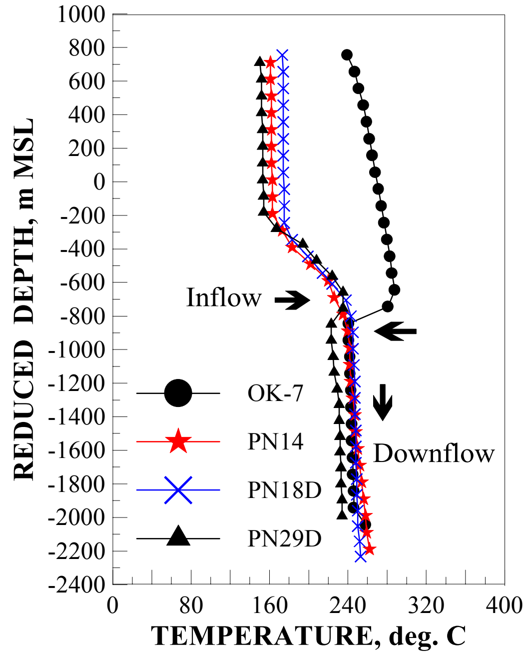

Figure 5. Temperature profiles of P1PF wells with inflow-downflow.

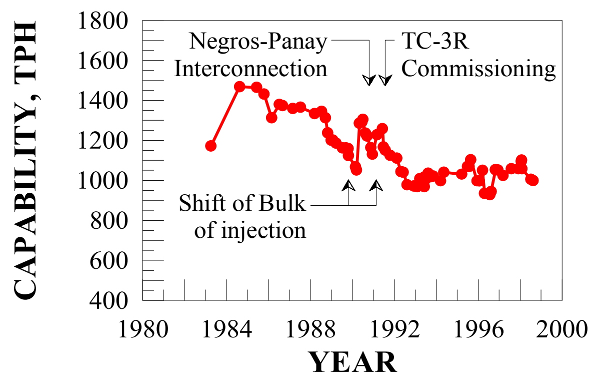

Figure 6. P1PF steam capability trend at wellhead pressure not less than separation pressure of 0.68 MPaa. Increase of capability in 1990 reflected additional steam from newly drilled wells, and output recoveries of worked over wells.