

INITIAL RESPONSE TO EXPLOITATION OF THE MT. APO GEOTHERMAL RESERVOIR, COTABATO, PHILIPPINES

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Abstract

Large scale exploitation of the Mt. Apo geothermal reservoir commenced after the commissioning of the Fluid Collection and Disposal System (FCDS) of Mindanao 1 Geothermal Production Field (M1GPF) in October 1996. The first 52 MWe power plant was commissioned in December 1996 and baseload operation started in March 1997. The Mindanao 1 is utilizing nine production wells located in the outflow sector of geothermal field. The separated brine and steam condensate from the power plant are reinjected to five reinjection wells. A second 50 MWe power plant, scheduled for commissioning by mid-1999, will utilize the production wells drilled in the Mindanao 2 Production Field.

The first year of continuous exploitation resulted to a steady rise in the field's average enthalpy of M1GPF. The most noticeable increases were on wells APO-ID and SP-4D. Four production wells, SK-2D, SK-3D, SK-5D and SK-6D, exhibited increases in their mass flows. However, the steam well SK-ID showed a decreasing mass flow. APO-ID and SP-4D experienced calcite blockage in their liners after prolonged commercial operation. This resulted to a substantial decrease in their mass flows. The decline in the mass flows of the three wells, however, was offset by a corresponding increase in the mass flow of four other production wells. In the reinjection sector pressurization was observed in the Kullay sector.

At this present stage, the reservoir responds distinctively to exploitation relying largely on the location of the feed zones of the wells in the production field.

1.0 Introduction

The Mt. Apo Geothermal Field with a known productive area of approximately 8.4 sq. km. is situated in the southwestern part of the island of Mindanao, approximately 700 kilometers southeast of Manila (Figure 1). It is the latest geothermal field commissioned by PNO Energy Development Corporation. Early geoscientific exploration in the field began in 1983. Following the discovery of a high temperature resource in this area, two deep exploratory wells were drilled in 1987 and were subsequently tested in 1987 and 1988. Development of the field commenced in 1992 with the drilling of reinjection and production wells. To date, 27 wells have already been completed.

The commercial exploitation of the Mt. Apo geothermal reservoir started in March 1997 with the commissioning of the 52 MWe condensing turbine. By mid-1999 an additional 50 MWe double flash unit power plant is set for commissioning which will increase the total installed capacity of the field to 102 MWe.

The objective of this paper is to develop a production model based on the response of the reservoir to exploitation. The resulting model would be a tool in formulating strategies for the proper management of the steam field.

2.0 The Natural State

The Mt. Apo geothermal field typifies an andesitic volcanic-hosted system featuring a high relief topography with an elevation of up to 2900 m above sea level. The geothermal field features three major structural features

namely the Sandawa Collapse in the Sandawa sector, the Marbel Fault Zone in the Marbel Corridor, and the Matingao Collapse located in the Matingao Block. These major structures are believed to influence the hydrological activity of the system (Figure 2).

The heat source is postulated to be beneath the Sandawa Collapse. The upflowing fluids in this sector have temperatures greater than 300°C. Overlying these upflowing fluids is a two-phase zone. There exists a steam zone at shallow levels beneath the Sandawa Collapse that extends above the outflowing fluids in the Marbel Corridor.

The outflow is towards the northwest where the various NW-SE trending faults in the Marbel Comdor serve as the conduits of the thermal fluids. It is characterized by relatively lower temperatures, liquid discharge enthalpies, and temperature reversals at depth. The first production field is situated in the Marbel Corridor.

East of the Marbel Comdor is the cold Matingao Block. The fluid and rock properties in this sector are characterized by even lower temperatures (<220°C) than in Marbel Comdor. Five reinjection wells were drilled in this sector. The fluids are believed to be diverted towards the north upon encountering an impermeable sector in the Matingao Block. They then discharged to the surface through the chloride springs of Imba, Marbel and Sisiman.

The topography of the field suggests that recharge comes from the surrounding areas of high elevation. Meteoric waters, together with the descending outflowing fluids, serve as the deep recharge of the system.

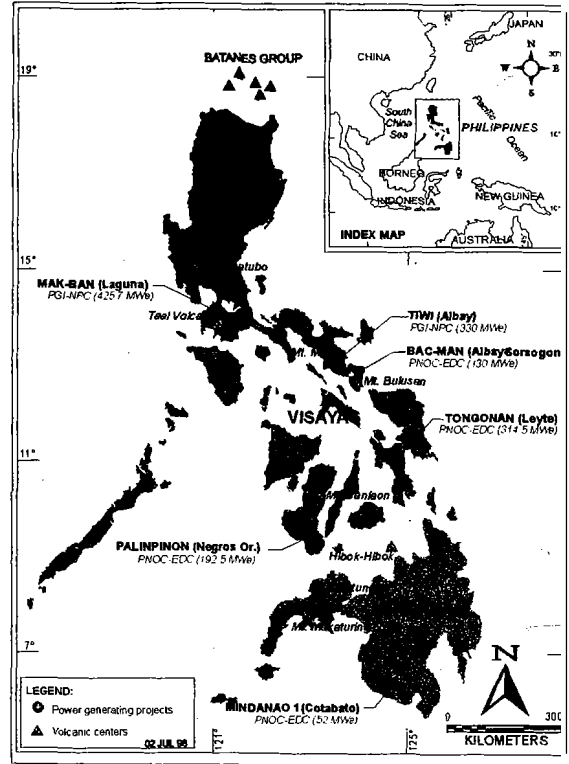


Figure 1. The Philippine geothermal areas.

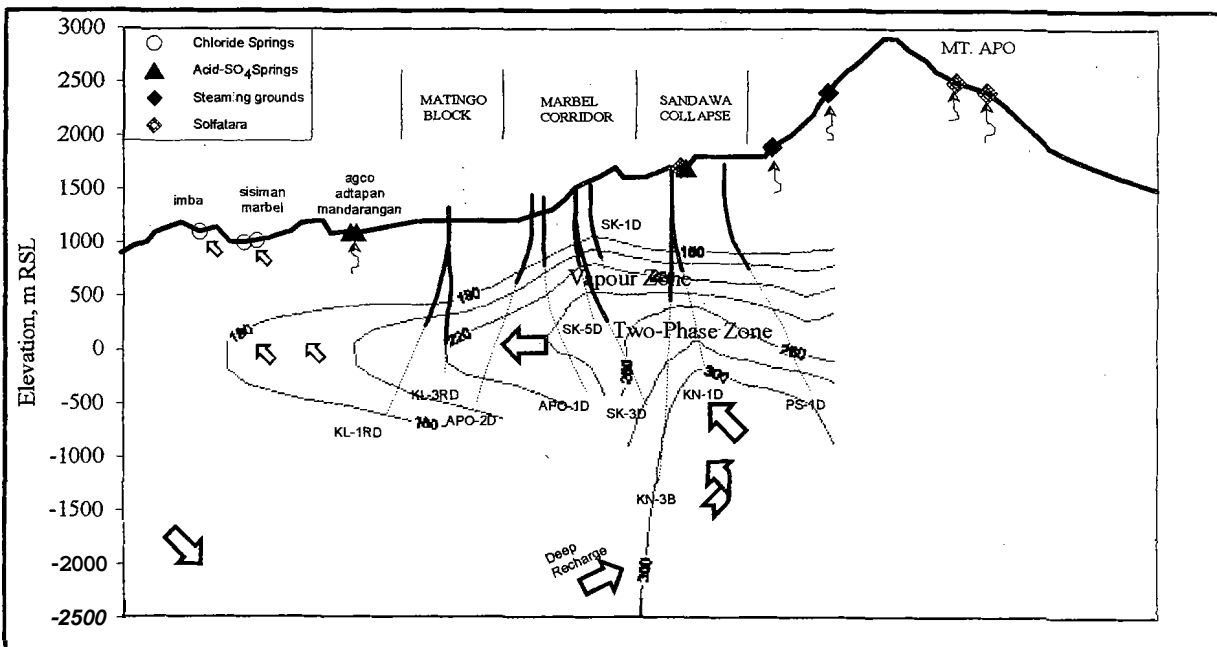


Figure 2. The hydrological model of the Mt. Apo geothermal system.

3.0 Baseline Production Data

PNOC-EDC is developing the Mt. Apo geothermal field in two stages. The first stage, commissioned in early 1997, was the installation of the 52 MWe power plant using the production wells drilled in the Marbel Comdor. This production field is referred as the Mindanao 1 Geothermal Production Field (M1GPF). By mid-1999, the second production field will be commissioned with an installed capacity of **50 MWe**. The steam for the second production stage will come from six wells in the Sandawa sector, two wells in the outflow sector (Marbel Comdor), and steam from the secondary flash of brine from MIGPF wells.

The MIGPF is utilizing nine production wells with a pre-exploitation capacity of 53.5 MWe at the wellhead. The nine wells were drilled between 1992 and 1994 except for APO-ID which was drilled in 1987. Two production wells, SK-2D and SK-3D, were perforated with the objective of tapping the steam zone. These two wells, as well as SK-4_{BH}, and SK-6D were acidized to further increase their capacities. The perforation and acidizing activities were conducted in 1995. All these wells were connected to the MIGPF Fluid Collection and Disposal System (FCDS) - a baseload station continuously supplying steam to a single 52 MWe turbine-generator unit.

Pad A wells (APO-ID, APO-3D and SP-4D) have large mass flows and have liquid-discharge enthalpies. SK-1D is a steam well and is the biggest producer in terms of power output. Other production wells have moderate mass flows with low to moderate enthalpies (Table 1).

Well	Design OWHP (MPag)	Mass Flow (kg/s)	Enthalpy (kJ/kg)	Water Flow (kg/s)	steam Flow (kg/s)	Power (MWe)
APO-1D	0.80	72.0	1083	58.9	13.1	6.4
APO-3D	0.79	66.4	1071	54.7	11.7	5.7
SP-4D	0.97	71.0	1080	58.1	12.9	6.2
Pad E upper Wells						
SK-1D	1.03	20.5	2782		20.5	10.0
SK-2D	1.02	44.2	1127	35.2	9.0	4.4
SK-4 _{BH}	1.02	37.0	1081	30.3	6.7	3.3
Pad E lower Wells						
SK-3D	1.09	37.3	1422	24.3	13.0	6.3
SK-5D	1.03	31.6	1260	23.1	8.5	4.1
SK-6D	1.13	47.3	1355	32.4	14.9	7.2
Total/ Ave		427.3	1239	110.3	317.0	53.5

Table 1. Baseline bore outputs of Mindanao 1 production wells.

4.0 Production Wells Utilization

The Mindanao 1 FCDS was commissioned on October 7, 1996. A series of performance tests on the system followed. During this period, medium to high enthalpy wells were utilized due to reinjection well constraints. The power plant started to accept steam on December 16, 1996. Most of the production wells were put on-line primarily to conduct additional performance tests for both the plant and the FCDS. Figure 3 shows the production well utilization since the start of FCDS.

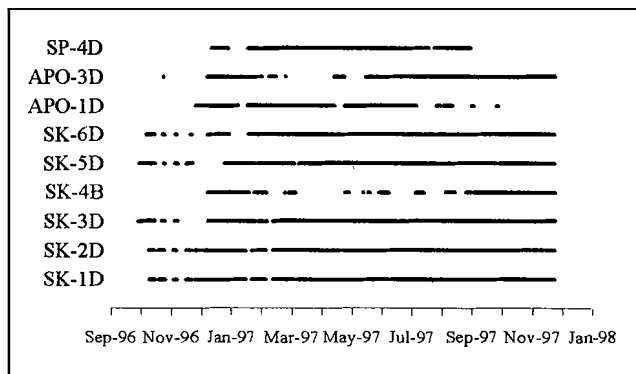


Figure 3. Production wells utilization of Mindanao 1 field.

The well utilization strategy initially adopted was to limit the use of watery wells in Pad A, which are proximate to the reinjection sector.

The objective was to minimize the amount of waste brine to be reinjected because of concerns of rapid reinjection returns. However, well SK-4_{BH} encountered choking problems upon its cut-in to the FCDS. This compelled the utilization of APO-1D and SP-4D in Pad A. By mid-1997, APO-ID and SP-4D exhibited declining mass flows causing the full utilization of APO-3D to meet the **steam** requirements of the power plant.

Well SP-4D ceased to discharge by September 1997. Fortunately, SK-4_{BH} was successfully put back in service after the choking problem was checked.

5.0 Steam Supply and Generation

The power plant was unveiled and inaugurated on December 14, 1996 and was fully synchronized to the Mindanao grid on December 23, 19%. From day 1 until November 25, 1997, gross generation power reached 264,672.60 MW-hr. This is equal to 2,757.6 metric tons of steam supply. The highest average plant load attained was 50.23 MWe. However, the gross baseload was limited to around 49 MWe because only the 69 KVa line was commissioned by the National Power Corporation (NPC).

6.0 Mass Extraction and Injection

From an initial mass extraction of 234.2 metric tons during the FCDS commissioning and power plant synchronization/testing, a total of 9,317.7 metric tons of mass have been extracted as of November 25, 1997. This is equivalent to 12,228.5TJ of heat extracted.

Individually, SP-4D is the biggest producer followed by SK-2D and APO-1D.

Mass extraction was biggest in the APO-ID and SP-4D area. The two wells, which intersected the Marbel Fault Zone, had a total extracted mass of 1,976.8 metric tons.

The **total** mass injected is 6,552.6 metric tons. Well SK-2D is the biggest contributor of injected fluids as of November 25, 1997. Before SP-4D ceased to discharge, the well was the biggest contributor of injected brine.

7.0 Mass Flow and Enthalpy Trends

There has been a steady rise in the field's average enthalpy as shown in Figure 4. There was initially a gradual increase in trend in the total mass flow relative to the baseline as depicted by the flow tests conducted in early 1997. The decreasing trend observed in the latter period was primarily due to the declining outputs of APO-ID, SP-4D and SK-1D.

The observed changes in the reservoir are not homogenous but rather vary distinctively for each production wells.

Pad A Wells

Three wells are spudded on Pad A. Wells APO-ID and SP-4D welltracks are generally towards the northeast. Both wells intersected the Marbel Fault Zone. APO-3D is directed towards the east. Figure 5 shows the mass flow and enthalpy trends of Pad A wells.

Wells APO-ID and SP-4D exhibited increasing enthalpy trends. Wellbore simulation studies on

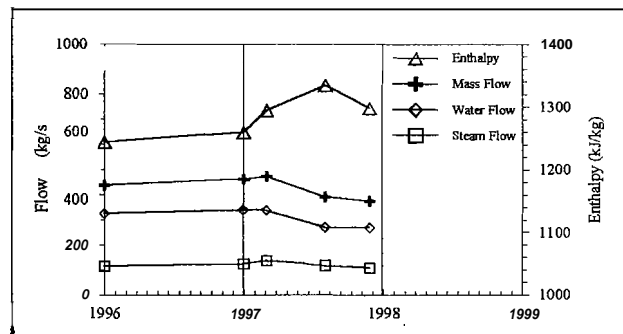


Figure 4. MIGPF fieldwide output trends

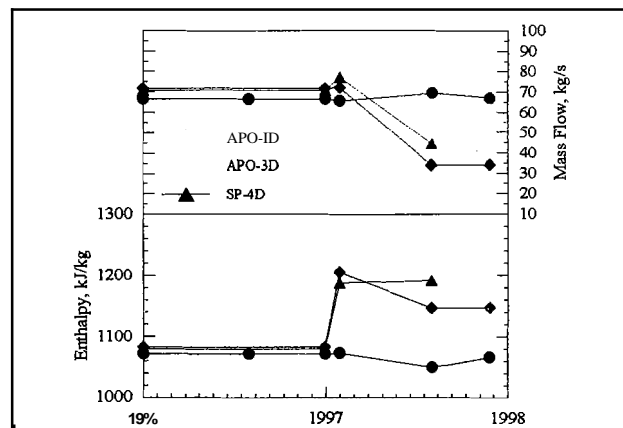


Figure 5. Bore output trends of Pad A wells

APO-ID suggest that the increase is associated with the shifting of its major contributing zone from the deepest low-enthalpy zones to the upper steam zones. Boiling in the wellbore of the low-enthalpy fluids as they ascend to the surface also contributed to the enthalpy rise. However, both wells exhibited significant mass flow decrease by mid-1997. This was primarily due to the calcite blockage tagged below the production casing shoes of both wells. The decrease in their mass flows significantly dropped the total steam availability of the field.

Well APO-3D was sparingly used during the initial production stage. Its mass flow and enthalpy remain stable since the well was put into service in mid-1997.

Pad E upper Wells

Wells in Pad E_{UPPER} were drilled in different directions. SK-ID, the shallowest well, was drilled towards the southeast. SK-2D was directed towards the south while SK-4_{BH} was drilled vertically. The bore output trends of Pad E_{UPPER} wells are shown in Figure 6.

Well SK-ID, a **steam** well, has been in constant use since the start of commissioning. Its enthalpy remained stable relative to the baseline but there was an observed decline on its **mass** flow. Chemical tracer flow measurements indicated a drop from 20.5 kg/s to 15.0 kg/s. The results of chemical tracer tests were confirmed by a decrease in blow-off opening. The observed drop in mass flow could be attributed to drawdown due to the continuous extraction in this sector of the field.

The enthalpy of SK-2D is slightly increasing relative to the baseline. The enthalpy increase can be attributed to feedzone interplay wherein the two-phase zone dominates the discharge. The increase can also be due to the inflow of hotter **fluids** as suggested by the significant increase of the well's mass flow. Note that this well was perforated and acidized in 1995.

SK-4_{BH} also registered an increase in enthalpy from 1081 kJ/kg to 1210 kJ/kg. The enthalpy **rise** could be most likely attributed to boiling inside the wellbore since the well has no two-phase or **steam** feed zone.

Pad E lower Wells

Three directional wells were drilled from Pad E_{LOWER}. SK-3D was drilled towards the east, SK-5D towards the northeast, and SK-6D to the southeast. Both SK-3D and SK-5D intersected the Kanlas North Fault and Marbel Fault Zone. Pad E_{LOWER} wells' output trends are illustrated in Figure 7.

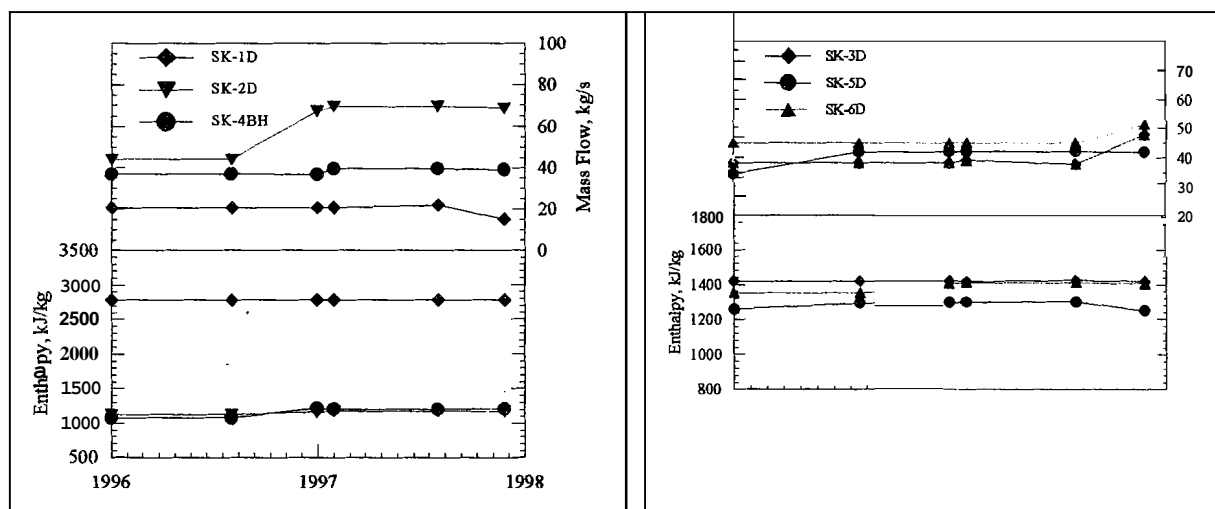


Figure 6. Bore output trends of Pad E_{UPPER} wells.

Figure 7. Bore output trends of Pad E_{LOWER} wells,

The three wells exhibited stable enthalpy trends since the start of exploitation. Their mass flows, meanwhile, depicted increasing trends relative to their baseline values. The increase in **mass** flow of SK-5D was observed even before the FCDS commissioning. The increases **can be** attributed to the acidizing job conducted in this sector of the field. Note that SK-3D and SK-6D were acidized in 1995. The chemical stimulation may have further opened up additional fractures after their pre-exploitation flow tests and during exploitation stage. The associated fracturing caused the inflow of hot and saline fluids with similar characteristics **as** that of the original fluids of this sector.

8.0 Reinjection Wells

Four reinjection wells were drilled to accommodate the waste brine from the production wells, while one reinjection well was dedicated for the reinjection of blowdown fluids from the power plant cooling tower. The reinjection wells were drilled in the two sectors of the Matingao Block. Wells KL-1RD, **KL-2RD**, and KL-3RD were drilled in Kullay sector while wells MT-1RD and MT-2RD were drilled in the Matingao sector. The baseline capacity of these wells is 606 kg/s. Table 2 compares baseline and actual measured capacities of the reinjection wells.

Latest flow measurements reveal significant drop in the capacities of KL-1RD and KL-2RD relative to their baseline values. Downhole pressure surveys conducted in well KL-2RD at shut condition measured a maximum pressure increase of 1.0 MPag at the well's most permeable zone. These observed changes in the Kullay reinjection sector may indicate that the maximum capacity has been reached.

Flow measurements on MT-1RD showed a significant increase of its capacity. From a baseline value of 82 **kg/s**, the well can now accommodate 141.0 **kg/s** of waste fluid. Well MT-2RD was not fully utilized due to its proximity to the production sector. However, at 1" opening and operating wellhead pressure of 0.47 W ag, well MT-2RD **can** accept 69 kg/s of waste brine.

9.0 Chemical Response

The observed chemical changes in the reservoir due to exploitation vary distinctively for each individual well.

Two production wells APO-1D and SP-4D experienced calcite blockage after prolonged commercial discharge. Calcite deposits formed when aquifer fluids undergo boiling during ascent to the surface. This is evident from the formation of the deposits above the 'flashpoint' level of the wells

Although these wells were found to have fluids with high calcite saturation at the aquifer, calcite did not form during the extended discharge tests before the commercial operation of the power plant.

The onset of calcite scale formation in both wells was marked by changes in the chemistries of the wells' fluids relative to the established baseline. Decreasing trend in chloride concentration coupled with increase in CO₂ in the discharge were observed. The apparent dilution resulted from the ingress of partially condensed **steam** at the shallower feedzones in both wells. The formation of calcite deposits is directly linked to this process. Higher discharge enthalpies caused the fraction of 'flashed' **steam** to increase. This in turn increases the calcite supersaturation as the fluid boils.

	Baseline Capacity		Operating Capacity	
	WHP MPag	RI Flow kg/s	WHP MPag	RI Flow kg/s
Matingao Sector				
MT-1RD	1.15	82	0.61	141
MT-2RD	1.15	175	0.47	69
		257		210
Kullay Sector				
KL-1RD	1.42	133	0.95	53
KL-2RD	1.42	134	1.22	51
KL-3RD	1.42	82	1.00	73
Sub-total		349		177
Total		606		387

Table 2. Baseline and actual measured capacities of the reinjection wells. KL-3RD is being used as a cold reinjection well.

The fluid chemistry of SK-2D has stabilized. However, the higher values relative to the baseline chemical data reflect inflow of higher salinity fluids coming from the main upflow zone of the field. Chloride concentration in the discharge increased from a range of 3100-3500 mg/kg to ~4000mg/kg. Fluid temperatures based on silica geothermometer likewise increased from 240°C to ~250°C. It is likely that more fluid contributions are coming from the perforated zone in the well which conducts hotter fluids from the Sandawa sector through Sabpangon Fault.

Other production wells are showing stable chemistry and do not show significant variation with respect to the established baseline chemical data.

At present, no production wells are showing increasing chloride chemistries and thermal degradation which are evidences of reinjection returns. Chloride concentration of reinjection brine is about 5500 mg/kg. So far only two wells reflect increases in chloride concentrations. However, their water geothermometers indicate increasing temperatures suggesting that the injected fluids are not ingressing towards the production sector.

An increasing NCG trend was observed because wells with high NCG, particularly the SK- wells, were mostly on-line in the second half of 1997. These values of NCG's, however, are still within the baseline, and below the contractual limit of 1% w/w.

10.0 Initial Reservoir Response

After almost a year of extensive mass extraction of the field, the initial reservoir response varies distinctively and depends largely on the well locations in the field. The production wells can be grouped into sectors based on their similar discharge characteristics in relation to the depth of the feeding horizons. The production field can be grouped into the five sectors: Sector 1 (APO-1D and SP-4D); Sector 2 (APO-3D and SK-4_{BH}); Sector 3 (SK-3D, SK-5D and SK-6D); Sector 4 (SK-1D); and, Sector 5 (SK-2D).

A field representation is given in Table 3 to compare the baseline values and the present field scenario of each sector after a year of exploitation. The mass flow, enthalpy and the postulated response of each sector are presented.

Generally, there is an increasing trend in the field's average enthalpy as a result of exploitation. This is attributable to the enthalpy rise in Sectors 1, 2 and 5. The increases are primarily due to the domination of the steam and two-phase feed zones, boiling of the aquifer fluids as they ascend in the surface, and the inflow of more saline fluids as evinced in well SK-2D.

The mass flow increase in Sectors 3 and 5 was due to acid stimulation done in these two sectors of the field. This mass flow increase in wells in Sectors 3 and 5 offsets the decrease in the mass flow of wells in Sector 1 (APO-1D and SP-4D) and Sector 4 (SK-1D).

BASELINE H = 1239kJ/kg				
Sector 1 APO1D/ SP4D	Sector 2 APO3D/ SK4 _{BH}	Sector 3 SK3D, SK5D/SK6D	Sector 4 SK1D	Sector 5 SK2D
MF=143.0 H= 1082	MF=103.4 H=1075	MF=116.2 H=1351	MF=20.5 H=2782	MF=44.2 H=1127
↓				
INITIAL RESPONSE H = 1297kJ/kg				
Sector 1 APO1D/ SP4D	Sector 2 APO3D/ SK4 _{BH}	Sector 3 SK3D, SK5D/SK6D	Sector 4 SK1D	Sector 5 SK2D
M=78.6 H= 1172	MF=105.9 H=1119	MF=151.1 H=1366	MF=15.0 H=2779	MF=68.8 H=1171
Feed zone interplay	Wellbore Boiling??	Recharge??	Mass Drawdown	Recharge?

Table 3. Field representation of the reservoir. MF is in kg/s and H is in kJ/kg.

11.0 Conclusion

An initial production field model was generated based on the observed changes that best represent the reservoir response to commercial exploitation (Figure 8). Hotter and more saline fluids are ingressing towards Sector 5, and probably as well towards Sector 3. There may also be a natural recharge in the northeast towards Sector 3. The decrease in the mass flow of SK-1D in Sector 4 may suggest that the steam zone is not as extensive as initially projected.

The increase in acceptance of waste brine by the Matingao reinjection wells may indicate a good outflow in this reinjection sector. The impermeable barrier in the northwest caused the pressurization of the Kullay reinjection sector.

The extensive mass extraction did not somehow trigger rapid reinjection returns. Currently, there are no confirmed production wells showing any reinjection returns.

Finally, with about a year of commercial production, no adverse changes for both production and reinjection well capacities has been observed that would warrant changes in the management of the field.

With the production data available, it is still difficult to come up with a concrete Mt. Apo production model. The programmed downhole measurements during the power plant shutdown and the planned workover of APO-1D and SP-4D may further support the postulated response of the Mt. Apo reservoir to exploitation.

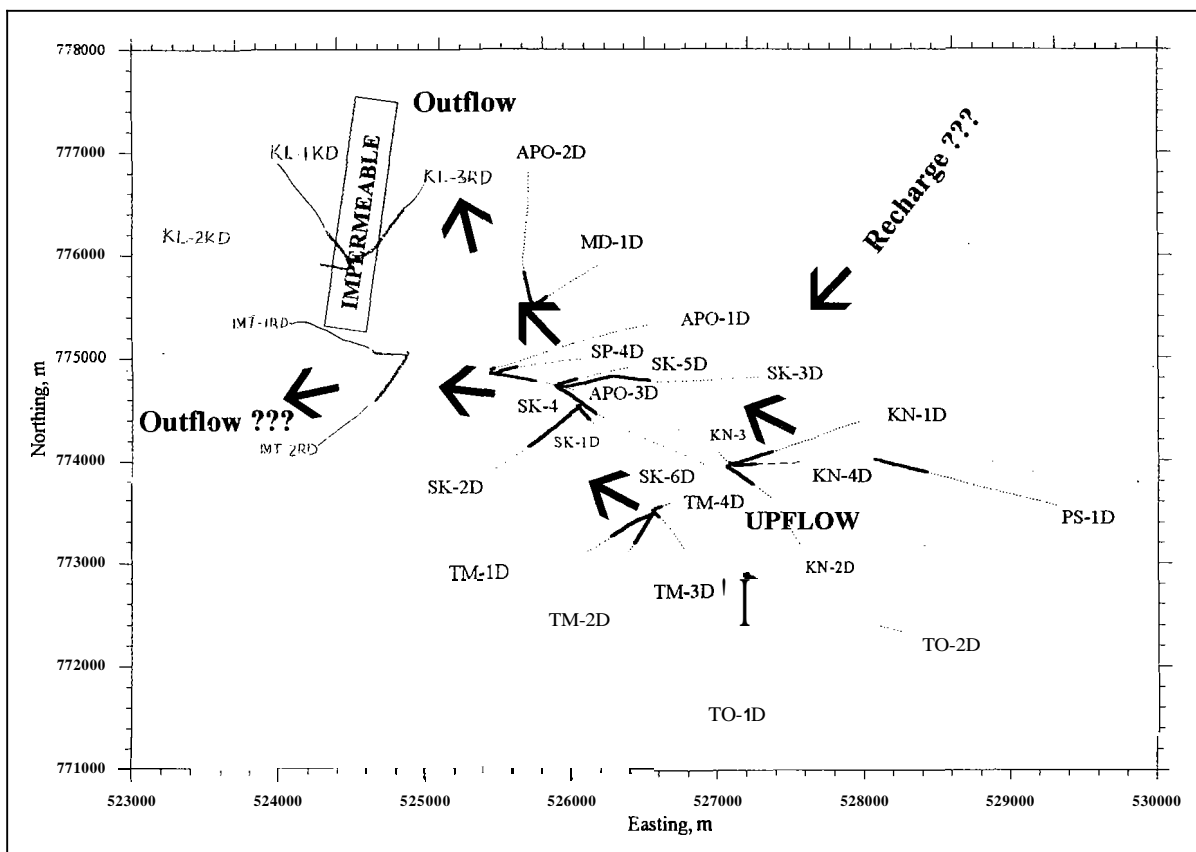


Figure 8. The Mt. Apo Geothermal Field initial production model.

12.0 References

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