

FIELD DEVELOPMENT STRATEGY IN THE EXPLOITATION OF MAHANAGDONG GEOTHERMAL RESOURCE, PHILIPPINES

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ABSTRACT

Results of drilling the first six deep exploratory wells in the Mahanagdong area, south of the existing Tongonan-1 geothermal field, revealed the presence of a commercially exploitable geothermal resource with temperatures of 260°-277°C at a depth of 2000-2100 m. Resistivity surveys delineated this separate geothermal system characterized by low resistivity values of 10-30 ohm-m and covering an area of 7.5-14 km². Volumetric stored heat estimates and numerical simulation of the area indicated a potential resource equivalent to 170MWe.

Full-scale delineation drilling of production and reinjection wells ensued based on an updated conceptual hydrological field model. Innovations on the casing and well design parameters were effected to achieve drilling targets and maximize steam production. Reinjection pads were sited at the peripheries of the postulated Mahanagdong production sector to provide additional pressure support and prevent rapid reinjection returns to the reservoir. Acidizing jobs were conducted on wells that were mud-damaged during drilling to improve their power outputs.

To date, nineteen production wells and ten reinjection wells have been drilled in the area with a total generating capacity of 209 MWe. This is sufficient for the start of the commercial operations of the installed 180 MWe capacity geothermal power plant by the year 1998.

1.0 INTRODUCTION

The Greater Tongonan Geothermal Field (GTGF) is located in the north central part of the Leyte Island, Philippines. It is within the Tertiary NW-SE trending calc-alkaline volcanic belt bisected by the Philippine Fault and occupies the northern part of the 1000-square kilometer Leyte Geothermal Province. The field consists of seven geographic sectors, namely; the Upper Mahiao, Mahao, Sambaloran, South Sambaloran, Malitbog, Mamban and Mahanagdong (Figure 1). Resistivity traversing conducted in 1974 delineated two low-resistivity anomalies consisting of the Mahiao-Sambaloran-Malitbog system and the Mahanagdong system (PNOC-EDC, 1990). The production field of the 112.5 MWe Tongonan-1 Power plant which has been operating since 1983, the installed 125 MWe power plant in Upper Maluao, and the 3 x 77 MWe power plants in Malitbog-South Sambaloran sector were developed within the Mahiao-Sambaloran-Malitbog resource while the 180 MWe modular power plants were completed in the Mahanagdong resource. Upon full commissioning of all the power plants by early 1998, GTGF will have a total power output equivalent to 708 MWe including the various optimization plants from each sector. These power plants were developed in response to the Philippine government's aggressive geothermal development program to meet the projected annual increase of 1.27% in electricity demand from 1991 to 2005. This paper will focus on the strategy applied by PNOC-EDC in the development of Mahanagdong as a distinct resource from the Mahiao-Sambaloran-Malitbog system and its implication to the development of other future geothermal prospects. The development of Mahanagdong is quite unique as the presence of acidic fluids, high Non-Condensable Gas (NCG) levels and multiple fracture zones necessitated the formulation of new drilling and production strategies to overcome the development constraints in this sector. Mahanagdong is separated into the A and B sectors where the 120 MWe and 60 MWe modular power plants are located, respectively (Figure 1). Additional 18 MWe of power will be produced by high-pressure steam separation (1.10 MPa) prior to main plant production at lower separation pressure (0.70 MPa).

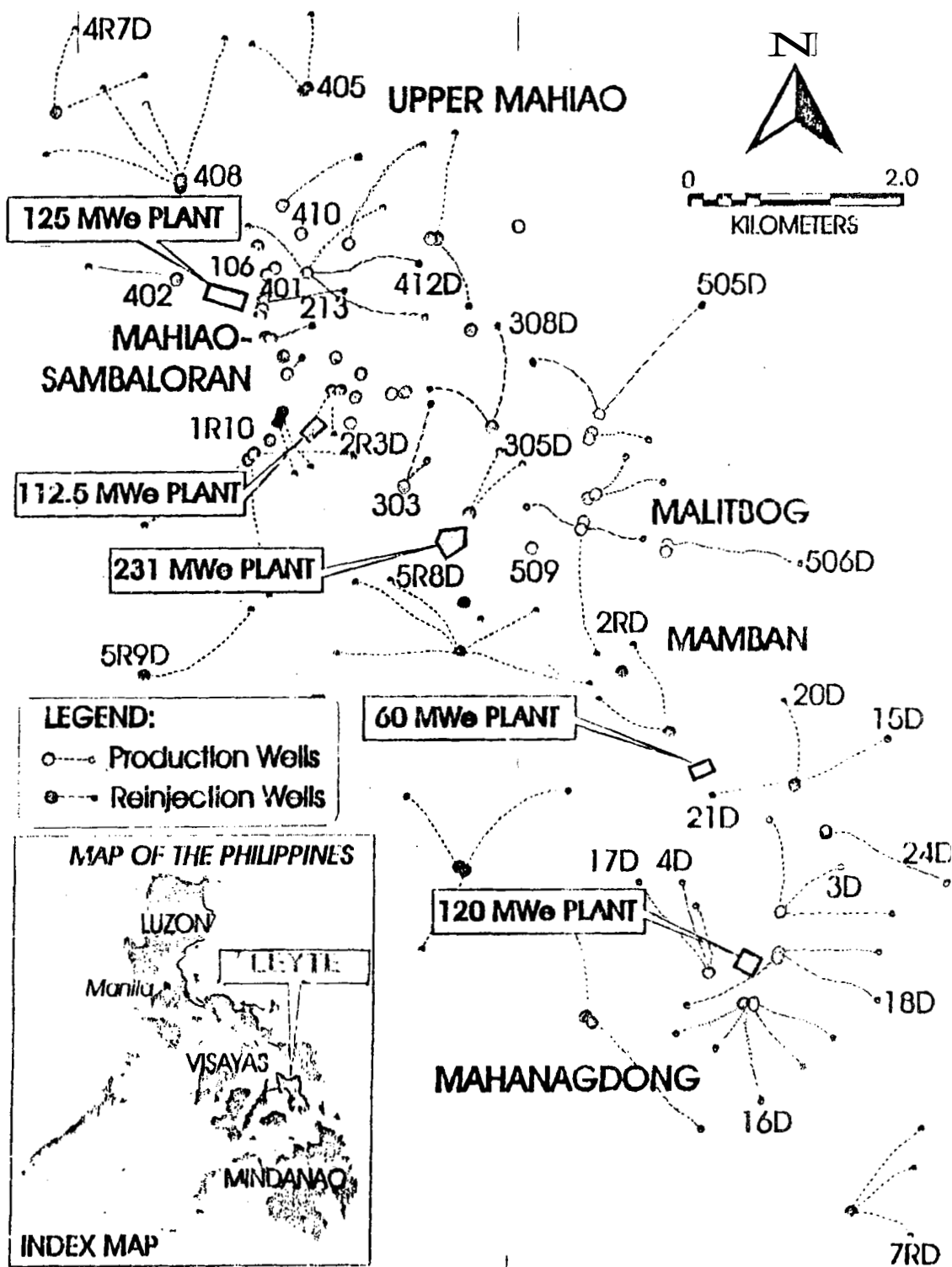


Figure 1: Sectoral Map of the Geothermal Tongonan Geothermal Field and their Corresponding Power Plants.

2.0 GEOSCIENTIFIC EXPLORATION SURVEYS AND SHALLOW EXPLORATORY WELL DRILLING

Initial surface geological exploration work in GTGF started in September 1972 on a reconnaissance level. In 1973, Kingston, Reynolds, Thom and Allardice (KRTA), in cooperation with the National Power Corporation (NPC), started shallow exploratory drilling **within** the Bao river valley on the basis of surface geology and distribution of surface manifestations. The unimpressive results of the first three shallow wells (i.e. <600m depth) drilled, e.g. TGE 1, TGE2, TGE3 (Figure 2), which encountered low chloride thermal waters and low temperature gradients initiated a Schlumberger resistivity survey which was conducted in November 1974 until October 1976 by KRTA and NPC personnel. The drilling of shallow exploratory wells, however, continued within the Bao Valley. Results from these wells (TGE 4, 5, 6, and 7) which encountered high chloride hydrothermal **fluids** indicated a possible source to the northeast, in the area of headwaters of the Malitbog, Banat-i, Hanipolong and Mamban creeks. TGE 8 and 9 were drilled to test this interpretation but yielded conductive thermal gradient of only 9°/100m which indicated the presence of an extinct geothermal activity in this sector based on abundant clays (KRTA, 1978).

The results of the Schlumberger surveys indicated two prominent areas of low apparent resistivity (PNOC-EDC, 1990), i.e. the **Mahiao-Sambaloran-Malitbog** anomaly and the Mahanagdong anomaly (Figure 3). In March 1976, well TGE-10 was drilled to test the **Mahiao-Sambaloran-Malitbog** anomaly. This well encountered a maximum measured temperature of 254°C but with poor permeability and hence, it did not sustain discharge. Both contained areas of current thermal activity and extensive areas of hydrothermally altered **ground**

3.0 DEEP EXPLORATORY WELL DRILLING

In 1976, a deep exploratory well (1950m depth), 401, was drilled and proved to be the discovery well (Figure 2) confirming the Mahiao-Malitbog-Sambaloran resource. This well encountered a maximum temperature of 321°C and a power potential of 9.9 MWe. Production drilling was subsequently conducted to provide steam for the 112.5 MWe Tongonan-1 power plant in 1980 and for the additional 125 MWe Upper Mahiao power plant and the 3 x 77 MWe Malitbog-So. Sambaloran power plant in 1994. For the Mahanagdong anomaly, the **first** well drilled in this sector, MG-1, proved to be a discovery well producing an estimated output of 11.5 MWe at 0.70 MPa separation pressure. MG-2D and MG-5D were drilled the succeeding years in Mahanagdong which yielded neutral to alkaline chloride brine with estimated temperatures of 260-277°C from chemical geothermometer and rated at 8.0 MWe and 5.0 MWe respectively.

After drilling three deep exploratory wells in Mahanagdong additional vertical electrical sounding surveys towards the south and southeast of Mahiao were conducted in October 1989 until February 1990 within the GTGF area. These were conducted simultaneous with semi-detailed surface geological mapping in order to **confirm** and redefine targets for **delineation** drilling. Additional geoscientific information gathered from surface and subsurface investigations **confirmed** the existence of a distinct geothermal resource in the Mahanagdong area, which is hydrologically separate to the **Mahiao-Sambaloran-Malitbog** system.

4.0 FIELD DEVELOPMENT STRATEGY

4.1 Delineation Well Drilling at Mahanagdong-A

From 1990-1992, three more deep wells were **drilled** in central Mahanagdong area. **MG-7D**, which was drilled southwest of MG-1 delineated the southwest **area** (Figure 2) **as** a good production sector based on its output of 13 MWe (i.e. at 0.70 MPa separation pressure). MG-3D on the other hand yielded **high** massflow **and high** enthalpy with predicted bottomhole temperatures of 324°C from heat up surveys and a measured power potential of 22 MWe. Well MG-3D **proved** that the northern and northeastern **part** of Mahanagdong **area** was still a potential expansion area for power development. **An** update on Mahanagdong's reserve estimates **based** on six **production** wells **drilled indicated** an output equivalent to

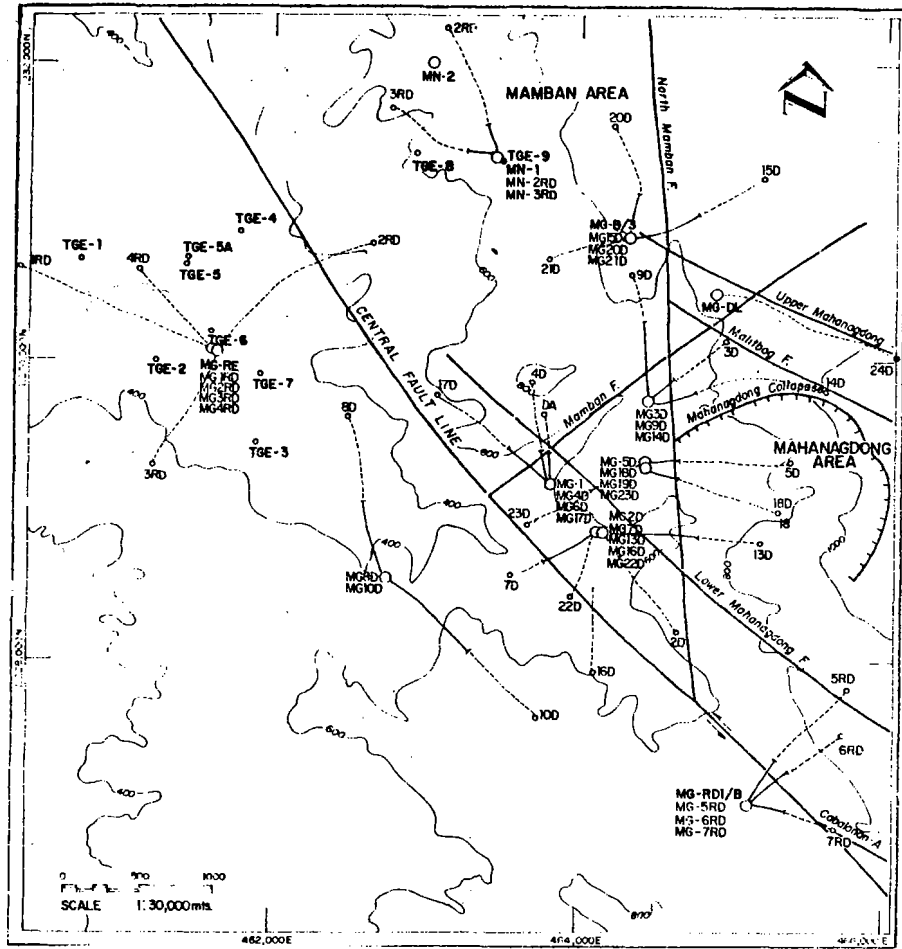


Figure 2: Location Map of Selected Shallow Thermal Gradient Wells (TGE's) in the Bao Valley and the Mahanagdong Sector and fault structures.

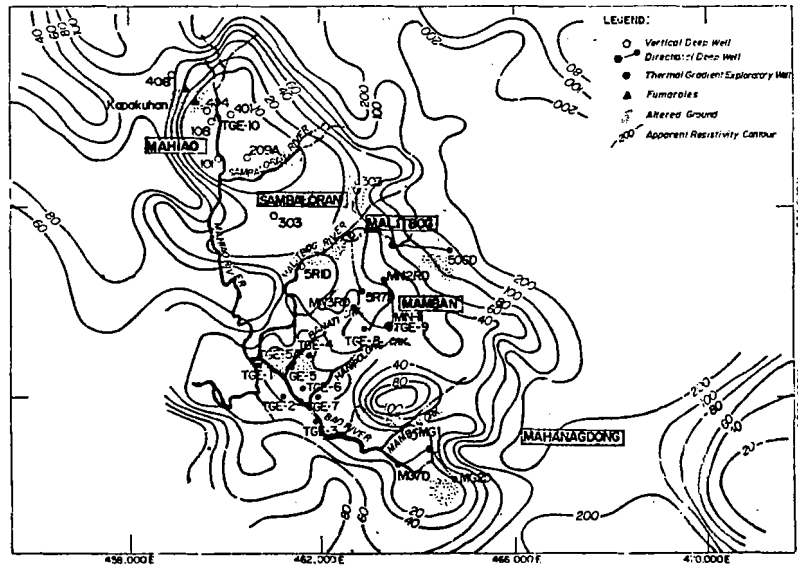


Figure 3: Schlumberger Resistivity Traverse Survey Results with $AB/2 = 500m$ in Greater Tongonan Geothermal Field

107-197 MWe for a 25-years plant life while Monte Carlo simulation **results** measured a **reserve** of about 170 MWe.

From late 1992 to early 1996, **full** scale drilling ensued where a total of additional 12 production **and** 8 reinjection wells were drilled for the 120 MWe Mahanagdong-A power plant. **Three** of the 12 production wells were non-commercial due to poor permeability while the other wells discharged acidic fluids. Fifty-percent or four out of the eight reinjection wells had very limited permeability.

4.2 Delineation Well Drilling at Mahanagdong-B

Production drilling in Mahanagdong B was **simultaneous** with Mahanagdong-A, which commenced early 1994 until early 1996. A total of 4 production wells were drilled from the north of the Mahanagdong-A where three of which yielded acidic fluids (**MG-20D, MG-15D, MG-21D**), while one well (MG-24D) which was drilled towards the east, yielded high gas fluids (>10% wt NCG). The acid fluids were characterized as having high Cl_{res} , high $SO4_{res}$ in the water and high H_2S in the vapour **phase** (Salonga et al., 1996).

A detailed reevaluation of chemical and physical characteristics of the wells drilled in Mahanagdong B was conducted to fully understand the chemical **trends** and identify other potential problematic areas. The assessment then **identified** three areas of geochemical constraints in the development of Mahanagdong B, namely: the inherently high **gas** contents of parent fluids in Mahanagdong B where wells MG-3D, MG-5D, MG-14D and MG-24D were **drilled** (Figure 4), the acid **area** where wells **MG-9D, MG-20D, MG-21D** and MG-15D were drilled and the inflow of cool fluids from the west towards **MG-4D/MG-17D** (Figure 5).

Following these **identified** development constraints, the strategy adopted to meet the **required** 60 MWe steam requirement was to maximize drilling targets towards the south-southwest from MG-DL pad where wells encountered low gas and neutral pH **fluids**. Moreover, these wells were designed to have **deep** production casing depths to case-off the postulated shallow high **gas** zone above the boiling parent fluids. Drilling of six production wells (MG26D, MG27D, MG28D, MG29D, MG30D and MG31D) **from** MG-DL pad subsequently yielded near-neutral pH geothermal fluids with low NCG level (≤ 2.5 wt%).

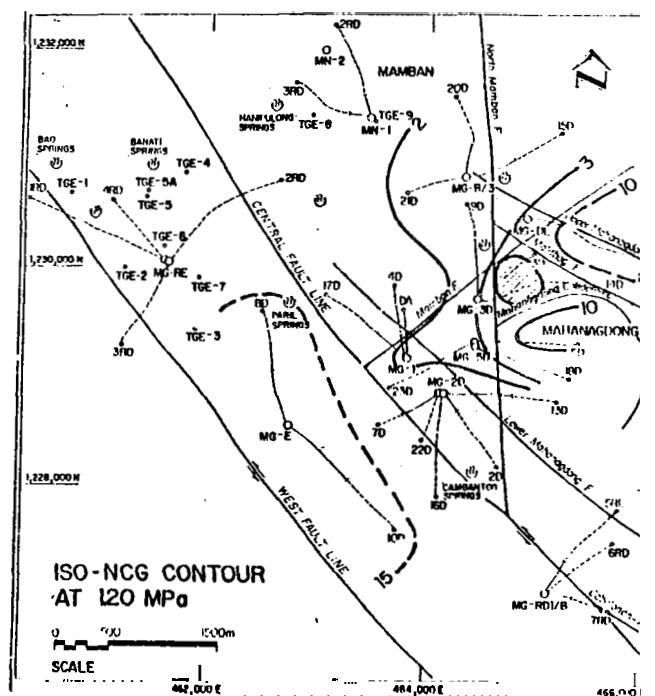


Figure 4: Iso-NCG Contour Map Across the Mahanagdong Geothermal Resource

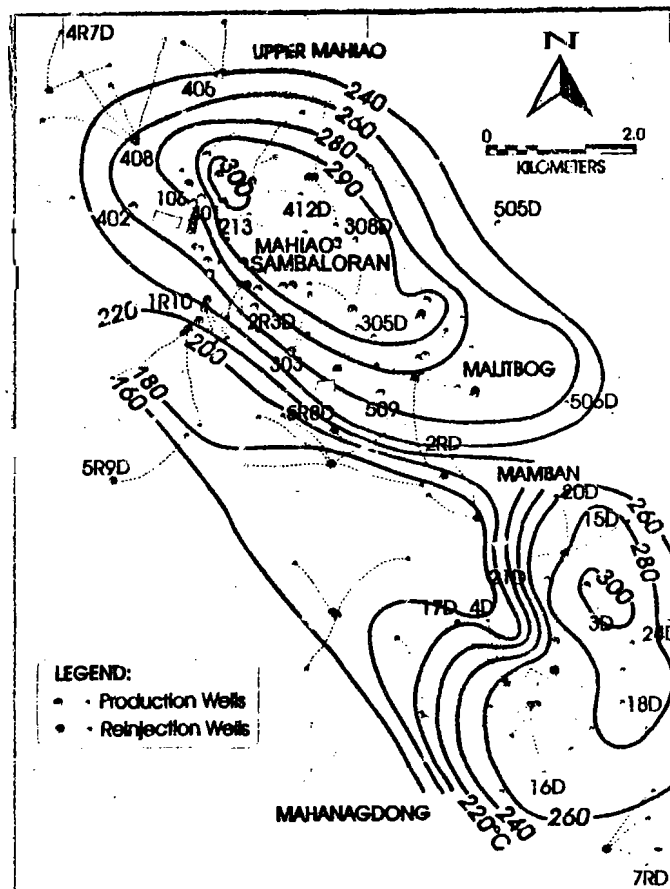


Figure 5: Isothermal Contours Across the Greater Tongonan Geothermal Field at -1000m RSL Based on Stable Field Measurements

4.3 Modified Well Casing Design

As early as 1995, PNOC-EDC has been adopting the scheme of drilling large-diameter wells (Sta. Ana et al., 19%) to meet the steam requirement in the shortest possible time based on an anticipated 30-60% increase in output from these wells. However, this strategy has not been so successful even with the standard size wells because of the premature termination of drilling due to persistent hole problems. In fact, only 18 of the last 32 wells (56%) drilled attained its programmed objectives in Greater Tongonan.

An in-depth analysis of the cause of the Mahanagdong drilling problems was then conducted to possibly improve on the drilling performance. The early termination of drilling was traced to the limited capacity of fracture zones to accept cuttings while drilling blind through multiple permeable zones (Talens et al., 1997). The solution drawn up which was termed as the "two liner system" (Figure 6.0), was to run a 9-5/8" liner after bottoming out the first interpreted permeable horizon. A 7-5/8" Ø slotted liner is set at deeper permeable zones. By temporarily casing-off the first permeable horizon, circulation is regained ensuring effective hole cleaning until the next permeable zone is encountered. Potential collapsing formation is also arrested. If the well performance is sub-commercial, an option to perforate the liner for additional production is possible. The application of these modifications on the next five wells drilled proved to be very effective in terms of intersecting the major producing zones (Table 1).

WELL NAME	DRILLING DAYS		TOTAL DEPTH	
	PROGRAM	ACTUAL	PROGRAM	ACTUAL
A. WELLS WITH TWO-LINER SYSTEM				
MG-27D	69	71	2400	2301
MG-28D	70	70	2500	2395
MG-29D	70	77	2500	2400
MG-30D	77	63	2450	2443
MG-31D	74	81	2350	2287
B. WELLS WHICH DID NOT ADOPT THE TWO-LINER SYSTEM				
MG-23D	77	97	2500	2160
MG-25D	77	114	2500	1998
MG-26D	77	83	2600	2075

TABLE 1. Comparison of drilling duration and total drilled depths of Mahanagdong production wells with and without the two-liner casing design.

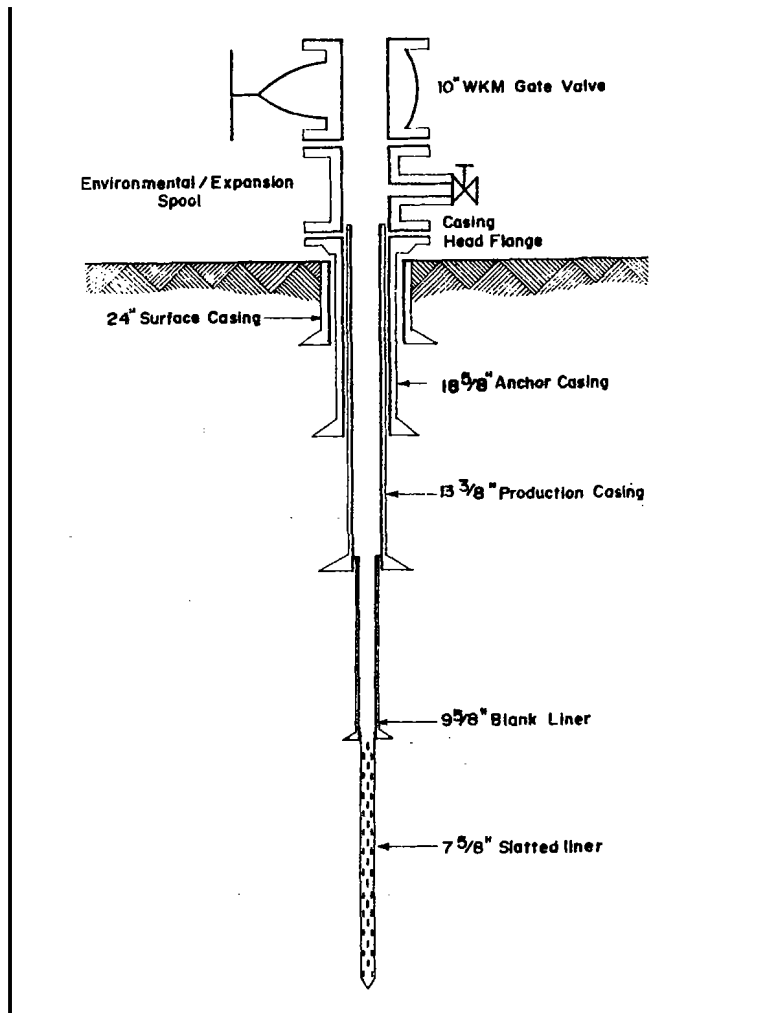


Figure 6: Schematic Diagram of the Two-Liner System

4.4 Stimulation by Acidizing

The timely completion of wells MG-27D, 28D, 29D, 30D and 31D however, was not synonymous to the fulfillment of the steam required for Mahanagdong-B. Although these wells encountered massive circulation losses while drilling and showed moderate transmissivity values, their injectivity indices were relatively low which indicated poor permeability (Malate et al., 1997). A review on the drilling records which accounted for the total volume of mud injected into the well was done to evaluate possibility of these wells as being mud-damaged. This was one of the major criteria in selecting candidate wells for acidizing. Records revealed significant amount of High Viscosity Mud (HVM) injected into these wells which warranted acidizing operations (see Table 2). Post-acid tests on these wells showed significant improvements in the overall well characteristics. Most remarkable were wells MG-27D, MG-30D and MG-31D.

WELL NAME	TOTAL HVM INJECTED (bbls)	PRE-ACID		POST-ACID	
		TRANSMISSIVITY (d-m)	INJECTIVITY (Li/s-Mpa)	INJECTIVITY (Li/s-Mpa)	OUTPUT (MWe)
MG-27D	45,605	2.4-2.9	27.3	62.2	5.0
MG-28D	1,215	1.37-1.85	32.8		7.5
MG-29D	5,530	2.8	28.1	30.0	7.4
MG-30D	2,448	4.9-5.7	26.0	138.0	14.4
MG-31D	5,179	2.7	24.9	104.3	19.0

TABLE 2 Summary of transmissivity and injectivity values of mud-damaged Mahanagdong-B production wells before and after acidizing activities.

4.5 Reinjection Strategy

In the early phases of development drilling of Mahanagdong-A, reinjection wells were concentrated in the Bao valley area, where numerous dispersed hot spring steam vents were found. These were located at the western edge of the Mahanagdong-A production area and was interpreted to be the outflow area of the Mahiao and Mahanagdong systems. Ironically, however, the first four deep reinjection wells drilled within the area displayed no permeability. Results showed that the fluids feeding these hot springs were channeled at shallow levels through the volcanic member of the Mamban Formation. Furthermore, pursuing shallow reinjection within the area had adverse environment implications.

A shift in reinjection strategy was initiated by transferring the reinjection sink to the southeastern edge of the Mahanagdong production field at MG-RD1 pad and targeting for permeability the extensions of known permeable faults. The succeeding reinjection wells drilled in this area showed significant reinjection capacities. However, the hydraulic connectivity between the production and reinjection sector of Mahanagdong-A still remains to be seen during its commercial operations.

For Mahanagdong-B reinjection, the three non-commercial acid wells drilled in MG-B3 pad were converted into reinjection wells which were located north of the Mahanagdong-B production sector. Two additional wells (MN2RD and MN3RD) were drilled within the edge of the Mahanagdong-B to fulfill its total reinjection requirements.

5.0 CONCLUSION

As of December 1996, a total of 38 wells have been drilled in Mahanagdong sector. In Mahanagdong-A, 13 out of the 18 production wells drilled will be put on line with an estimated total output of 145 MWe, while 4 out of 8 reinjection wells drilled with a total capacity of 819 kg/s will be utilized. For Mahanagdong-B, six out of the 10 production wells will be put on line with an estimated output of 64 MWe while the remaining three acid wells will be converted to reinjection wells. These are sufficient for the start of the commercial operations of the installed 120 MWe capacity power plant in Mahanagdong-A and the 60 MWe capacity power plant in Mahanagdong-B in March 1998.

The development of the Mahanagdong resource into a commercially-exploitable resource was done through:

- 1) Delineation drilling based on hydrological model;
- 2) Creation of innovations in casing design such as the "two-liner system" to adapt to current hole problems; **and,**
- 3) Well stimulation through acidizing.

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