

## PROVING THE MAHANAGDONG B RESOURCE: A CASE OF A LARGE-SCALE WELL STIMULATION STRATEGY, LEYTE GEOTHERMAL POWER PROJECT, PHILIPPINES

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### ABSTRACT

The Mahanagdong-B production sector of the Leyte Geothermal Power Project was faced with a serious steam supply problem in the first half of 1997, with only 14 MWe available at the wellhead of seven production wells for a 60 MWe power plant.

Significant thermal degradation of the resource block brought about by extensive drilling prevented the discharge of most wells even with the aid of air compression and nitrogen gas lifting. Detailed analysis of reservoir and drilling data also revealed that all the wells had been mud-damaged.

The problem was compounded by the contractual obligation of PNOC-EDC to produce 60 MWe equivalent of steam to the power plant by the middle of the year.

A comprehensive well stimulation strategy was laid out through which the situation was put to a manageable level by June 1997. The strategy involved the simultaneous use of two coiled tubing units, one rig and two acidizing equipment spreads all in one pad, to stimulate, discharge and commission the seven production wells in less than three months.

### BACKGROUND

The Mahanagdong production sector of the Leyte Geothermal Power Project represents a postulated 11.3 km<sup>2</sup> production block at the southern end of the Greater Tongonan Geothermal Field (Figure 1). Reserve estimates have placed the power potential of this area at 213 MWe. The main production area alone comprising 9.7 km<sup>2</sup> of the entire production block is already 190 MWe. Such a promising assessment prompted PNOC-EDC to initially

venture into a 160 MWe development program for this sector. This was later increased to 180 MWe after receiving offers for more efficient steam turbines from potential build-operate-transfer (BOT) contractors. Geographical and topographical considerations favored the operation of two independent plants in the sector. Thus, the development was further divided into two independently operating production sectors, Mahanagdong A to supply 120 MWe equivalent of steam to one plant and Mahanagdong B to supply 60 MWe to the other.

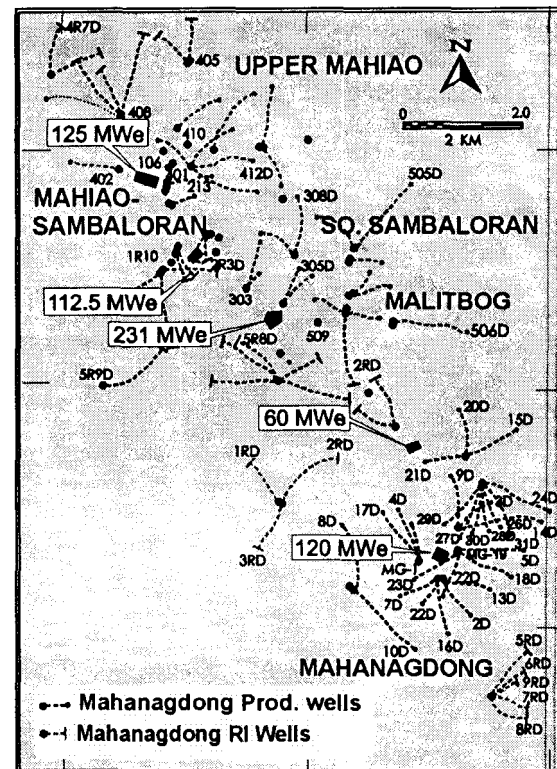


Fig. 1. The Greater Tongonan Geothermal Field

## EARLY DEVELOPMENT

Early exploratory drilling delineated low permeability and low temperature boundaries to the south, and acidic environments to the north. Productive horizons of high temperature and good permeability were eventually tapped towards the western and northeastern sectors of the resource block. The western sector was developed to supply the 120 MWe steam requirement for the Mahanagdong A power plant. By early 1995, this requirement had already been met with 13 production wells capable of producing a total of 132 MWe.

Development drilling of the Mahanagdong B resource block ensued between September 1995 and December 1996, with 7 production wells and 6 reinjection wells completed within the period. Despite promising indications from completion tests (Table 1), the production wells failed to deliver during the initial discharge attempts in 1996. Except for one well, **MG-24D**, the other two wells (MG-27D and MG-29D) could not be discharged even with nitrogen gas-lifting. Even MG-24D could only produce a maximum of about 3 MWe at commercial wellhead pressures (WHP).

Several notable wellbore characteristics were observed during the heat-up and initial stimulation and discharge stages of the Mahanagdong B wells which shed light on the apparent low productivity of the wells. Downhole temperatures were low compared to those in the neighboring Mahanagdong wells, particularly during the early heat-up period (Figures 2 and 3). The other wells were able to reach temperatures above 200°C within a week of heat-up after drilling while those in Mahanagdong B attained temperatures of only 160-190°C. After three weeks, maximum temperatures averaged a mere 220°C. Temperature recovery of the wells after drilling was also rather slow. MG-27D and MG-29D were air-compressed, two-phase injected and gas-lifted several times to stimulate discharge, but all to naught. Immediate-shut temperature surveys indicated cooling at the bottom by as much as 30°C at MG-27D and 10°C at MG-29D during the discharge attempts. The low temperatures and rapid cooling during these early discharge attempts all coincided with the drilling of wells MG-29D, MG-30D and MG-31D within the vicinity of the completed wells. Based on these observations, it was deduced that drilling fluids could have temporarily cooled the resource block, and that any attempt to discharge any of the completed wells while drilling was in progress would be futile. This was proven in

November 1996 when the last two attempts to gas-lift MG-27D and MG-29D again failed to make them flow. It was then decided to defer testing of all the wells until the completion of the drilling activities.

Additional analysis of the completed wells was then undertaken. It was revealed that large doses of high viscosity mud (HVM), reaching as high as 47,000 barrels for a single hole, had been injected in the openhole section of the wells to contain the massive drilling losses (Table 2). These could have caused severe wellbore damage in the wells. Nevertheless, Buijing et al (1995) have confirmed that such problems can be successfully treated with a matrix type of acid treatment.

Well	Injectivity Index (li/s/MPa)	Injection WHP (MPa)	Transmissivity (darcy-meters)
MG-24D	15.0	vacuum	1.9
MG-26D	13.1	0	1.0
MG-27D	27.3	vacuum	2.7
MG-28D	32.8	vacuum	1.6
MG-29D	28.1	vacuum	2.8
MG-30D	26.0	vacuum	5.3

*Table 1. Post-drilling well characteristics of Mahanagdong B wells*

Drilling in the sector was completed in December 1996, and so discharge testing of the wells were resumed between January and February 1997 after the wells were thought to have attained sufficient thermal recovery. Downhole temperatures during this time were already in the range of 250-320°C. This confirmed the earlier suspicion of massive cooling by the drilling fluids. Only two wells were able to self-discharge (MG-24D and MG-28D), one was untested (MG-26D), while the rest were stimulated, through two-phase injection, air compression and gas lifting. The two wells that self-discharged were able to attain commercial outputs. Both MG-27D and MG-29D were initially discharged through two-phase stimulation. MG-27D was non-commercial and its flow collapsed after throttling. MG-29D was unable to sustain its flow. Both wells were then re-discharged through gas lifting. The output of MG-27D remained non-commercial while MG-29D failed to produce at all. MG-30D and MG-31D were stimulated by air compression. The former was able to flow and attain a commercial output of 4.3 MWe at a 0.95 MPa WHP, while the latter failed to flow. MG-26D was never discharged because of a casing break.

Well	Total Mud Lost (barrels)
MG-24D	6,853
MG-26D	2,710
MG-27D	47,074
MG-28D	32,361
MG-29D	8,088
MG-30D	2,100
MG-31D	7,653

Table 2. Mud losses in the open hole during drilling of Mahanagdong B wells

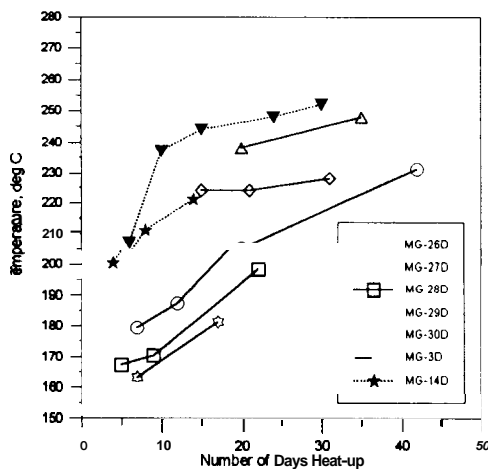


Fig. 2. Heat-up trend of Mahanagdong wells at -600 mRSL

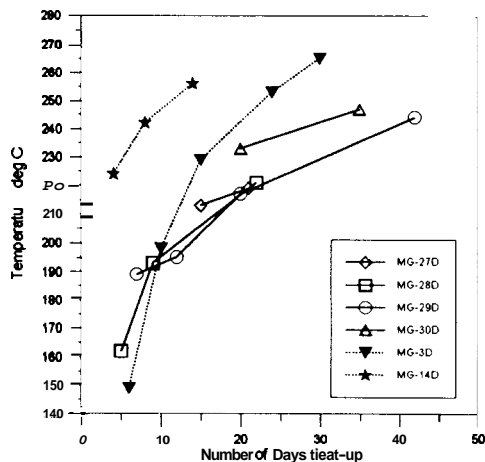


Fig. 3. Heat-up trend of Mahanagdong wells at -1000 mRSL

## PROBLEM EVALUATION AND PLANNING

At the completion of the initial discharge tests by February 1997, a **ve production** capacity of only 14 MWe was **l** at the wellhead of the seven  **wells** (Table 3). This  **it a**  **l situation for NOC-EDC** since it was barely three months  **way** before its contractual obligation to  **produce** at least 60 MWe  **alent of €** for the Mahanagdong B power plant by Ji 15, 1997. A steam  **u**  **t**  **f**  **e** therefore imminent at so a comprehensive plan had to be devised that could immediately address the situation

Well	WHP MPag	MF kg/s	H kj/kg	SF kg/s	MWe
MG-29D					
MG-27D	0.36	23.1	1477		
MG-31D					
MG-28D	0.75	27.7	1835	15.2	5.9
MG-30D	0.95	40.7	1268	11.2	4.3
MG-24D	1.03	17.0	1896	9.9	3.8
MG-26D					
TOTAL				36.3	14.0

Note: Based on 0.70 MPaa SP and 2.6 kg/s/MWe SR

Table 3. Initial discharge characteristics of Mahanagdong B wells (pre-acidizing)

One of the options considered to deal with the impending crisis was the interconnection of Mahanagdong A with B. However, this was deemed more appropriate as a long-term solution since it was impossible to complete in due time. Drilling of additional wells was also discarded due to the limited time. Only one option remained available to PNO-EDC if it were to beat the contract deadline - acid treatment of the wells followed almost immediately by discharge testing. The latter activity would have to be assisted by gas-lifting if a well failed to self-discharge. This strategy was strengthened by the fact that PNO-EDC has had a quite successful history in the field of acid stimulation (Buiing et al, 1995; Malate et al, 1997) and gas-lifting (Aqui et al, 1997; Buiing et al, 1998).

Several factors became critical in planning for the large-scale well stimulation program. The very short period involved required simultaneous treatment of at least two wells at a time. All the wells were confined in a single pad (MG-DL) measuring about 15,000 m<sup>2</sup>. Space was therefore a luxury. The wells all lie in single deep cellar, with only 11 m between each wellhead. This presented difficulty in

positioning and moving the necessary equipment. As such, only one drilling rig could be used to acidize at a time. Furthermore, the need to test and discharge every completed well in such a limited space would not allow for two rigs. Treatment would have to be done in such a way that the movement and operation of one set of acidizing equipment would not interfere with the operation of the other set. This was also true for the gas-lifting equipment vis-a-vis the acidizing units.

The need for simultaneous acid treatment of two wells in the same pad despite the space limitation was satisfied with the use of a drilling rig and a 2-inch coiled tubing unit (CTU). PNOC-EDC has been using drilling rigs in the past to conduct its acidizing operations, but this was the first time that a CTU was to be utilized side-by-side with a rig so that two independent jobs could proceed at the same time. This required two complete acidizing spreads to work with both the CTU and the rig. After the acidizing, all the wells would then be quickly discharge-tested so that capacity information would be immediately known. Thus, another CTU also had to be mobilized to handle the gas-lifting operations intended for wells which would not readily flow. This scheme also minimized the heat-up period so that the discharge could proceed earlier. Testing had to be just long enough to obtain sufficient output information and to allow each well to clear. While the treatment and testing were ongoing, the two-phase lines also had to be installed on the same pad, which made matters more complicated. Initial plans also called for the immediate cut-in of the tested wells to the fluid collection system.

The equipment and personnel requirement to acidize, discharge, test and commission the seven wells within three months was immense. The major sets of equipment that were mobilized and installed for the entire operation are summarized below:

- 1 Acidizing rig
- 1 2-inch CTU for acidizing
- 1 1.25-inch CTU for gas-lifting
- 1 Nitrogen converter
- 6 2,000-gallon liquid nitrogen tanks
- 2 Acidizing spreads complete with
  - 6 132-barrel fiberglass acid tanks for the HCl
  - 6 320-barrel mixing tanks
  - 3 injection pumps with at least 400 HHP capacity each mixers, compressors, and transfer and centrifugal pumps

- 3 Cranes
- 6 Sets of twin stack silencers

Immediate mobilization of all necessary equipment was accomplished through the use of chartered LCTs and trucks. The same set-up also provided for the timely delivery of the acid chemicals and liquid nitrogen from three islands (Mindanao and Cebu for the HCl, and Luzon for the chemicals and liquid nitrogen).

The three-month period to accomplish the program was extremely limited. Each component of the program had to be well-defined and their appropriate sequencing strictly followed with nil to minimal allowance for delays. Coordination and timing of all operations were critical. In the process, this large-scale strategy reached a magnitude unprecedented in PNOC-EDC operations.

#### ACID TREATMENT

The normal matrix acid treatment was used on the seven wells. The same methodologies applied on the previous jobs were adopted in terms of candidate evaluation, job design and execution (Bufiing et al, 1995; Bufiing et al, 1997; Malate et al, 1997).

The multiple successive acidizing jobs that were performed required massive quantities of stimulation chemicals (Table 4). An adequate supply had to be stocked and maintained at the pad to ensure their availability at site whenever needed throughout the program for a continuous unhampered stimulation operation. This became a major logistical task in itself since the bulk of the ammonium bifluoride and corrosion inhibitors were imported while the HCl originated from a local source about 400 km from the job site. Chemical deliveries were continuous and appropriately timed to prevent any downtime due to insufficient chemicals. Storage and preparation of the large volume of acidizing chemicals were accomplished with the installation of sufficient containment vessels (see summary of equipment) capable of accommodating some 80,000 gallons of raw HCl and 160,000 gallons of mixed acid solution. The acidizing equipment were configured so that mixing and acid injection could proceed simultaneously in one or both spreads. To achieve the desired maximized injection rates even during simultaneous jobs, multiple independent pumping units from the two acidizing spreads were available to satisfy the pumping requirement.

Acidizing chemicals used	Quantity consumed
Hydrochloric acid	253,324 lb
Hydrofluoric acid	2,515 pounds
Corrosion inhibitor	334 gall

**Table 4. Total quantity of acidizing chemicals used for Mahanagdong B**

### STIMULATION RESULTS

Downhole tests were conducted after the acid treatment in all the wells except in MG-28D and MG-24D due to wellbore problems (Table 5). In all cases, significant improvement in downhole characteristics was achieved. Increases in injectivity index were remarkable, from at least a three-fold increase in MG-27D to at most a six-fold rise in MG-30D. Injection pressures dropped by as much as 1.5 MPa at similar injection rates. Declines in water levels were also significant from as little as 30 to as much as 150 m. Electronic spinner logs measured enhanced flows across permeable zones. In some cases, increases in permeable zone thickness were also logged. Such results are clear indications of better acceptance and reduced restriction to flow.

Well	Pre-Acidizing	Post-Acidizing	
	Injectivity Index (li/s/MPag)	Injectivity Index (li/s/MPag)	Drop in Injection Pressure (MPa)
MG-26D	13.1	12.4	1.5
MG-27D	24.2	62.2	1.5
MG-29D	28.1	29.8	1.5
MG-30D	23.0	138.0	0.7
MG-31D	24.9	104.3	-

**Table 5. Well characteristics of Mahanagdong B wells before and after acidizing**

As planned, the wells were discharged at once after a brief shut-in period following the acid treatment. Heat-up was limited to only one to three weeks. The shortest was in the case of MG-31D when it was gas-lifted and discharged after only five days from being acidized. The testing that followed generally lasted for no longer than a week at fullbore. Discharge at throttled conditions was possible only in a few short periods as in MG-24D, MG-26D, MG-28D and MG-30D.

The post-acidizing discharge tests also showed substantial improvement compared to the initial

discharge (Table 6). Only two wells required gas lifting, MG-29D and MG-31D. All the wells were able to sustain their discharge and attain commercial wellhead pressures (above 0.80 MPag) except for MG-26D. There was a significant increase in massflow from as little as 50% to more than double the previous values in the pre-acidizing discharge tests. As a result, one month to the June 15, 1997 target for a 60-MWe steam availability, PNO-EDC already had 62.5 MWe from six of the seven production wells. This was in fact in line with a program revision implemented on April 23 which called for a 60 MWe capacity as early as May 15 to meet the "deemed completion" provision of the contract with the plant operators.

Well	WHP MPag	MF kg/s	H kj/kg	SF kg/s	MWe
MG-29D	0.75	48.5	1508	19.0	7.3
MG-27D	1.10	93.7	1207	23.1	8.9
MG-31D	1.38	75.0	2102	51.0	19.6
MG-28D	0.88	37.8	1867	21.4	8.2
MG-30D	1.33	100.3	1483	38.1	14.7
MG-24D	1.26	38.6	1470	14.4	5.6
MG-26D	0.50	12.7	1902		
TOTAL				167.	64.3

Note: Based on 0.70 MPaa SP and 2.6 kg/s/MWe SR

**Table 6. Discharge characteristics of Mahanagdong B wells after acidizing**

### POSTSCRIPT

By June 15, 1997, the capacity of Mahanagdong B was established at 62.4 MWe, enough to meet the full-load requirement of the 60 MWe plant. The end of June 1997 saw it slightly up at 64.3 MWe after the latest testing of one of the wells (MG-24D).

The plant is now operating at 60 MWe load, with only six wells supplying steam. Before the year ended, two more production wells were completed in Mahanagdong B. With the eventual commissioning of these wells, and the soon-to-be worked over MG-26D, Mahanagdong B is estimated to have at least 20 MWe in reserve capacity for its 60 MWe power plant.

The capability of the wells at Pad MG-DL to supply the Mahanagdong B power plant by exploiting the northeastern resource of the Mahanagdong production block has thus become a reality, at least in the short term. With these results, the next level of development would focus on the long-term

sustainability of the sector by interconnecting other sectors in **case** production declines.

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