Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

A LARGE-SCALE WELL STIMULATION CAMPAIGN AT MAHANAGDONG GEOTHERMAL FIELD (TONGONAN), PHILIPINES

David Yglopaz, Jaime Jemuel Austria, Ramonchito Cedric Malate, Balbino Buñing, Francis Xavier Sta. Ana, Jesus Reymundo Salera and Zosimo Sarmiento
Philippine National Oil Company Energy Development Corporation, Merritt Road, Fort Bonifacio, Makati City 1201, Philippines

Key Words: geothermal well stimulation, acidizing, gas lifting, Mahanagdong, Tongonan, wellbore damage

ABSTRACT

The Mahanagdong B production sector of the Greater Tongonan Geothermal Field 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 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 the 60 MWe equivalent of steam to the power plant by the middle of the year.

A comprehensive well stimulation campaign was executed through which the situation was returned 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 on one pad, to stimulate, discharge and commission the seven production wells in less than three months.

1. BACKGROUND

The Mahanagdong production sector covers a postulated 11.3 km^2 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^2 of the entire production block, is already 190 MWe of the total potential reserves. Such a promising assessment prompted PNOC-EDC to initially venture into a 160 MWe power plant development 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.

2. DEVELOPMENT, TESTING AND ANALYSIS

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 north-eastern 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^{o}C within a week of heat-up after drilling while those in Mahanagdong B attained temperatures of only 160-190^{o}C. After three weeks, maximum temperatures averaged a mere 220^{o}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 with no success. Immediate-shut temperature surveys indicated cooling at the bottom by as much as 30^{o}C at MG-27D and 10^{o}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.

Drilling in the sector was completed in December 1996, and so discharge testing of the wells was 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^{o}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 MPag WHP, while the latter failed to flow. MG-26D was never discharged because of a casing break.

Aside from the cooling of the resource block, damage near the wellbore may have also affected the production capacity. Drilling records revealed that large doses of high viscosity mud (HVM) had been injected in the openhole section of the wells to contain the massive drilling losses (Table 2). This could have caused severe wellbore damage that constrained the wells productivity. Such problems can be successfully treated with a matrix type of acid treatment as discussed by Buñing et al (1995).

3. PROBLEM EVALUATION AND PLANNING

At the completion of the initial discharge tests by February 1997, a cumulative production capacity of only 14 MWe was available at the wellhead of the seven production wells (Table 3). This presented a critical situation for PNOC-EDC since it was barely three months away before its contractual obligation to produce at least 60 MWe equivalent of steam for the Mahanagdong B power plant by June 15, 1997. A steam supply shortfall was therefore imminent and so a comprehensive plan had to be devised that could immediately address the situation.

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 time. Drilling of additional wells was also discarded due to the limited time. Only one option remained available to PNOC-EDC if it were to beat the contract deadline - acid treatment of the wells followed 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 PNOC-EDC has had a quite successful history in the field of acid stimulation (Buñing et al, 1995; Malate et al, 1997) and gas-lifting (Aqui et al, 1997; Buñing 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^2. 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-à-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 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 their production capacities 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 in Table 4.

Immediate mobilization of all necessary equipment was accomplished through the use of chartered sea transports and trucks. The same system 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 campaign reached a magnitude unprecedented in PNOC-EDC operations.

4. 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 (Buñing et al, 1995; Buñing et al, 1997; Malate et al, 1997).

The multiple successive acidizing jobs that were performed required massive quantities of stimulation chemicals (Table 5). 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 continual 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 Table 4) capable of accommodating some 80,000 gallons of concentrated 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.

5. 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 6). In all cases, significant improvement in downhole characteristics was achieved. Increases in injectivity 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.

As planned, the wells were discharged 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 which 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 maximum flow. Discharge under throttled conditions was possible only for 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 7). Only two wells required gas lifting, MG-29D and MG-31D. All 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, within one month of the June 15, 1997 target for a 60-MWe steam availability, PNOC-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.

6. CONCLUSION

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 capability of the wells at Pad MG-DL to supply the Mahanagdong B power plant by exploiting the north-eastern 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.

ACKNOWLEDGEMENT

The authors extend their gratitude to the management of PNOC-EDC for the permission to publish this work.

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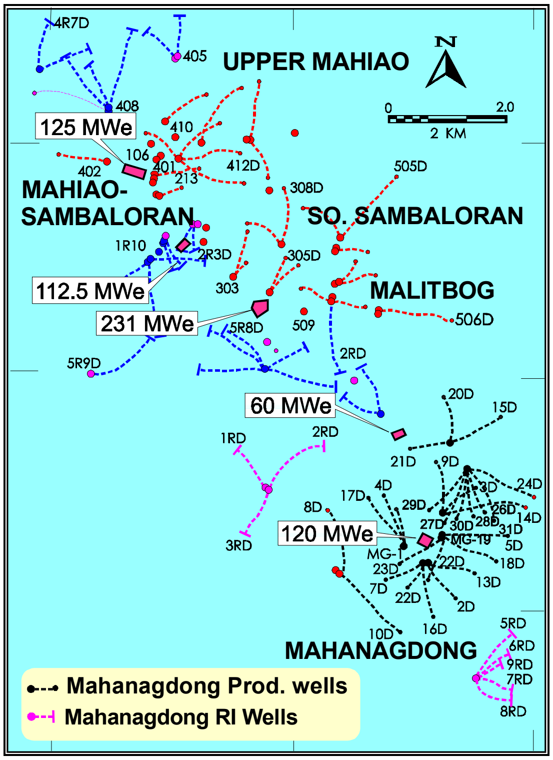

Fig. 1. The Greater Tongonan Geothermal Field

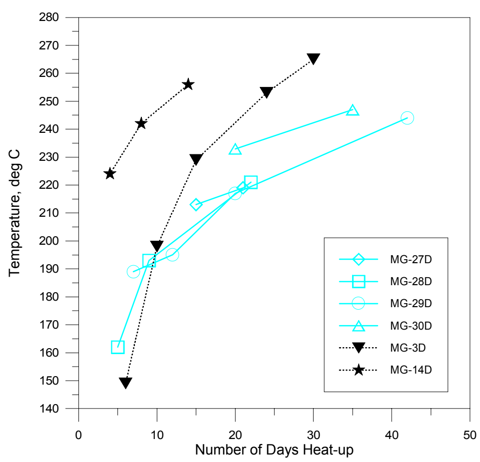

Fig. 3. Heat-up trend of Mahanagdong wells at -1000 mRSL

Table 1. Post-drilling characteristics of Mahanagdong B wells

Well	Injectivity Index (li/s/MPa)	Injection WHP (MPag)	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
MG-31D	24.9	vacuum	2.7

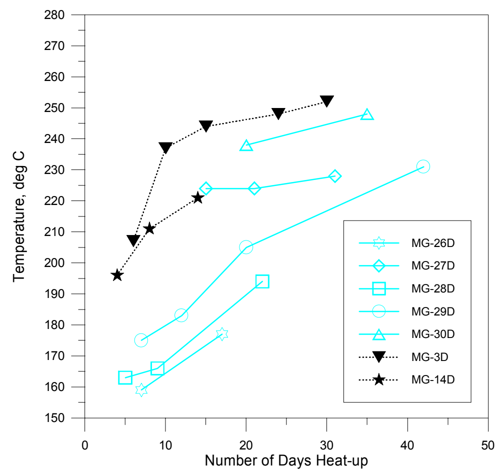

Fig. 2. Heat-up trend of Mahanagdong wells at -600 mRSL

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

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 3. Pre-acidizing discharge characteristics of Mahanagdong B wells (based on 0.70 MPaa separation pressure and 2.6 kg/s/MWe steam rate)

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

Table 4. Major equipment used in the Mahanagdong B stimulation campaign

1	Drilling rig for acidizing		
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	400 HHP capacity injection pumps
			mixers, compressors, and transfer/centrifugal pumps
3	Cranes		
6	Sets of twin stack silencers		

Table 5. Total quantity of acidizing chemicals used for Mahanagdong B stimulation campaign

Acidizing chemicals used	Quantity consumed
Hydrochloric acid (HCl)	253,324 gallons
Ammonium bifluoride	262,515 pounds
Corrosion inhibitor	33,841 gallons

Table 6. Mahanagdong B well characteristics before and after acidizing

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 7. Discharge characteristics of Mahanagdong B wells after acidizing (based on 0.70 MPaa separation pressure and 2.6 kg/s/MWe steam rate)

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