DRILLING GEOTHERMAL WELLS EFFICIENTLY, WITH SPECIAL REFERENCE TO THE MUTNOVSKY GEOTHERMAL POWER PROJECT

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ABSTRACT

Drilling geothermal wells efficiently is dependent on a number of factors. Good forward planning is essential. The well design, contracts and site preparation are normally prepared well before resources are mobilized to drill a well. Well design is largely influenced by the subsurface constraints and the primary objective for drilling the well. However, there are some aspects of well design that ought to be considered in improving drilling efficiency. The contract type and technical specifications are one of the key areas that can influence on whether or not a well can be drilled efficiently and cost effectively. Matching a drilling rig to the well design is critical. If the rig is undersized, or under capacity, it can result in compromises having to be made. This has a negative impact on efficiency. There are many devices and materials available on the international market that can enhance efficiency in making wells but some of these come at a price that can impact negatively on the cost of a well. This paper looks at examples of wells that have been drilled at the Mutnovsky Geothermal Project. Site isolation and the severe weather conditions have affected drilling efficiency at this project. The paper also examines types of equipment, practices and procedures that can enhance safety and drilling efficiency. Examples of drilling geothermal wells in Makban, Philippines and Lihir, Papua New Guinea, are used as benchmarks. It is concluded that drilling at Mutnovsky can be carried out efficiently and cost effectively, in spite of the climatic conditions and physical isolation of the Kamchatka region.

1. INTRODUCTION

Between December 2000 and December 2002, four geothermal wells were drilled for the 55 MWe Mutnovsky geothermal power development. This power development is located on the flanks of Mt Mutnovsky, about 160 kilometres south of Petropavlosk, the largest city in Kamchatka, Eastern Russia. This development also utilised existing wells drilled in the 1980s and early 1990s. However, the political and economic environment under which these wells were drilled was very different to the system that prevailed with the earlier drilling During that period, the government provided funding for all activity at Mutnovsky.

This current development was a commercial undertaking by Geoterm Joint Stock Company and finance was provided by the European Bank of Reconstruction and Development [1]. The drilling and well testing was let to a local contractor, SE Mutnovka-Vostokgeologia. The contract was a lump sum type that meant that contractor carried all of the risk for completing the well within the specifications for a fixed price. This type of contract for drilling is not common and was probably one of the main reasons why international bidders did not submit proposals during the tendering stages. A contract of this type is best suited for a contractor that has considerable local drilling experience. Downer Energy Services Ltd. (now Century Resources based in Wairakei, New Zealand) successfully completed such contracts in the central volcanic region of New Zealand [2]. This local contractor from Kamchatka had considerable experience in drilling and testing the earlier wells. The Mutnovsky geothermal field has been under exploration for more than 20 years and to date more than 90 exploratory wells have been drilled. The majority of senior rig personnel with the contractor (and with Geoterm) had been involved with the drilling of these earlier wells.

This paper examines the Mutnovsky drilling performance and compares this with drilling performance and efficiency trends in other countries. In particular, recent drilling of geothermal wells in the Makban Geothermal Field, Philippines, is used to bench mark performance at Mutnovsky. This field is operated by Philippine Geothermal Inc. (PGI), a Unocal company. Unocal strives to be the clear international leader in drilling wells efficiently. The drilling at Makban demonstrates how one can learn from past drilling performance, and the performance of others, resulting in the achievement of some excellent results in drilling efficiency.

Geothermal drilling information from Lihir in Papua New Guinea is also used to illustrate what can be achieved by implementing an effective drilling efficiency program. Lihir is a gold mine operated by Lihir Management Company Limited (LMC). The gold mineralisation is associated with an active geothermal resource with measured well temperatures in excess of 230 degrees C. The 8 wells covered in this paper were drilled during the years 1999 and 2000 to investigate the geothermal resource.

2. DRILLING WELLS EFFICIENTLY – SOME REQUIREMENTS

2.1. General

Completion of wells in the shortest time possible is a key driver for most geothermal operators. Time is money and is the primary measure of efficiency. Efficiency can be measured in other ways or in conjunction with other key performance indicators (KPI), eg. conducting a drilling operation safely without any lost time incident or accident.

The key elements to drilling geothermal wells efficiently are

- Preparation
- Equipment, Materials and Personnel
- Execution of the work

Preparation is the most important element. Without good preparation, efficiency gains from the other elements can easily be negated.

2.2. Preparation

Preparation and planning for a drilling campaign of 2 or more wells needs to be carried out well before hand. If done properly, there are many time saving features that can be captured in a new drilling program. Preparation for drilling at Makban, Darajat, and Lihir were carried out with the primary objective of drilling efficiently and safely. The main issues considered in preparing for these programs included:

1. Making sure that the design met objectives established for the well.
2. Manipulating the well design to incorporate measures that allows the well to be drilled efficiently.

3. Benchmarking and establishing achievable key performance indicators (KPIs) using offset well information.
4. Examining the time line activities and eliminating (non-critical) activities from the critical path.
5. Establishing a contractual basis to ensure that all parties benefit from good performance.
6. Specifying and procuring materials and equipment designed to carry out an efficient drilling operation.
7. Choosing personnel with the appropriate skill level and in sufficient numbers with the motivation to be team players in an efficient drilling operation.
8. Conducting pre-drilling preparation, eg.

    - driving or setting of conductor and surface pipe.
    - pre- drilling rat hole.
    - pre-welding or providing quick attachment casing head flanges.

2.3. Makban Drilling - Efficiency Objectives

In August 2002, PGI embarked on a 3 well drilling campaign at its Makban geothermal project after a 3 year hiatus in drilling activity. In the preparation for this campaign, there was an intention of invoking a high level of efficiency in drilling these wells.
A Unocal benchmarking study showed that Indonesian geothermal wells completed in the mid to late 1990s were drilled faster than most geothermal wells drilled in South East Asia at that time. The measures that were implemented for the Indonesian geothermal wells were adapted by PGI for the proposed drilling at Makban. With the Makban drilling being a new drilling campaign, and initially involving the drilling of only 3 wells, efficiency objectives concentrated on eliminating the "learning curve". The program was extended to 6 wells including one lateral well (a well with two producing holes connected to a single production casing).

2.4. Preparation for Drilling Efficiently at Makban

The well design had to first address pressure containment and casing integrity issues. On economic grounds, it was considered better to drill blind with mud instead of attempting to seal losses. Tie back strings were run to guarantee that casing to casing annular spaces were completely filled with cement slurry in one attempt.
The primary design efficiency gain was the building of a pad with production facilities that could accommodate 8 well heads (2 rows of 4 well heads). This required the rig to be capable of skidding or sliding the 14 m between well heads, thus reducing rig move duration. Rig moves took 2.4 to 2.9 days. This time was from rig release (after the completion test) to spudding or commencement of drilling of the next well.
Aerated fluid drilling was used for a major part of drilling in PGI and UGI wells until the late 1990s. This was eliminated primarily because it did not contribute to enhancing drilling performance and was expensive. These were the same reasons for eliminating the air package part way through the last drilling campaign at Darajat, Indonesia [5].

2.5. Equipment Requirements

The drilling rig (derrick, substructure and draw works) and pumps are key to drilling wells efficiently. The drilling rig must be capable of carrying and hoisting all loads (with allowance for drag) required to complete a well. In addition it must have spare capacity to hoist above the maximum of these loads. Normal rule of thumb is for this spare capacity to be least 45,000 kg (100,000 lb). For geothermal, volume is more important than pressure because drilling

fluids are relatively low density. The pumps must have sufficient power to pump high flow rates for cleaning the design hole configurations and at pressures dictated by system frictional losses.
Table 2.1 lists rig power and pull capacity for various geothermal drilling locations. For Mutnovsky, the Minimum Pull capacity was specified to be 100 tonnes. Geoterm considered that rigs of this capacity had drilled the earlier Mutnovsky wells.

Table 2.1. Rig Capacity

Geothermal Locations	Type of Contract	Planned Depth of Wells[1]	Minimum Input Power Rating of Draw works (kW)		Pull capacity (tonne)	
			Specified	Supplied	Specified	Supplied
Darajat	Unit rate	2400 m D	745	1120	340	454
Makban	Unit rate	3900 m D	745	900	NS	454
Lihir	Unit rate	1000 m D	225	410	100	154
Mutnovsky	Lump sum	2249 m D	NS	300	100	100
New Zealand	Lump sum	1000 m V	NS	225	NS	55
Iran	Unit rate	3000 m D	745	1490	340	454

Note to Table:
1. D = directional well, V= vertical well, NS = Not Specified.

In Mutnovsky, the contractor provided a mechanical rig fitting the specification exactly. The capacity was compromised with the pumps compound connected to the draw works and rotary table. Table 2.2 illustrates how much the Mutnovsky rig capacity is below that used in other geothermal fields. This has had a significant bearing on the efficiency of completing the wells. The severe stuck pipe and casing may have been avoided if the rig capacity was greater. Furthermore, the 245 mm (9-5/8 inch) casing could not be reciprocated (which meant that it could not be pulled out if there was a need to do so).

Table 2.2. Rig Capacity Ratios based on Planned Depths

Geothermal Locations	Power Ratio (kW/ m)	Pull Ratio (kg/ m)	Pump Power
Darajat	0.466	189	Independent
Makban	0.229	116	Independent
Lihir	0.410	154	Independent
Mutnovsky	0.133	44	Compound
New Zealand[1]	0.280	68	Independent
Iran	0.497	151	Independent

Note to table:
1. The New Zealand ratios were based on 800 m directional (assumed to be equivalent to the planned 1000 m vertical indicated in Table 2.1). Directional wells were planned for all other locations.

Other equipment can enhance drilling efficiency. Top drives were used in Darajat and Makban. These tools were invaluable for back reaming out of tight holes. Also, good equipment design or layout can help reduce time for carrying out efficient operations.

2.6. Incentive Schemes

Incentive payments to contractors and their personnel for good performance were established in Darajat, Lihir and Makban. These incentive schemes had a common theme. A portion of the cost savings in drilling a well in less time than planned was provided as a cash reward. This has played a significant role in improving drilling performance. These were day rate type contracts in which the operator had overall control.

In Mutnovsky and the New Zealand example, the lump sum contracts had no such incentives. The primary motivation for a lump sum contractor is to ensure his costs are covered or exceeded by his payment receipts for completing milestones. This means that personnel and sub-contractors must be "incentivised" directly by the contractor. It is unknown how, or if, this was implemented for these lump sum contracts. It is known that the Mutnovsky contractor invoked penalty and liquidated damages clauses of the contract as a result of not meeting some of the required milestones.

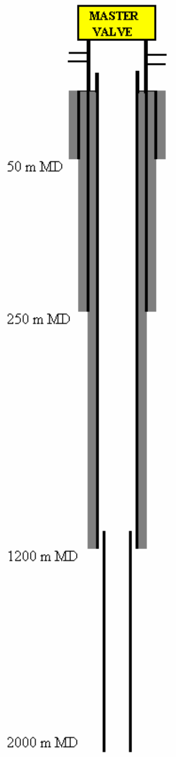
3. WELL PROFILES

3.1. Standards and Properties

Casing in the Russian Federation is manufactured in accordance with GOST 632-80 [3]. Generally, the casing sizes and bit diameters are derived from imperial units. Steel grades have properties corresponding to the American Petroleum Institute (API) [4] standards. Casing steel grades used at Mutnovsky GOST 632-80 were Grade E and D (with strength properties equivalent to API N80 and K55, respectively). It should be noted that API L80 equivalent casing is not included in GOST 632-80. This casing is less susceptible to sulfide stress cracking than the N80 or E grade, equivalent. OTTM couplings are used (a square thread and equivalent to the API buttress threaded couplings (BTC)).

3.2. Well Profiles

Under the lump sum contract at Mutnovsky, the contractor was required to provide the final well design based on specific requirements set by Geoterm. The contractor also provided all materials, equipment, personnel and other services required to drill, complete and test the wells. The Mutnovsky well profile for the 3 standard sized holes and the 1 big hole (well A-4) was as shown in Figure 3.1. Generally, the casing and hole sizes were the same as that used in the earlier wells that were drilled at Mutnovsky (all vertical). Casing sizes, bit sizes, steel grades and OTTM couplings are commonly used for wells in the Russian Federation.



Surface	Hole Size: mm (inches)	Depth MD
426 mm (16-3/4 inches) OD, 10 mm, D, HOPM	490 (19-1/4)	50 m MD

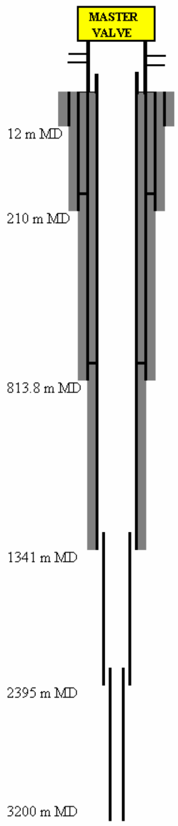
Intermediate (Anchor)	Hole Size: mm (inches)	Depth MD
324 mm (12-3/4 inches) OD, 9.5 mm, D, OTTM	394 (15-1/2)	250 m MD
Big Hole Production (Anchor)		
324 mm (12-3/4 inches) OD, 11 mm, D, OTTM	394 (15-1/2)	350 m MD

Standard Hole Production	Hole Size: mm (inches)	Depth MD
245 mm (9-5/8 inches) OD, 11.1 mm, E, OTTM	295 (11-5/8)	1200 m MD

Directional (all standard sized wells)	
Kick off Point Depth (metres)	306 to 410
Build rate (degrees per 30 m)	3
Final deviation angle (degrees)	15 to 33

Standard Hole Perforated liner	Hole Size: mm (inches)	Depth MD
168 mm (6-5/8 inches) OD, 8.9 mm, E, OTTM	216 (8-1/2)	2250 m MD
Big Hole Perforated liner		
245 mm (9-5/8 inches) OD, 10 mm, D, OTTM	295 (11-5/8)	1200 m MD

Figure 3.1. Schematic of Mutnovsky Well Profiles (Wells A-3 and A-4 (big hole))



Conductor	Depth MD
762 mm (30 inches) OD, 320 lb/ft.	12 m MD

Intermediate	Hole Size: mm (inches)	Depth MD
508 mm (20 inches) OD, 94 lb/ft., K55, BTC	660 (26)	210 m MD

Tie Backs 1 and 2	Depth MD
340 mm (13-3/8 inches) OD, 68 lb/ft., L80, Vam Top	213.5 m MD
273 mm (10-3/4 inches) OD, 45.5 lb/ft., L80, AB TC-II	783.3 m MD

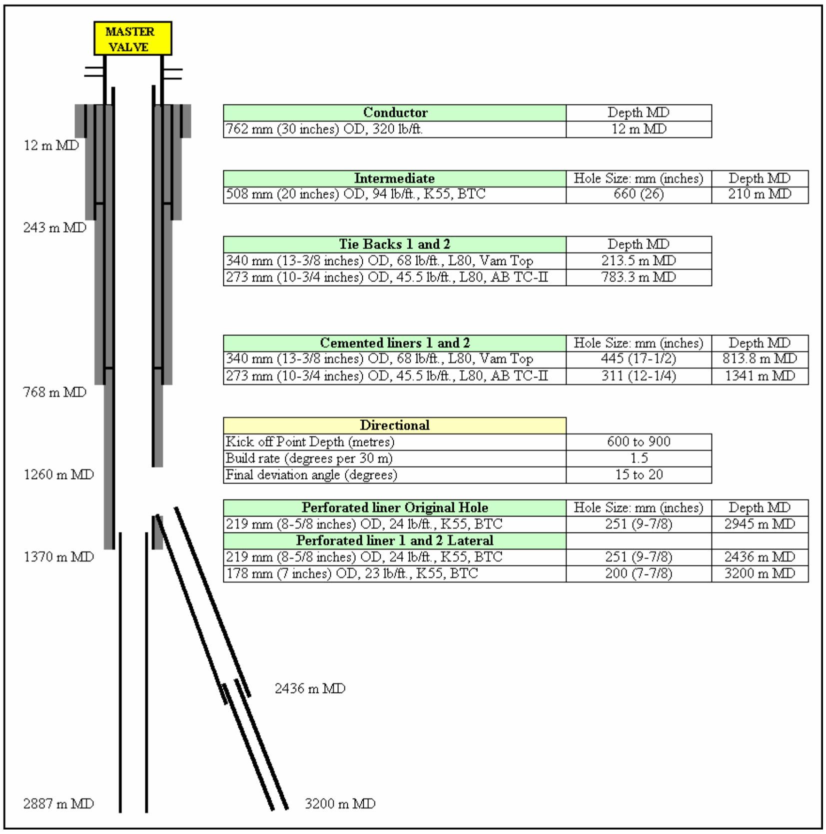
Cemented liners 1 and 2	Hole Size: mm (inches)	Depth MD
340 mm (13-3/8 inches) OD, 68 lb/ft., L80, Vam Top	445 (17-1/2)	813.8 m MD
273 mm (10-3/4 inches) OD, 45.5 lb/ft., L80, AB TC-II	311 (12-1/4)	1341 m MD

Directional (all wells)	
Kick off Point Depth (metres)	600 to 900
Build rate (degrees per 30 m)	1.5 to 3
Final deviation angle (degrees)	10 to 40

Perforated liners 1 and 2	Hole Size: mm (inches)	Depth MD
219 mm (8-5/8 inches) OD, 24 lb/ft., K55, BTC	251 (9-7/8)	2395 m MD
178 mm (7 inches) OD, 23 lb/ft., K55, BTC	200 (7-7/8)	3200 m MD

Figure 3.2. Schematic of Makban Well Profile (well D)

In Makban, the detailed design was carried out by PGI. The latest design was as shown in Figure 3.2. PGI was also responsible for the procurement of all materials, equipment, personnel and other services required to drill, complete and test the wells. The original PGI design for the big hole involved the drilling of 324 mm (12-1/4 inch) hole as the main production hole into which was run a 273 mm (10-3/4 inch) perforated liner. The use of 324 mm (12-1/4 inch) production hole size is common in most big hole designs coupled with the use of 245 mm (9-5/8 inch) perforated liners [5] [6].
Well F was the most recent well drilled at Makban. This was completed with a second open leg (referred to as a lateral). This is shown schematically in Figure 3.3. This is the second lateral well drilled by PGI, the other in the Tiwi field [7]. Immediately after the perforated liner was run in the original hole, a drillable plug was installed inside the 273 mm (10-3/4 inch) casing (liner 2 in figure3.3). A window was then cut through the side of the casing and the lateral drilled. After the lateral was completed, the drillable plug was then removed exposing both the original and lateral hole to the production casing and well head.



Conductor	Depth MD
762 mm (30 inches) OD, 320 lb/ft.	12 m MD

Intermediate	Hole Size: mm (inches)	Depth MD
508 mm (20 inches) OD, 94 lb/ft., K55, BTC	660 (26)	210 m MD

Tie Backs 1 and 2	Depth MD
340 mm (13-3/8 inches) OD, 68 lb/ft., L80, Vam Top	213.5 m MD
273 mm (10-3/4 inches) OD, 45.5 lb/ft., L80, AB TC-II	783.3 m MD

Cemented liners 1 and 2	Hole Size: mm (inches)	Depth MD
340 mm (13-3/8 inches) OD, 68 lb/ft., L80, Vam Top	445 (17-1/2)	813.8 m MD
273 mm (10-3/4 inches) OD, 45.5 lb/ft., L80, AB TC-II	311 (12-1/4)	1341 m MD

Directional	
Kick off Point Depth (metres)	600 to 900
Build rate (degrees per 30 m)	1.5
Final deviation angle (degrees)	15 to 20

Perforated liner Original Hole	Hole Size: mm (inches)	Depth MD
219 mm (8-5/8 inches) OD, 24 lb/ft., K55, BTC	251 (9-7/8)	2945 m MD
Perforated liner 1 and 2 Lateral		
219 mm (8-5/8 inches) OD, 24 lb/ft., K55, BTC	251 (9-7/8)	2436 m MD
178 mm (7 inches) OD, 23 lb/ft., K55, BTC	200 (7-7/8)	3200 m MD

Figure 3.3. Schematic of Makban Well Profile with Lateral (Well F)

The standard hole profile used by LMC, PNOC [5] and Amoseas [6] is as shown in Figure 3.4. The production hole size, into which is run the perforated liner, was the same diameter as that drilled at Mutnovsky. However, the perforated liner size in Mutnovsky wells was smaller diameter.

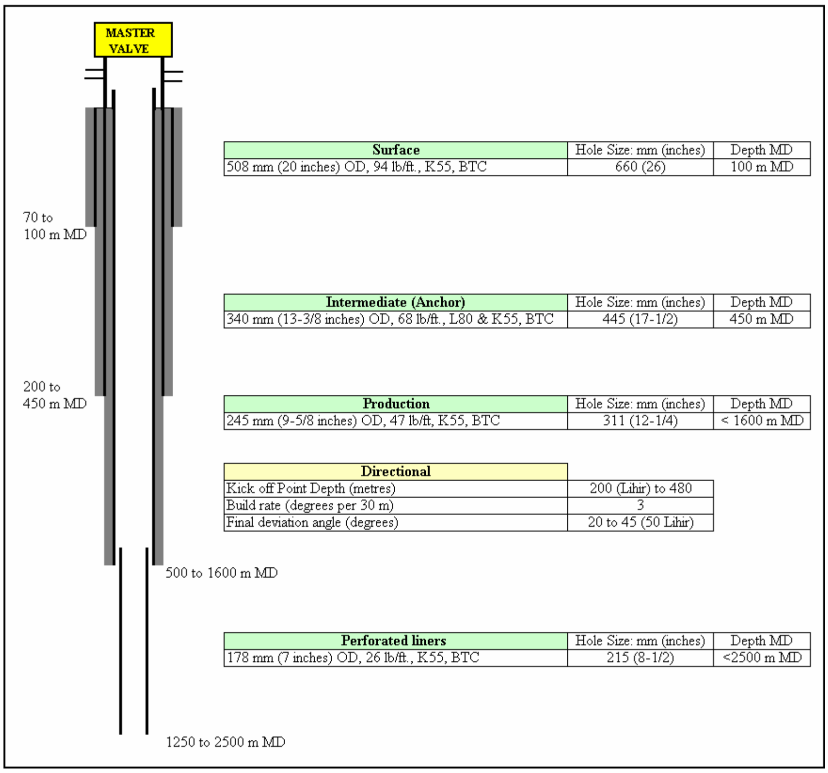


Figure 3.4. Schematic of Standard Well Profile used at Lihir, Mahanagdong [5] and Darajat [6] (depths of each casing shoe may vary)

4. DRILLING CONDITIONS – DIFFERENCES AND SIMILARITIES

4.1. Isolation of Mutnovsky

A significant feature of the Russian drilling scene is the absence of a local equipment rental service. Some multinational oilfield service companies have established offices in Sakhalin and Moscow. It is presumed that these services were deemed too expensive for the contractor with little or no experience in using such services. The end result was that the rig contractor was compelled to buy items like directional drilling equipment, cementing equipment and other items. In all other projects covered in this paper, service companies supplied this equipment and services on a daily rental basis. The relative isolation of the Kamchatka peninsular from international and national suppliers meant that the rig contractor had to be careful what he purchased and to seek out and purchase the lowest cost equipment available. This meant choosing equipment and consumables manufactured in Russia. The choice was further limited because there was often only one manufacturer to choose from. This supply environment has to be considered when comparing the efficiencies of drilling wells at Mutnovsky with drilling of wells in the other locations covered by this paper.

4.2. Formations

In most geothermal fields, extrusive volcanic rocks have similar properties with regards to drillability. Principal concern is the abrasiveness of such formations. In Mutnovsky, the geothermal reservoir is hosted in rocks of predominantly extrusive volcanic origin, with subordinate intrusives, epiclastics and sediments. Compositions range from dacite to basalt but are most commonly andesitic.

In Makban the formations are similar to Mutnovsky with volcanic tuffs interspersed with andesite. During the drilling of the recent wells, it was found that aggressive drilling practices (higher weights on bits, using mud motors and keeping bits down hole longer) allowed for faster drilling and the establishment of new drilling records. It is considered that more efficiency gains can be achieved by enhancing this approach. It is also considered that the formations at Mutnovsky can be drilled much faster than what the daily records show. It requires good bit selection and a number of changes in drilling procedures.

4.3. Winter Conditions

Climate has played a significant part in the exploration and development of the Mutnovsky field. Snow storms occur on average 64 days per year with winds reaching speeds of 40 m/ second. Average annual precipitation is 2000 mm. The height of annual snow cover in open areas is 4 m and in depressions up to 17 m. The average annual temperature is minus 1.9 ^{0}C with an average temperature of the coldest month (February) of minus 13 ^{0}C and of 12.4 ^{0}C during the warmest month (July). The contractor was expected to winterise his rig to enable him to conduct drilling operations around the clock. This was done to a limited extent with

- the enclosure of the mud pumps, generator sets and rig engines,
- the wind protection to the monkey board and the rig floor,
- the use of geothermal brine and steam from adjacent wells as an all purpose equipment anti-freeze solution.

Equipment not protected from the elements included pipe racks, cementing equipment, mud tanks, and the portion of the derrick up to casing height. Operations in these exposed areas were carried out with difficulty. In severe winter conditions, operations had to be shut down. These shut downs could last for several days as it was impossible for personnel to move around under such conditions.

5. OVERALL DRILLING PERFORMANCE

The overall average meters per day to complete a well provides a reasonable assessment of drilling performance. As an introduction to further analysis, Table 5.1 lists drilling rates from various geothermal developments. The PNOC experience indicates that big holes are slower to drill than standard holes. This is also confirmed with the one standard sized well shown for Amoseas in the table.

In spite of an improvement in performance with the last well, A-4 (a big hole), the drilling at Mutnovsky took more than twice the time of the next slowest location. Time allocated to force majeure and others (waiting on instruction) were eliminated from the Mutnovsky data to arrive at the time values given in this paper. It is assumed that time lost due to severe weather conditions was recorded as force majeure. This “sanitisation” of the Mutnovsky data provides some degree of equalisation when comparing the unusual Mutnovsky drilling conditions (as described in this paper) with drilling projects in South East Asia. Some efficiency problems due to the climatic conditions still remains in the data used in this paper but this is minimal. Additional winterisation could have eliminated the effects of these problems.

Table 5.1. Overall Drilling Performance

	Field	No. of Wells	Average m/day	Average Depth (metres)	Average Days
Geoterm Standard Hole	Mutnovsky	3	13.6	1980	146.0
Geoterm Big Hole	Mutnovsky	1	17.4	957	55.0
PNOC Big Hole [4]	Mahanandong	14	36.3	2347	64.6
PNOC Standard Hole [4]	Mahanandong	16	37.3	2280	61.2
Amoseas Big Hole [5]	Darajat	11	44.3	2230	50.4
PGI Big Hole (1993 to 2000)	Makban	8	50.0	2466	49.4
Amoseas Standard Hole [5]	Darajat	1	53.5	2890	54.0
LMC Standard Hole	Lihir	8	65.1	1581	24.3
PGI Big Hole 2002 to 2003	Makban	6	77.1	3068	39.8

Table 5.1 shows that the recent drilling by PGI was significantly faster than previous drilling at Makban. The efficiency gains were due to the following:

1. improvements on earlier drilling programs (at Makban and Unocal's geothermal operation in Indonesia) through the specification and procurement of performance enhancing materials and equipment eg. top drive and MWD steerable tools.
2. bringing together and motivating key personnel to work as a team .
3. providing a bonus incentive scheme based on key performance indicators being achieved or exceeded.
4. changing procedures to save time like drilling blind with mud instead of spending time sealing losses with cement plugs.
5. detailed examination of the critical path activities and taking some activities off the critical path that could be done concurrently with other critical path activities, eg. making up next drilling assembly while waiting on cement.

6. DAYS VERSUS DEPTH

6.1. Flat Spots

Flat spots are defined as the time consumed when making hole is suspended while casing is run, cemented and well head activities are conducted. These flat spots are pre-planned activities and form part of the drilling program. Flat spots can overrun the scheduled time allocation due to unforseen events or they can arise separately during the drilling process. Normally, the extra flat spot time is due to unplanned activities like stuck pipe (drill string or casing). In the case of abandoning a fish and side tracking, the time of drilling back to the original measured depth where sticking occurred, is considered part of the flat spot.

Table 6.1 provides time spent on flat spots. The stuck pipe flat spots are unplanned time and are not normally part of the flat spot time. The BOP times were added to illustrate the differences in equipment design and layout. The space provided beneath the rig was very confined for the rig at Mutnovsky compared with rest of the rigs covered by this paper. It took 4.79 average days to complete this activity compared with 1.46 days at Makban.

The Mutnovsky flat spots correspond to shallower depths than the Makban wells (refer figures 3.1, 3.2 and 3.3). This should mean lesser time spent on flat spots. However, the three standard wells averaged a flat spot time of 50.9 days per well compared with 16.6 days per well for the 3 Makban wells (the second perforated liner flat spot time was not included in this calculation).

Table 6.1. Flat Spot Performance

	Days Spent in Carrying Out Flat Spot Activity						
	Makban Wells			Mutnovsky Wells			
Flat Spot	D	E	F	A-1	A-2	A-3	A-4
Surface Casing	2.54	2.52	2.11	7	3.15	ND	4.92
Anchor casing	5.44	8.10[1]	4.18	17.96	6.00	11.00	12.43
Production casing	5	5.94	4.72	20.04	18.00[1]	9.58	
First perforated liner	2.02	1.79	5.42	9.33	22.81	22.81	10.99
2nd perforated liner	4.92	5.49	8.00				
Stuck & side track	7.00	2.83		20.38	72.50	10.35	
BOP up/down	1.46[2]	1.46[2]	1.46[2]	5.29	6.33	3.7	3.85

Note to Table: 1. Dealing with stuck casing included in this time. 2. Averages.

The stuck pipe and side track time was significant for well A-2 at Mutnovsky. This time involved getting stuck at about the same depth more than once suggesting that little was learned from the first stuck incident. A large improvement was recorded in well A-3.
For the 8 wells drilled at Lihir, no time was lost due to stuck pipe and side tracking. The last 3 wells drilled deleted a casing string from the original 3 cemented casing string design. Figure 6.4 provides a comparison of the flat spot duration for these wells with the best at Makban and Mutnovsky.

6.2. Days Versus Depth Plots

Days versus depth plots were compiled for the wells in Makban, Lihir and Mutnovsky.

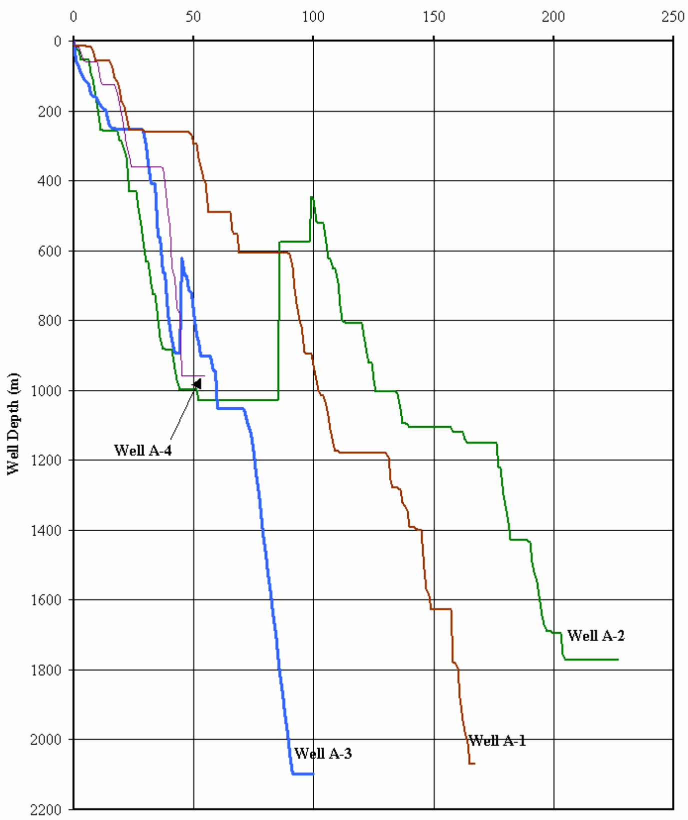


Figure 6.1. Mutnovsky Days versus Depth Plots

Some of the Mutnovsky daily drilling reports were not available, in particular during long duration stuck pipe incidents. The plots have been interpolated between known data points (Figure 6.1). Well A-2 drilling was a setback from the already poor performance in completing Well A-1. However, an improvement in performance was clearly evident in many aspects of drilling of the last two wells. In well A-4, the rate or penetration should have been faster because water was being used as the drilling fluid. This is indicated in Table 6.2 that shows a 120 m/day result compared with the highest for mud drilling of 73 m per day. These rates of penetration were not consistent for each day. This inconsistency was not due to formation changes but due to frequent drilling interruptions, eg. inappropriate bits, circulation for hours, and pulling out bottom hole assemblies to conduct directional surveys in the open hole. As indicated earlier in this paper, formation drillability should be similar to that at Makban where daily rates as high as 403 m per day were recorded (refer table 6.2).

Table 6.2. Mutnovsky Rates of Penetration

	Maximum Daily Meterage			
Hole Size	A-1	A-2	A-3	A-4
490 mm (19-1/4 inch)	ND	24	ND	24
394 mm (15-1/2 inch)	43	63	26	48
295 mm (11-5/8 inch)	73	64	49	120
216 mm (8-1/2 inch)	84	68	65	

The drilling days versus depth curves for Makban (Figure 6.2) clearly shows a steady improvement in performance from the first well, Well A, until the last, and fastest drilled well, Well F. This well broke many drilling records established for geothermal drilling in PGI and Unocal geothermal drilling in Indonesia. These Makban records are noted in Table 6.3.

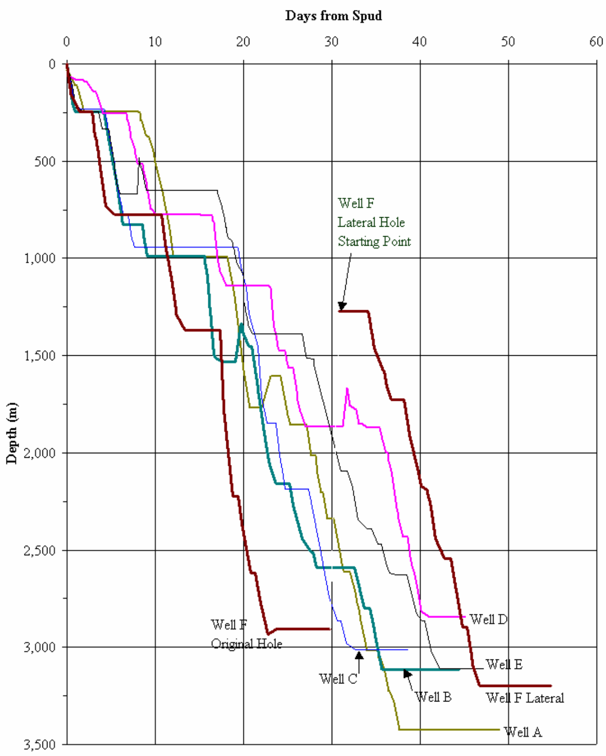


Figure 6.2. Makban Days versus Depth Plots

Table 6.3. Makban Well F Drilling Rates

660 mm (26 inch) hole drilling rate (average including connections)	403.2 m /day
445 mm(17-1/2 inch) hole drilling rate (average including connections)	319.2 m/day
311 mm (12-1/4 inch) hole drilling rate (Drilled 597 m continuous in 47.75 hrs)	300 m/day
251 mm (9-7/8 inch) hole drilling rate	249.6 m/day
251 mm (9-7/8 inch) single bit run record meterage	851.3 metres

In the 311 mm (12-1/4 inch) and 251 mm (9-7/8 inch) size holes, it was found that, between connections, rates of penetration as high as 60 m/hour could be achieved while drilling blind with water. This created tight hole problems due to the inability of the formation to take away the cuttings as fast as they were produced. As a result of these problems, the rates of penetration have been kept under control. However, it does show from these performance figures that even faster rates of penetration can be achieved. PGI plan to drill at least 4 more wells in 2004. When drilling recommences in 2004, it is proposed to address these problems of cuttings disposal into the permeable zones.
Bits used at Makban were confined to two of the major bit manufacturers (Hughes and Reed). The IADC codes that were used to maximise performance from 4-3-X to 5-1-X with sealed friction or roller bearings (represented by the X).

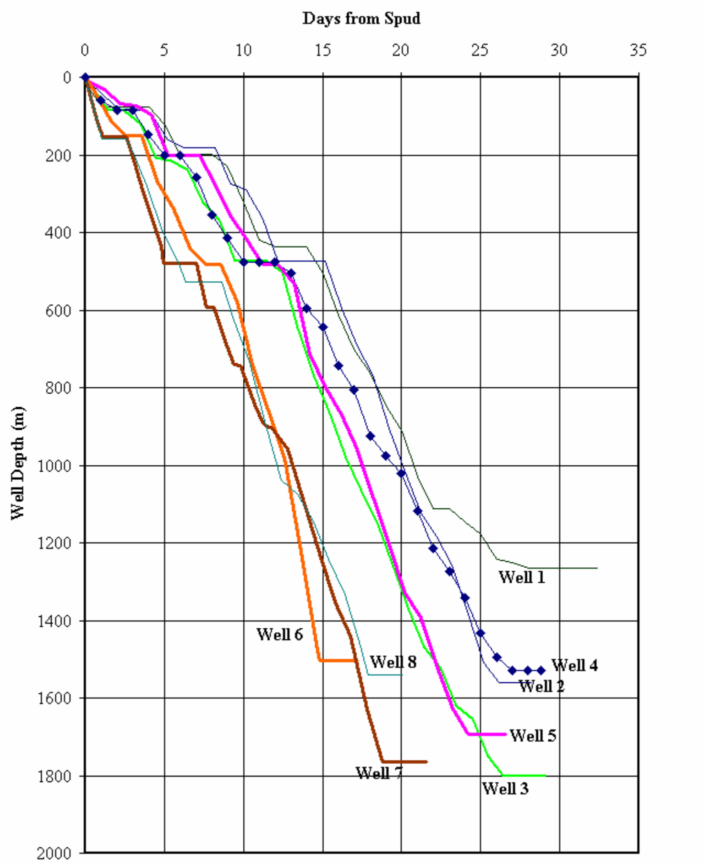


Figure 6.3. Lihir Days versus Depth Plots

As with Mutnovsky and Makban, the Lihir wells were drilled in the order indicated by the well number (or letter). Except for well 4, there had been a progressive improvement in overall rate of penetration at Lihir. The first well got off to a good start by being completed under the programmed time to complete the well (35 days). This was a vertical standard well while all the following wells were directional with deviation angles up to 50 degrees. As with Makban, continuous improvements by the team consisting of LMC personnel, contractor and service companies resulted in faster drilling for each succeeding well. The incentive bonus scheme was one of the factors that helped in this continuous improvement. This bonus scheme also applied to rig moves between well sites. It should be noted that the last 3 wells were completed with 2 cemented casing strings. Core hole and other information indicated that the first string of casing was not required.

LMC (Lihir) and PGI (Makban) both had programs in place that were designed to attain the fastest completion of a geothermal well that was physically possible. Figure 6.4 compares these two projects with Mutnovsky. Mutnovsky formation drillability at Mutnovsky is expected to be similar to that at Makban or Lihir. This leads to the possibility that wells can be drilled to 2200 m in less than 45 days at Mutnovsky. Significant changes will be required to the current drilling setup in order to achieve this realistic target.

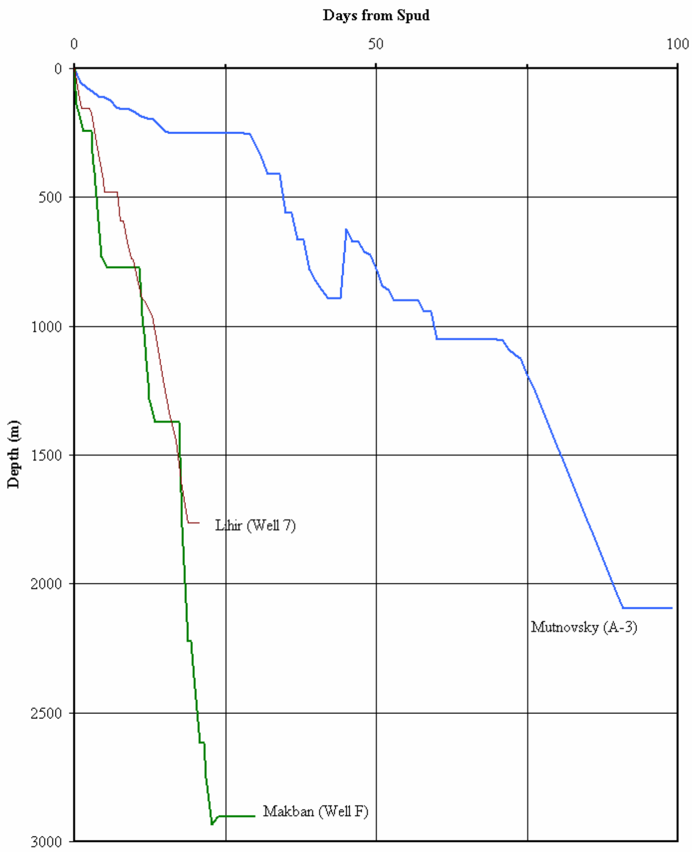


Figure 6.4. Days versus Depth Plots – The Best from Makban, Lihir and Mutnovsky

7. CONCLUSIONS

The foundations for drilling wells efficiently are set down in the planning stages. A case study of Makban has demonstrated what good preparation can achieve when executing a program. New drilling records were established. Based on the concept of continuous improvement, the next wells are likely to see further records established. Drilling performance at Lihir was also exceptional and followed the same concept of continuous improvement.

It is clear that major improvements are required at Mutnovsky for drilling operations to emulate the drilling performance at many other geothermal drilling operations in the world. This paper has demonstrated that neither the severe climatic conditions nor the site's isolation

from supplies contributed to the lack of drilling efficiency at Mutnovsky. Drilling can definitely be carried out much faster in Mutnovsky. This paper identifies some key problem areas that have affected drilling efficiency at Mutnovsky. Much can be learned from the Makban and Lihir experience.
Well F at Makban has shown that it is possible to drill a 3000 m directional well in less than 30 days. Based on information gained from drilling at Makban, it is feasible that future 3000 m deep wells can be drilled in less than 25 days.

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