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ACTIVITY REPORT ON DRILLING AND LOGGING TECHNOLOGY OF THE IEA DEEP GEOTHERMAL RESOURCES TASK

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ABSTRACT

The target depth of geothermal energy development has increased in many countries. During the drilling and logging of deep wells, many problems have occurred due to severe conditions related to increasing well depth and rising temperatures and pressures. Developers concerned with drilling and logging of wells probably have encountered similar problems and have had similar experiences in solving them. Therefore, it is very useful to compile and exchange these experiences. Cooperative investigations on drilling and logging technology under the IEA Deep Geothermal Resources task started in March 1997. Five research programs related to drilling and logging technology were proposed by the USA, Mexico, and Japan for the mutual exchange of information. Drilling and logging data from deep geothermal wells in several countries, obtained from published papers, have been stored in the database in the DGR web site. This paper outlines the status of geothermal drilling technology experienced by the participants, based on published reports, and a future technological proposal on drilling and logging for DGR development.

1. INTRODUCTION

Many 4000 m wells have been drilled in Italy, the USA and Mexico, and many 3000 m wells have been drilled in Japan, New Zealand and the Philippines. In some wells the formation temperatures exceed 350°C and in well DY-1A, temperatures greater than 500°C were encountered. This well was drilled with the objective of investigating the characteristics of the deep geothermal system in the Kakkonda geothermal field, Japan (Uchida, 1997).

In Japan, the cost of electricity generated by geothermal energy is high compared to other sources, such as oil, gas, coal, and atomic energy. This is one of the reasons preventing further development of geothermal power generation. Therefore, cost reductions by technology development are very important for geothermal energy, especially the reduction of drilling costs which amount to about half the total construction cost of power plants. Glowka (1997) reported that a typical geothermal well costs two to three times that of a typical oil and gas well drilled to the same depth. Therefore, it is logical to seek drilling cost reductions as a way of making geothermal power more cost competitive.

In March 1997, a cooperative study on drilling and logging technology was started under the framework of the IEA deep geothermal resources (DGR) task by a group of the participants. The work program of Subtask B is composed of three items. These include: a) review of drilling and logging data stored in the database; b) exchange of R/D information provided by the participants; and, c) integration and future recommendations.

2. DRILLING AND LOGGIN SUBTASK OF DGR

2.1 Attempt to make a database on drilling and logging technology

One of the main objectives of Subtask B is to carry out collaborative research on drilling and logging technology, through the exchange of information, and to develop a database on drilling and logging. Work on this program was carried out with the participants sharing the tasks.

As a significant activity of subtask B, drilling and logging technology, an information network was developed to promote the mutual exchange of information between the subtask members. Thirteen members from eight counties including Japan, Mexico, NZ, the USA, Australia, Italy, the Philippines, and Indonesia were involved in the network. The network members, especially Dr. John Rowley, provided information and papers for the database. About 150 papers related to drilling and logging of deep and/or normal geothermal wells have been stored in the database in the DGR web site, URL:www.ieageo.or.jp.

Most of these papers are from the USA (70) and Japan (45), others are from Italy (8), Mexico (4), Germany (4), Russia (4), Indonesia (3), New Zealand (3), and other countries. Papers were grouped roughly into several categories: (a) trouble assessment during drilling (11); (b) drill bits (9); (c) field case studies on drilling (59); (d) cost evaluation on drilling (6); (e) materials (3); (f) new drill systems (32); (g) logging technology (27); (h) general reports on deep geothermal resources (9); and others (3). The figures represent the number of papers included in the category. Several papers are related to two or three categories.

2.2 Proposed Program for Technical Information Exchange

At the first meeting of the DGR in 1997, the following five programs were proposed by participants from Japan, Mexico and the USA for exchange of technical information:

a) Development of polycrystalline diamond compact (PDC) drill bits for downhole motor drilling by Karasawa, Ohno and Kobayashi (NIRE, Japan);
b) Development of drilling technology for deep-seated geothermal resources by Wada and Bessho (NEDO, Japan);
c) Development of an advanced geothermal drilling system (AGDS) by Rowley (Pajarito Enterprises, USA), Saito (JMC, Japan) and Long (US DOE LV/YMP, USA);
d) Development of production technology for deep geothermal resources by Wada and Akazawa (NEDO, Japan);
e) Borehole logging based on optical fiber technology by Iglesias, Arellano, and Rodriguez (IIE, Mexico).

Progress on these proposed programs during this cooperative period will be reported at the WGC 2000.

3. ARANGEMENT OF DATA AND DISCUSSIONS

Based on information that appeared in the database, several topics on drilling and logging are discussed in the following section.

3.1 Drilling experiences to develop DGR in several countries

Since the beginning of geothermal energy development, the target depth has increased to expand geothermal power generation. For example, in the early 1970s, a drilling program to explore DGR occurred in Italy. At Cerro Prieto in Mexico, the well depth has increased gradually. Well depths in Japan also have increased, and well WD-1a, the deepest geothermal well in Japan, has been drilled to investigate DGR at the Kakkonda field.

Italy: 1n the early 1970s, the first oil crisis occurred which resulted in new proposals on the exploration of DGR. In contrast to the previous two-dimensional expansion, seismic surveys revealed the existence of a deep reflected plane and the drilling program for DGR commenced at three geothermal areas in Italy. In the late 1970s, a deep exploration program was started to investigate the existence of deep permeable layers with fluids at temperature and pressures that were higher than those of the shallower reservoirs. The number of wells and average depths were reported by a mission to Italy from Japan (JGEA, 1993) as shown in Table 1. In Italy, more than 140 wells have been drilled to depths greater than 2,500 m, about 100 of them are deeper than 3,000 m and 24 of these are deeper than 4,000 m (Baldi, 1997).

In Larderello, 82 wells were drilled between 1971 and May of 1994. The average depth was 3,350 m (Barelli,1995). There are few severe problems with deep well drilling, if adequate separation is maintained between the drill hole and the surrounding shallower reservoir by installing casing. But most deep wells drilled in the central area of Lardelrello encountered several kinds of problems due to extremely fractured formations which compose the shallower reservoir, and corrosive fluid at high temperature (Baldi, 1997). A total of 257 temperature surveys carried out in 121 deep geothermal wells at the Larderello, Monteverdi, Travale and Mt. Amiata fields were analyzed in order to determine their temperature range and to compare the surface thermal anomalies and the deep temperature trends (Fig. 1; Baldi, 1995).

Philippines: Drilling for geothermal resources in the Philippines has extended over a period of more than two decades. The majority of all geothermal drilling has been carried out by the Philippine National Oil Company (PNOC). The depth of PNOC wells drilled up to 1994 is shown in Figure 2 (Southon, 1994). The average depth of these wells is about 2,400 m. Most of PNOC's directional wells with standard configurations can be drilled for less than US \$1.5 million, which does not include access roads, rig moving, site preparation or permanent well head costs. They reported that when fluid losses were encountered in the production hole, fresh water was used, and that water had many advantages as a drilling fluid. PNOC's experience has shown that one of the major causes of past drilling difficulties while using water was probably due to poor hole cleaning through the use of low pump rates for the hole being drilled. A large percentage of the successfully drilled wells were completed with high pump rates. Time distributions for drilling a 2,500 m directional well, averaged for the period 1980-1992 (71.5 days) were analyzed. Drilling job classifications reported by PNOC, are divided into 15 categories such as drilling, reaming, tripping, directional surveys and circulation, other minor activities, run casing, casing and cementing, working stuck pipe, cement plugging, fishing, side tracking, operator standby, rig contractor standby and completion testing. This classification is the most detailed when compared to those of other field examples in section 3.3. The cost distributions for these wells are also reported by Southon (1994).

USA: A relation between drilling depth and bit penetration rate was reported by Ross (1992). The well, State 2-14, was drilled to 3,220 m in 160 days in the Salton Sea Geothermal Field in California's Imperial Valley for scientific study of a deep, high-temperature portion of this active geothermal system. The well was drilled mostly with tricone bits. Only 240 m was drilled with core bits. The average hourly penetration rates during drilling are summarized in Figure 3. The average penetration rate was relatively constant at approximately 7.5 m/hr from 900 m to 2,400 m including approximately 165 m that was directionally drilled at an average penetration rate of 5.5 m/hr. Even if formation rocks are different at depth, it is obvious that the average hourly penetration rates decrease with increasing depth.

Japan: The depth of wells drilled in Japan for geothermal resources development has increased year by year, but the average well depth in Japan is not as deep as it is in Italy, the Philippines, The Geysers in the USA, and Cerro Prieto in Mexico. Only five wells were drilled deeper than 3,000 m in Japan. A durability study of tricone bits at very high temperature was carried out (Saito, 1996). A total of thirty 8-1/2" tricone bits, which were used for drilling Well-21 and Well-22 at Kakkonda, were disassembled and inspected primarily for the conditions of their bearing sections. The formation temperature and depth where these bits were used were over 300°C below 1,500 m and over 350°C below 2,000 m. In this study, the bottom hole circulation temperature was estimated from the temperature survey conducted inside the bore hole assembly by thermometer runs. The surveys were carried out within one hour after mud circulation ceased. O-ring and diaphragms were found to start to fail at mud circulation temperatures of 140 to 150°C. Also, the bearing body diameters were slightly worn as long as the lubricating oil existed, even after many hours of drilling. Very minor bit drilling performance differences were noted among the different manufactures. Bits produced by 5 manufactures were used. It was found that the O-ring and diaphragm lives are 30 to 40 hours, 20-30 hours and less than 10 hours, where the formation temperatures are 300, 350 and over 400°C respectively. The rate of penetration recorded with bits used in Well-22 is summarized in Figure 4 (Saito, 1996). It is clear that ROP decreases with increasing depth due to extreme temperatures and pressures in the well.

Mexico: Development of the Cerro Prieto geothermal field has been expanding since the early 1970s and is still progressing. About 120 wells have been drilled in the field to tap the reservoir. The average well depth and bottom hole temperature at Cerro Prieto 1, 2, and 3 are 1,728 m and 308°C, 2,582 m and 326°C, and 2,319 m and 336°C, respectively. The maximum depth and temperature of exploration well M-205 is 4,389 m and 350°C (CFE, 1994).

New Zealand: To recover the reservoir pressure at the Wairakei geothermal field, drilling of make-up wells began in the mid 1980s. A total of 10 reinjection wells has now been drilled. The inclinations of some wells are significant and are as much as 70º from the vertical. A typical profile for WK306 is given as follows: drilled depth is 2505 m, true vertical depth is 1196 m, displacement is 2003 m, and inclination from true vertical depth of 600 m to the bottom is 70º. With respect to the progress of drilling technology in NZ, the drilling performance of several wells drilled at Wairakei were reported by King (1998) and are shown in Figure 5. In this figure, it is obvious that drilling performance has improved considerably. Even though the depth of well WK239, drilled in 1998, is about two times that of WK208, drilled in 1957, drilling days required for WK329 are only about 1/3 of those of WK208. It may be very useful if we could obtain more precise information on how such high performances were achieved.

3.2 Drilling Cost Analysis

At Sandia National Laboratory, several studies related to geothermal drilling cost reduction were undertaken as part of the U.S. Department of Energy's Geothermal Drilling Technology Program. Factors contributing to the relatively high cost of geothermal drilling were investigated, and potential technology improvements that could reduce those costs were identified and are shown in Table 2. When added together, the cost reduction goals for the various program areas exceeded 25%. If the overall cost-reduction goal can be achieved, geothermal power plant costs will be reduced by 10-15% (Glowka, 1997).

A project to estimate well costs in regions of current geothermal activity in the USA has been initiated. Costs associated with both normal drilling activities and commonly encountered drilling problems will be estimated. In addition to estimating well costs, the sensitivity of these costs to a number of parameters such as rate-of penetration and daily operating costs were examined. Figure 6 is an example developed from the costs associated with the drilling of a single interval of 12 1/4-inch hole from 4,000 feet to 8,000 feet. Because costs of casing, cement, logging and testing are constant in this interval, drilling costs including bit, tripping and turning are strongly affected by the rate-of penetration (Pierce, 1997).

Japan: A feasibility study on technical innovation of drilling technology was carried out by NEDO (1998) to investigate: a) the state of drilling costs and technology; and b) future recommendation on drilling strategy.

A drilling cost analysis was conducted based on well depths of 2,000 m, 2,500 m and 3,000 m and two casing programs of 4 and 5 stages. Parameters for sensitivity analysis of the cost analysis are the rate of penetration, the life of the bit, time required for lost circulation, casing cementing, costs of labor, materials, equipment ownership cost, and period of rig up and down. In this study, the drilling cost of a 3,000 m depth well and a 5 stage casing program is 878M Yen. One example of costs estimated with improvements in drilling and logging technologies reduces the total drilling costs by about 23% and 19% compared to the base case due to 2 stage cementing and tie back cementing respectively. In this example, technological improvements are expected as follows:

rate of penetration 110 %
bit life 200 % (from 15/hr to 30/hr)
tripping time -10 %
lost circulation -50 % (from 30 days to 12.5 days)
cost of labor, materials and equipment ownership -10 %
rig up and down -50 % (on the same drill site)

In this analysis the rate of penetration is summarized according to three different definitions: (drill length)/(total drill hours), (drill length)/(drilling, coring, tripping related to drilling), and (drill length)/(real drill hours). These values are 0.99 m/hrs, 1.66 m/hrs and 3.15 m/hrs respectively. The ROP of 0.99 m/hr was used as a basic value in this sensitivity analysis. When we consider the values of ROP, it is necessary to consider how the ROP was calculated. To achieve the drilling cost reduction, future tasks are envisaged as shown in Table 3 (NEDO, 1998).

3.3 Job time distributions of drilling wells

Based on the database, a comparison on the time distribution of drilling wells at several geothermal fields in different countries was attempted. Data were provided on well K6-2 at Kakkonda (Japan), a PNOC well (Philippines), an ENEL well (Italy), a Geysers well (USA), and a trouble-free well from Yamagawa (Japan). Depending on the data source, the degree of partitioning are different as shown in Table 4. For example in the case of Kakkonda, the total drilling effort is divided into 12 categories whereas ENEL's well is divided into 6 categories as shown in the bottom cells. For easy comparison and evaluation, we think it is necessary to aggregate these data into the same categories. Therefore, we classified these five different data sets into 6 categories: drilling and tripping, L/C treatment and other troubles, casing cementing, logging and coring, completion and well test, and others. Using this classification method, the time distributions of drilling are shown in Figure 7. If we add the time ratio of L/C treatment and other troubles to the time ratios of drilling, the values of 5 different fields are almost the same at about 70% of the total drilling time. It is clear that a reduction of L/C treatment and other troubles can provide a higher percentage of actual drilling time even if the drilling category includes both the real drilling time and tripping time. Figure 7 is an example of the time distribution of drilling. It allows us to compare and evaluate data obtained at different geothermal fields. Up to now, we have not been able to present an acceptable standard form of job categories. However, it seems necessary to make a standard classification of job categories for easy and effective usage of the database and for compiling drilling knowledge and experiences.

3.4 Logging Technology

Because of the heat resistance restriction of Teflon insulating material, the maximum temperature of the cable available today is less than 315°C. Therefore, it is not acceptable to run the cable into wells drilled into deep geothermal resources where high temperatures of about 400°C are expected. It is also very difficult to make a very long logging cable covered with electric insulating and heat resistance materials. The development of two logging tools acceptable for conditions within deep geothermal resources is being carried out by NEDO. One is a PTSD (Pressure, Temperature, Spinner and Density of fluid) logging tool using a memory gage that is free of the temperature limitations of the logging cable. The other is the development of a PTC (Pressure, Temperature and Chemicals; acts as a fluid sampler) tool which utilizes an optical fiber and a capillary tube (Isaka, 1997).

Reliable downhole data in geothermal wells is essential to understand the reservoir and optimize operation of the field. To reduce the high cost of conventional wireline logging, the following research is underway at Sandia National Laboratory (Glowka, 1997,b):

- high temperature memory logging tools (>10hrs at 400 °C)
- core tube data logger
- logging tool circuit employing Silicon-on–insulator semiconductor technology
- FS of thermal batteries for logging operations (>300 °C)
- FS of a high-temperature slimhole televiewer

SNL has developed a rolling float meter (RFM) that is mounted on the top of the rig's outflow line. It monitors fluid returns to rapidly detect lost circulation, which is a prevalent problem in geothermal wells and which can add as much as 10% to the total cost of drilling (USDOE, 1999).

4. PROPOSAL FOR THE FUTURE PROGRAM

Through the experiences on the development of DGR in Italy, they commented that increasing depth did not relate directly to the increase in power generation cost from geothermal fluids. The depth of the reservoir is one of the parameters that influence production costs of electricity from geothermal fluids. To minimize production costs of geothermal energy per unit kWh, ENEL pointed to three major themes. These are: a) reduce the drilling cost and drilling period; b) reduce cost and time for the surface production plant and power generation plant; and c) reduce the maintenance cost and time for operation of the plant including additional wells. To achieve this objective, standardization of the drilling rig and drill site (base) to allow equipment compatibility and standardization of the power generation plant to shorten the period between finding the geothermal fluid and the start of commercial power generation is needed. The only way to shorten the construction period is to begin the planning and ordering of the power generation plant before finishing the drilling of the wells and reservoir evaluations. The plant must have wide applicability for different types of geothermal fluids. They finally designed and manufactured a unit power generation machine of rather small output, ranging between 15 and 20 MW (Condenser type) (Cappetti, 1988).

Through information exchanged between the participants, the following research programs have been envisaged as a part of the future recommendations:

a) Development of a downhole percussion drilling system with mud circulation (Rowley, 1997);
b) Technology transfer from the oil and gas industries to the geothermal industry on casing drilling (Tessari, 1999) and the small exploration rig effectively employed in Italy (Gaddy, 1999).

These programs will contribute to the reduced drilling cost of deep geothermal wells under extremely high temperatures and within hard rocks. Additional discussion between members will be necessary to decide on the future research programs.

5. PAPERS PUBLISHED AS A PART OF SUBTASK B

The following papers related to drilling and logging technology were presented at international meetings organized by the operating agent NEDO:

Bessho, N., Wada, T., (1998), Development of Drilling Technology for Deep-Seated Geothermal Resources, Proceedings 20 th NZ Geothermal Workshop, p. 81-84.

Iglesias, E.R., (1997), Contributions form IIE, Mexico to the Deep Geothermal Resources Task of the IEA GeothermalImplementing Agreement, NEDO International Geothermal Symposium, March.

Isaka, S., Ikawa, T., Akazawa, T., (1997),Development of Drilling and Production Technology for Deep Geothermal Resources, NEDO International Geothermal Symposium, March.

Karasawa H., Ohno, T., Kobayashi, H., (1997), Research on Drilling techniques for Deep Geothermal Wells, NEDO International Geothermal Symposium, March.

Kobayashi, H., Karasawa, H., Ohno, T., (1997), The Drilling and Logging data and Technology Relate4d to the Development of Deep Geothermal Resources, GRC Council Transaction, Vol.21,p.289-298.

Kobayashi, H., Miyairi, M., Wada, T., (1998), The Logging data and Technology Related to the Development of DeepGeothermal Resources in Japan, The 20th NZ Geoth. WS.

Lalladay, N., (1997), Development of a high temperature borehole fluid sampler, NEDO International Geothermal Symposium, March.

Osato, K., Yamane, K., (1998), The Resistivity structure of the Deep Geothermal Reservoir in Kakkonda – TheExploration by the Borehole EM and MT/CSAMT Survey, Proceedings 21th NZ Geothermal Workshop, p. 115-120.

Rowley, J.C., Saito, S., Long, R.,(1997), New Drilling System Concept Could Reduce Geothermal Drilling Cost, Proc.of NEDO International Symposium, March, Sendai, p. 164-169.

Vaaca Serrano, J.M., Puente, H.G., Deep Well GeothermalDevelopment in Cerro Prieto, B.C. Mexico, NEDO International Geothermal Symposium, March 1997.

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References

Baldi, P., Bellani, S., (1995), Geothermal Anomalies and Structural Features of Southern Tuscany (Italy), Proceeding of WGC 1995, p. 1287-1291.

Baldi, P., Chccarelli, A., Fiordelisi, A., (1997), R&D of DeepGeothermal Resources in Italy, Proceedings of NEDO International Geothermal Symposium, March, 1997, p. 99-106.

Barelli, A., Cappetti, G., Stefani, G., (1995), Results of Deep Drilling in the Larderello-Travale/Radicondli Geothermal Area, Proceeding of WGC 1995, p. 1275-1278.

Cappetti, G. (1988), Development and its Economics of DeepGeothermal Resources in Italy, 8 th Symposium of New energy and Industry, Tokyo 10/20/1988.

Comision Federal de Electricidat, (1994), Cerro Prieto Geothermal Field, 25pp.

Gaddy, D.E., (1999), Italian land rig exploits small reserves, Oil & Gas Journal, Mar.22.

Glowka, D.A (1997a), The Role of R/D in Geothermal Drilling Cost Reduction, GRC Council Transaction, Vol.21, p.405-410.

Glowka, D.A (1997b), Geothermal drilling technology update, Proceedings Geothermal Program Review XV, p. 5.3-12.

JGEA (1993), Study Mission Report on Geothermal Development in Italy, J. of JGEA, Vol. 29, No.5, p. 1-57.

King, T.R., Robinson, Q.J. (1998), Drilling History at Wairakei, Proceedings 20 th NZ Geothermal Workshop 1998, p. 45-50.

NEDO, (1998), Feasibility Study on technical innovation of drilling technology (in Japanese), NEDO-P-9702, 215pp.

Pierce, K.G., Livesay, B.J., (1994), A study of Geothermal Drilling and Production of Electricity form Geothermal Energy, SAND92-1728.

Pierce, K.G., Bomber, T.M., Lieversay, B.J., (1997), Well Cost Estimates in Various Geothermal Regions, GRC Transactions, Vol. 21, p. 119-122.

Ross, H.P., (1992), Salton Sea Scientific Drilling Project, A summary of Drilling and Engineering Activities and Scientific Results, Final Report, April 1992, DOE/CE-12429-H1, 186pp.

Saito, S., (1996), Durability Study of Tri-Cone Bits in Very High Temperature Geothermal Wells (in Japanese), Chinetusu, Vol. 33, No.2, p. 1-15.

Southon, J.A.N., Dacanaay, J.U., Geothermal Drilling in the Philippines, Proceeding of Int, Geothermal Conference,Manila, Feb.,1994.

Tessari, R.M., Madell, G., (1999), Casing Drilling – A Revolutionary Approach to Reducing Well Costs, SPE/52789.

Uchida, T., Akaku, K., et al., (1997), Deep Geothermal Resources Survey Project in the Kakkonda Geothermal Field, Proc. of NEDO International Symposium, March, Sendai, p. 215-222.

USDOE, (1999), Sandia Instrumentation Assists Drilling Operations, Geothermal Technologies, Vol.4, Issue 2.

Table 1 Number of wells and their average depths in several geothermal fields in Italy (JGEA, 1993)

	Larderello		Travale		Monte.Amiata	
	Av.depth(m)	No.	Av.depth(m)	No.	Av.depth(m)	No.
1974	656	639	644	34	780	60
1984	1800	39	1874	25	2796	12
1991	2581	46	2673	4	2948	25
1992	3040	9+	3692	1+		

Table 2. Several research works on well cost reduction being carried out at SNL (after Glowka, 1997).

	Contents	Effect of cost reduction	Total Reduc-tion
Lost Circu-lation	Development of drilling-mud flow measurement system, expert system and drillable straddle packer. Evaluation of cements.	L/C cost is about 15% of a typical well cost. Reduce 30% of L/C costs.	5%
Hard Rock Bit	Improvement of PDC bits for hard rocks	Doubling the ROP and the bit life.	15%
High-Temper-ature Instru-menta-tion	Development of PTS memory tool, mamma memory tool, downhole steam sampler. Improvement of downhole logging methods.	5% reduction of wells to operate the reservoir and number of replacement wells.	1%
Slim-hole Drill-ing	Demonstrate slimhole test data can be used to predict production rates in large-diameter wells in the same reservoir	10% for exploratory wells. A 40% cost reduction by slimhole.	4%

Table 3. Envisaged research tasks to reduce drilling cost (NEDO, 1998).

	Future recommendation
Technical element develop-ment	Aerated mud drilling, DHM available high temperature, PDC bit for geothermal well drilling
Technical element improve-ment	Conventional bit improvements, application of stellarble motor, effective mud cooling, light and strong cement, evaluation of cement bond log, selection of adequate casing
System develop-ment	Percussion hammer drilling, coiled tubing drilling
System Improve-ment	Aerated mud drilling, inclination drilling, horizontal drilling, well cleaning during production, coiled tubing for well repairs

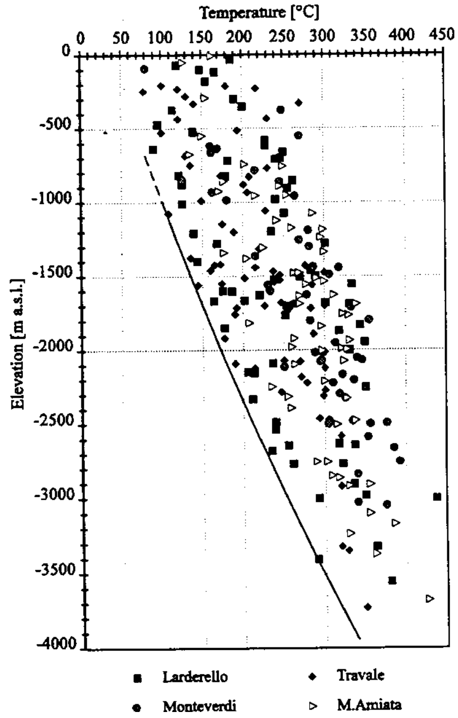

Figure 1 Formation temperature vs elevation in geothermal wells of southern Tuscany, Italy (Baldi, 1995)

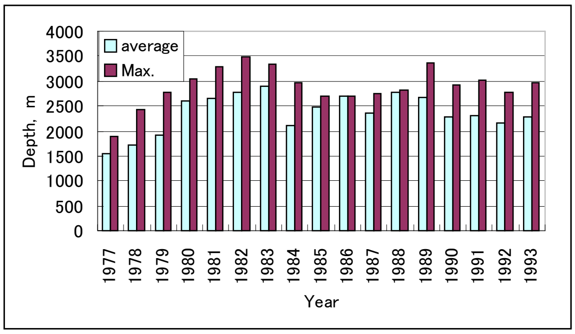

Figure 2. Depth of PNOC's wells (after Southon, 1994)

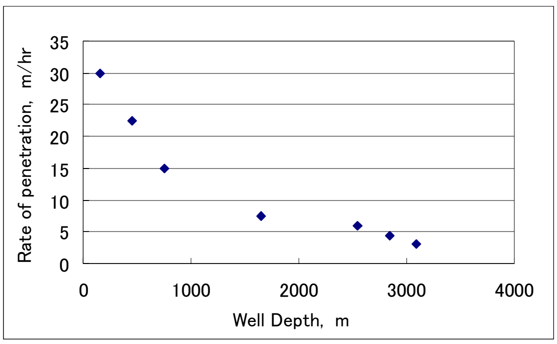

Figure 3. Relation between well depth and rate of penetration, Salton Sea scientific drilling program (after Ross,1992)

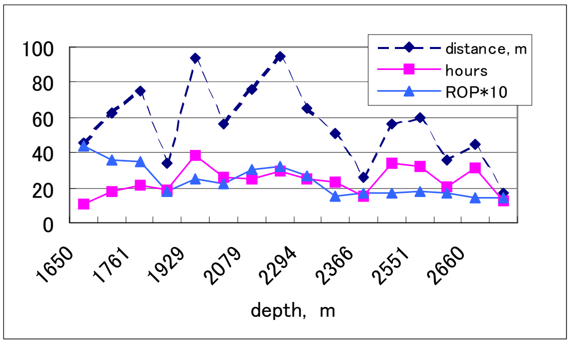

Figure 4 Performance of bits used in Well-21, Kakkonda, (Saito, 1996).

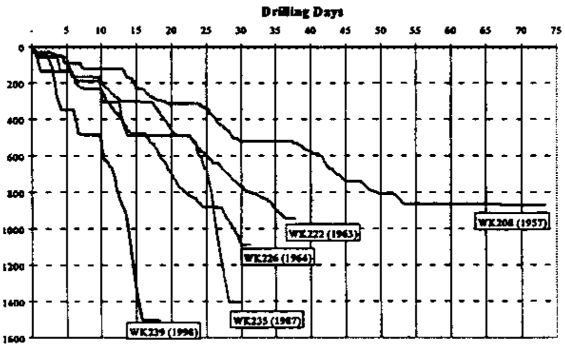

Figure 5 Timelines for random 200 series wells at Wairakei (King, 1998).

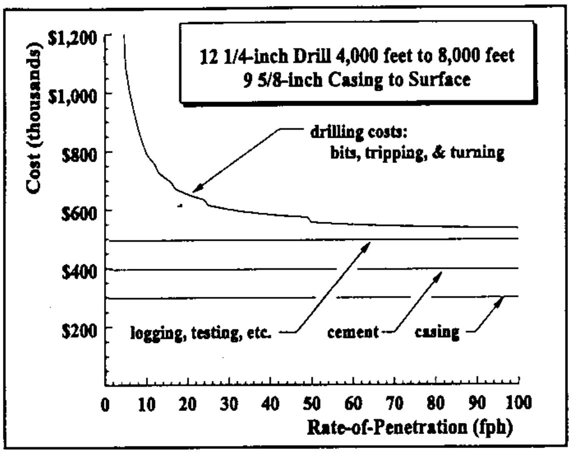

Figure 6. Influence of ROP for cost estimation (Pierce, 1997).

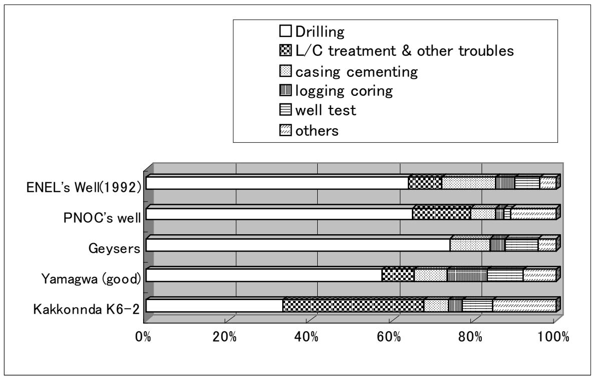

Figure 7. Time distribution of drilling wells at different geothermal fields

Table 4. Examples of drill job classification at several geothermal fields.

Japan	Philippine	Italy	USA	Japan
Kakkonnda K6-2	PNOC's well	ENEL	Geysers	Yamagawa
Drilling	drilling	drilling	drilling	Drilling
Reaming	reaming	directional drilling,	tripping	reaming
DH motor drilling	tripping	fishing etc		DH motor drilling
Tripping	working stuck pipe			tripping
Lost circulation	cement plugging			L/C & Blowout prevention
Drag hole	fishing			collapsing treatment
Circulation	side tracking			mud circulation
Casing cementing	run casing	casing cementing	casing	casing cementing
	casing and cementing		cementin g	
Logging	directional surveys & circulation	logging coring	logging	logging
Coring	coring			Coring
Well test	completion test	production test	completio n	completion test
Others	other minor activities		Well head/BOP	others
	operator standby			
	rig contractor standby			
12	15	6	7	12