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RESERVOIR EVALUATION FOR THE TANGGU GEOTHERMAL RESERVOIR, TIANJIN, PEOPLES REPUBLIC OF CHINA

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ABSTRACT

The Tanggu geothermal reservoir is situated in the North China Sedimentary Basin. Twenty three successful production wells, yielding water with an average temperature of about 70°C, have been drilled into this reservoir since 1987, in an area exceeding 300 km^2. *The hot water is mostly used for space heating. In 1995 the annual production exceeded 5 million tons. The hot water extraction has caused the water level to drop to a depth of 80 m in production wells, and it continues to decline at a rate of 3 - 4 m per year. This has raised the question whether the reservoir may be overexploited. The principal purpose of a reservoir evaluation carried out in 1996 was to estimate the long-term production potential of the Tanggu reservoir. Two simple models were developed for this purpose. The potential is determined by specifying a maximum allowable pump setting depth of 150 m. On this basis the potential of the Tanggu reservoir is estimated to be about 10 million tons per year, for the next ten years. A comprehensive reservoir management program must be implemented in Tanggu. The first priority of such a program should be to improve the energy efficiency of space heating in the district, which would potentially result in about 50% reduction in hot water consumption. Another management option is re-injection, which will counteract the water level draw-down.*

INTRODUCTION

China is rich in geothermal resources, some of which have traditionally been used for washing, bathing, therapeutic purposes and in agriculture. During the last two decades the use of geothermal energy has been growing rapidly. In addition to minor power production it is mostly used directly, principally for space heating. High-temperature geothermal system are found in tectonically and volcanically active areas, such as in SW-China (Wang et.al., 1995). Low- to medium-temperature systems of the convective type, where the geothermal water has circulated to great depths to mine the heat, are mostly found in tectonically active areas, with above average geothermal gradients, such as in SE-China. Other low-temperature geothermal systems are found in major sedimentary basins, in particular in E and NE-China.

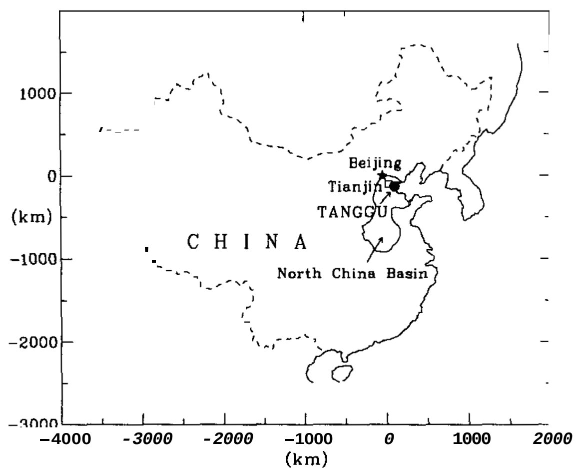

Figure 1. *Location of the Tanggu geothermal field.*

The Tanggu geothermal reservoir is situated in the North China Sedimentary Basin. It is located in the District of Tanggu, on the coast of the Bohai Bay in Tianjin in NE-China (Figure 1). Tanggu District has a population of about 450.000 and is located 120 km ESE of Beijing and 50 km east of Tianjin City. Tanggu City, a major seaport and industrial area, is a part of Tanggu District, with a population of approximately 360.000. Since 1987 twenty three successful production wells have been drilled in the Tanggu field. The majority of these wells is used for producing hot water, mostly for space heating. Currently about 720.000 m^2 of living space are heated by geothermal energy. The wells are drilled in an area of more than 330 km^2, making the Tanggu geothermal field very large in comparison to many other geothermal fields in the world.

In Tanggu the hot water is produced from the deepest part of the Guantao formation, which is mostly composed of upper Tertiary sandstone. The depth to the productive aquifer varies from 1500 to 2200 m and it's thickness is between 60 to 90 m. The temperature of the production aquifer ranges from 64 to 78°C. The existence of the geothermal resource is the result of permeable sediments found at relatively great depth in the basin and the above average heat flow from depth. The Guantao formation is very extensive in area, stretching over 900 km^2 in the district of Tanggu alone.

The hot water production has caused the water level in the geothermal system to drop by 40-50m. At present it declines at a rate of 3-4 m per year, which has been a matter of increasing concern for the utilities producing from the field. The question has arisen whether the geothermal reservoir may be overexploited.

The Tanggu geothermal system has been comprehensively explored by the Tianjin Geothermal Research and Development Institute (1990). A part of that study was an assessment of the reservoir's potential by the use of volumetric methods. Such methods, however, tend to overestimate the potential of a geothermal resource and can not be used to predict the response (water level decline, cooling) of a reservoir to production. They only provide a rough first estimate of a reservoir's potential. The only modeling carried out for the Tanggu reservoir to date is the one presented by long (1996a).

This paper presents the principal results of a recent reservoir evaluation for the Tanggu geothermal reservoir (Axelsson, 1996). It constitutes a part of a geothermal development project being undertaken by Virkir-Orkint Consulting Group of Iceland (VO), on one hand, and the Tanggu Geothermal Office (TGO) and the local authorities in Tanggu, on the other hand. The principal purpose of the evaluation was to estimate the long-term production potential of the geothermal reservoir, by predicting the future water-level changes in the reservoir. The purpose was, therefore, partly to answer the question whether the geothermal reservoir is, or will become, overexploited. The reservoir assessment also addressed several other aspects of the management of the reservoir.

Geothermal reservoir engineering has become an integral part of the management of geothermal systems worldwide, and modeling studies constitute the most important tools of this discipline (Bodvarsson and Witherspoon, 1989; Stefánsson et.al., 1995). Therefore, the main part of the Tanggu reservoir evaluation involved the development of two simple models which have been used to simulate the water level decline in the geothermal system.

The paper is organized as follows: This general introduction is followed by a presentation of the drilling and production history of the Tanggu geothermal field, including a discussion of the response of the reservoir to production. Following this the two models developed for the reservoir are discussed. Consequently water level forecasts for different future production scenarios are presented, followed by a brief summary and recommendations regarding the future management of the reservoir.

PRODUCTION HISTORY

The Tanggu geothermal reservoir was discovered during intensive oil-exploration drilling in the eighties, and the first geothermal well in the field was drilled by the BOHAI oil-company in 1987. Presently twenty three successful production wells have been drilled into the Guantao formation. Some information on these wells is presented in Table 1 and the locations of the wells are shown in Figure 2. These wells are drilled and operated by several different companies or enterprises. The wells range in depth from 1450 m to 2200 m and the discharge temperatures from 60° to 74°C. Most of the wells are utilized for space heating, except a few which are utilized for various other purposes (recreation, fish-farming, etc.).

During the official heating season, from the middle of November till late March, pumps with capacities of about 35 l/s are installed in most of the wells (VO Consulting Group, 1994). For the rest of the year much smaller pumps, for tap water production, are installed. Since well TR-1 was drilled, the hot water production has been steadily increasing, from about 600,000 tons in 1988 to 5 million tons in 1995. The average monthly production from the Tanggu reservoir is presented in Figure 3. The production was about 100 l/s during the winter of 1988/1989, but reached almost 310 l/s during the winter of 1995/1996. The production is more or less constant during each heating season, because speed controlled pumps and automatic controls are lacking.

Table 1. *Wells in the Tanggu geothermalfield.*

Well	Drilled	Depth (m)	Use(s)
TR-1	1987	2034	heating
TR-2	1988	2049	- " -
TR-3	1988	2042	- " -
TR-4	1988	1935	- " -
TR-5	1988	2025	- " -
TR-6	1989	2120	- " -
TR-7	1990	2150	various
TR-8	1989	2072	heating
TR-9	1990	1994	- -
TR-10	1990	2004	observation well
TR-11	1991	1912	various
TR-12	1991	2070	heat/tap water
TR-13	1991	2025	- -
TR-14	1993	2000	heat/recreation
TR-15	1993	1448	heating
TR-16	1994		- " -
TR-17	1994		- -
TR-18	1995	2200	not in use
TR-19	1995	2200	- " -
TR-20	1995		- " -
TR-21	1996	1940	heating
TR-22	1996	2050	- " -
TR-23	1997		not drilled
TR-24	1996	1960	- -
TRI-1	1992	2000	injection well

The hot water is mostly used for space heating (Cao, 1992 Zheng and Cao, 1995). During the 1995/1996 heating season about 720.000 m^2 of living space were heated by geothermal energy, and the heated area will probably have increased by 200.000 m^2 at the end of 1997, or by almost 30 %. The hot water for this increase will mostly be provided by wells TR-21, 22 and 23. It must be pointed out, however, that at the return water temperatures prevalent in Tanggu (45-50°C), the production during the 1995/1996 heating season must only have partly met the heating demand of those 720,000 m^2. The district heating systems in Tanggu are operated separately, i.e. one system per well (VO Consulting Group, 1994). Only a few of the pumps currently in use are fitted with speed converters for controlling the well production. These aspects seriously impede the optimization of geothermal utilization in Tanggu.

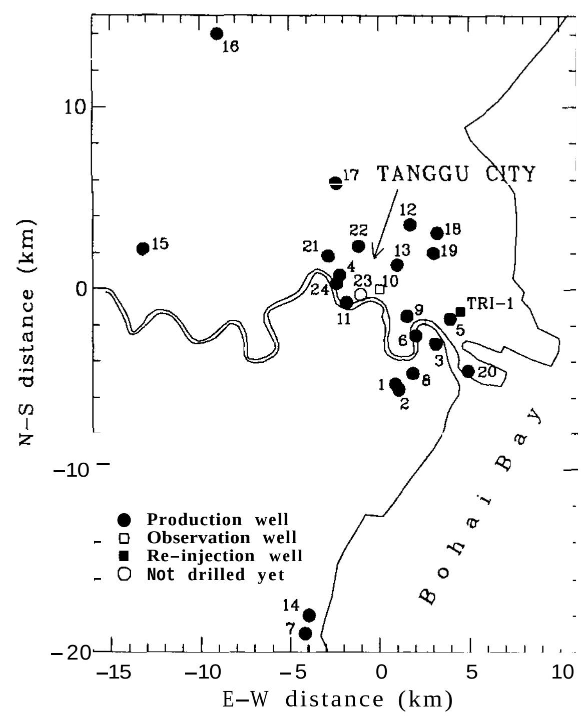

Figure 2. *Locations of wells in the Tanggu field.*

The hot water extraction has caused the water level in the geothermal system to drop by 40-50m since 1987, which is the most pronounced production induced response seen in the Tanggu reservoir. The water level in most production wells drops, of course, even more during production. During the 1995/1996 heating season the water level in production well TR-4, which is centrally located, fell to a depth of 80 m. The water level continues to decline at a rate of 3-4 m per year, which has been a matter of increasing concern for the utilities producing from the field. In addition the water level is now approaching the setting depths of many of the pumps presently in use (80 m).

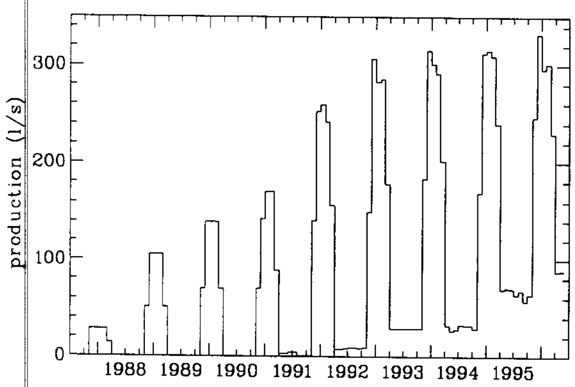

Figure 3. *Monthly production from all wells in the Tanggu geothermal field.*

Monitoring of the production response of the Tanggu geothermal reservoir has been very limited. Yet some water level monitoring has been carried out and the most important data are a five year continuous record from the only observation well in the field, well TR-10. These data are presented in Figure 4. Some data are also available from well TR-1, also shown in the figure. Limited water level data, not presented here, are available from a few other wells.

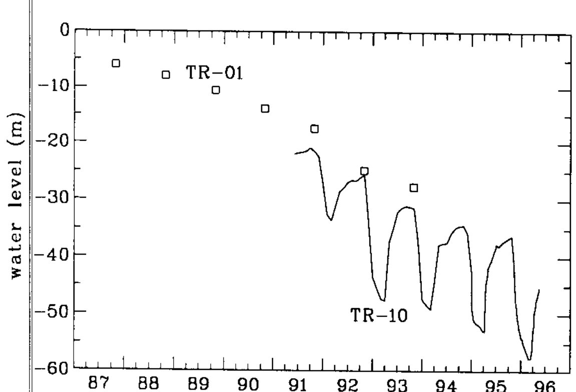

Figure 4. *Water level monitoring in well TR-10 along with annual (Oct/Nov) measurements from well TR-01.*

The production response may also manifest itself in other changes besides the drop in water level. These are possible colder water inflow, which will eventually cause the production reservoir to cool down, sea water intrusion and land subsidence. Inflow of water from outside the geothermal reservoir should manifest itself in changes in the chemical content of the water produced. Chemical analyses of the geothermal water in Tanggu do not indicate that cooling or sea water intrusion will hamper production from the reservoir in the near future (Axelsson, 1996). In addition the subsidence, which has taken place in Tanggu in recent years (40 cm since 1984) is believed to be only partly because of geothermal production.

RESERVOIR MODELING

The principal purpose of the reservoir evaluation was to estimate the long-term production potential of the Tanggu geothermal reservoir. In view of this, two simple analytical models were developed and used to simulate the observed water level decline. Firstly, a lumped model wherein only the total production from the field is considered, but neither the effects nor locations of individual wells. In this model no a-priori assumptions on the nature or geometry of the system are made. Secondly, a distributed model of a horizontal reservoir with a very great areal extent, wherein the location and production of each individual well are taken into account. No detailed numerical modeling was carried out during this study, principally because the limited data available was not considered enough to warrant such modeling. The reservoir modeling is described in detail by Axelsson (1996).

Lumped models have been used extensively to simulate data on water level and pressure changes in geothermal systems in Iceland (Axelsson, 1989; Axelsson and Arason, 1992). The lumped model for Tanggu simulated the water level decline quite accurately. In this paper the main emphasis is on the distributed model, however.

The distributed parameter model simulates a horizontal reservoir with a constant thickness, as well as constant properties (permeability and porosity), with an infinite areal extent. In addition a fault is introduced in the model, which may either serve as a no-flow or a constant pressure (recharge) boundary. Permeability anisotropy is also allowed. In this model the location and production of each individual well are taken into account. The two simple models are, therefore, very different. On one hand there are no geometrical constraints inherent in the lumped model, in contrast to the fixed geometry of the distributed model. On the other hand the effects of individual wells may be simulated in the distributed model, while this is not the case for the lumped model.

The properties of the distributed model were varied until the calculated response simulated the observed water level changes sufficiently well. These were the transmissivities in the x- and y-directions, T, and T, respectively, defined by $T_j = k_j h/\mu$, and the storage-coefficient, $c_t h$, with k the reservoir's permeability, h it's thickness and c_t it's compressibility defined by $c_t = c_w\phi + c_r(1-\phi)$, where c_w is the water compressibility, ϕ the porosity and c, the compressibility of the rock matrix. The fault was assumed a no-flow boundary located 18 km west of well TR-IO, striking 30° E of N, coinciding with the so-called Cangdong fault (TGR&DI, 1990). Including this fault in the model turned out to result in a better fit, which is believed to show that the Cangdong fault plays a major role in the Tanggu reservoir, acting as an impermeable boundary. This is no surprise since the Guantao formation is both thinner and found at shallower depth west of the fault. The fit of the model calculations to the field data is shown in Figure 5.

The properties of the best fitting model are the following:

$$k_x h/\mu = 5.1\times10^{-7}\,m^3/Pa\,s$$

$$k_y h/\mu = 1.3\times10^{-7}\,m^3/Pa\,s$$

$$c_t h = 2.1\times10^{-8}\,m/Pa$$

A moderate anisotropy, $k_x/k_y = 3.9$, was incorporated in the model resulting in a slightly better fit than obtained without anisotropy. The explanation may be that some fractures in the reservoir, striking approximately E-W, cause higher permeability in that direction.

Based on a drill core porosity of $\phi = 0.2$ and compressibility $c_t = 1.2\times10^{-10}\,1/Pa$, the storage coefficient yields a reservoir thickness of 180 m. This is in a very good agreement with the geological conditions in the reservoir. Based on this thickness an average permeability of $5.5\times10^{-13}\,m^2$, or 0.55 Darcy, results. Similar permeabilities have been estimated independently on the basis of the lumped modeling and by analysing short-term well test data (Axelsson, 1996).

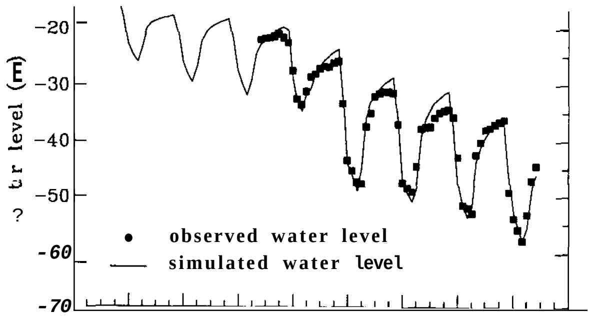

Figure 5. *Water level changes in well TR-IO simulated by the distributed parameter model.*

RESERVOIR POTENTIAL

The simple models were consequently used to estimate the production potential of the Tanggu geothermal reservoir. This was done by calculating water level forecasts for different future production scenarios, since the production response of the reservoir is chiefly manifested as water level draw-down. Both the lumped and distributed models simulate the water level decline in the Tanggu reservoir quite accurately. Yet, since the geometry and properties of the distributed model are in a very good agreement with the geological conditions in the geothermal system, the distributed parameter model was considered more reliable.

A maximum allowable draw-down determines the production potential. Specifying such a lower limit is not straight-forward, however, but was done on the basis of several criteria: Firstly, on the basis of the setting depths of well pumps. Even though, many of the pumps presently in use in Tanggu have a maximum setting depth of less than 80 m, there are pumps produced in China, with maximum setting depths of 100 - 200 m. Secondly, by the design of the production wells. Some of the earlier Tanggu wells are cased with a 13 3/8" pump pipe, down to 150 m only. Thirdly, by the danger of colder water inflow, and hence cooling of the reservoir. This danger is considered minimal, but increases rapidly with increasing draw-down. The fourth criteria is set by land subsidence. It is considered unlikely, however, that some increase in production will influence the subsidence seriously.

Based on the above considerations, as well as the nature of the Tanggu reservoir, the maximum allowable draw-down will here be set at 150m depth. Therefore, the reservoir should sustain some increase in production. Extending the limit much further, however, is not warranted at this stage. In the future, if the draw-down in the reservoir approaches this limit and a re-evaluation allows, the limit may be extended to a greater depth and the potential of the Tanggu reservoir revised. It should be mentioned that the pressure or water level draw-down, during production, is quite variable in other geothermal systems in the world. In Iceland, for comparison, it varies from practically zero in highly permeable systems with sufficient recharge to more than 400 m in poorly permeable geothermal systems in the older parts of the Icelandic crust.

The water level predictions were calculated for four different production scenarios: First a scenario (I) where the 1995/1996 production is maintained for the next ten years, i.e. an average yearly production of 170 l/s with a heating season average production of 300 l/s. Secondly a scenario (II) where all the available wells have been put into full use in 1998. In this case the average production increases to 360 l/s, or by 125% and the maximum production increases to 580 l/s, or by 90%. The predictions for these cases, calculated by the distributed model, are presented in Figure 6, which shows the water level in well TR-10. The water level in well TR-4 may be expected to be about 20 m below the water level in well TR-IO. This can be seen in Figure 7, which shows the water level in well TR-4, again calculated by the distributed model. The water level in other production wells is in most cases expected to be higher than the water level in TR-4, in particular in the wells which are located some distance from the center of the well field.

These figures show that for scenario I, the water level in the geothermal system will stay above 65 - 70 m, whereas the water level in production wells will stay above 90 - 100 m. For scenario II, the water level in the geothermal system will drop to 110 - 125 m, whereas the water level in production wells will decline to 135 - 155 m.

Based on these results the production potential of the Tanggu reservoir is estimated to be about 10 million ton per year, or about 320 l/s on the average for the next ten years. The maximum production for shorter periods (few weeks) should not exceed 550 l/s. The reservoir is clearly not overexploited, but this potential estimate assumes utilizing well pumps with setting depths of at least 150 m. It must be kept in mind, however, that the operational costs of pumps increases rapidly with increasing depth, which may set an economical limit to the maximum draw-down. The estimated potential of the Tanggu reservoir is based on predictions for the coming ten years only. The maximum pump setting depth and hence the reservoir potential should be revised on a regular basis in the future, i.e. every five years.

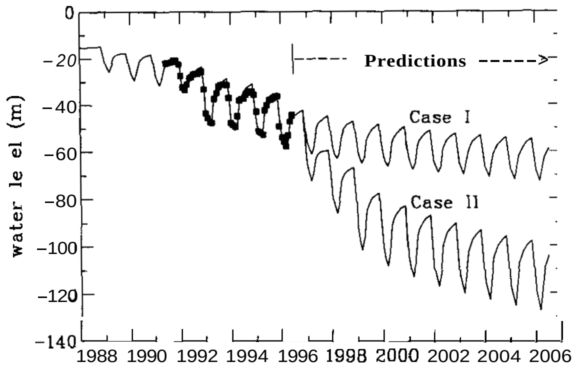

Figure 6. *Water level in well TR-10 as predicted by the distributed model, for production scenarios* **I** *and II.*

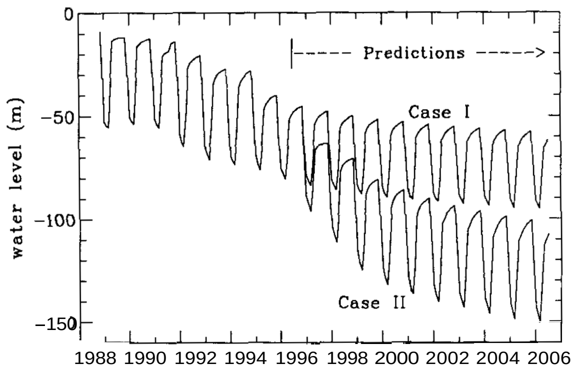

Figure 7. *Predicted water level in production well* ***TR-4,*** *for scenarios I and II.*

Water level predictions were calculated for two additonal production scenarios which assume that drastic measures will be taken during the next 5 years to improve the energy efficiency of space heating in Tanggu. These involve: 1) integrating the separate district heating systems into one system, with improved distribution system insulation, *2)* installing speed controlled pumps in all wells, and

3) improving the indoor heating systems by increasing radiator size and installing automatic controls. Principally these measures would result in a 50% reduction in hot water consumption per unit heating area. The results are presented in Figure 8. First considered is a scenario where the currently heated living space (720,000 m^2) is not assumed to increase during the next ten years (scenario 111). This would keep the water level in the geothermal system well above 60 m (TR-10), and above 90 m in production wells. Secondly a scenario where the geothermally heated area increases in steps during the next ten years, from 720,000 m^2 to 1,320,000 m^2, or by 83% (scenario IV). This would cause the water level in the geothermal system to decline to a depth of about 90 m, and the water level in production wells to about 120 m depth, by the end of the prediction period. In spite of this great increase in heated area, this would still be well above the maximum allowable draw-down of 150 m, used to estimate the potential of the reservoir

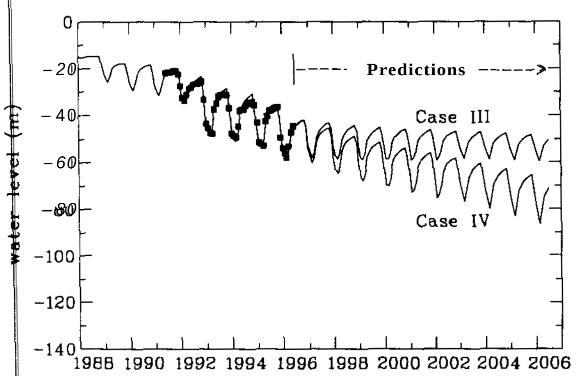

Figure 8. *Water level in well TR-10 as predicted by the distributed model, for production scenarios III and IV.*

Re-injection will counteract the water-level draw-down to some degree, and hence increase the production potential of the Tanggu geothermal system. This was studied in detail during the reservoir evaluation (Axelsson, 1996). The results indicate that to achieve a significant benefit the re-injection must be a substantial part of the production. Therefore, several re-injection wells are required, at least 4 - 8 wells. This will increase the production potential of the Tanggu reservoir by 10 to 20%. According to the distributed model re-injection wells must be drilled relatively close to production wells to achieve a maximum benefit. Too short a distance, however, will cause an untimely thermal breakthrough and cooling of production wells. Calculations indicate that a minimum distance of 1000 m is required. A re-injection test is already under way in Tanggu (Dong, 1996b).

CONCLUDING REMARKS

The Tanggu geothermal system is an extensive, highly permeable, horisontal sandstone reservoir, bounded to the west by the Cangdong fault. The depth to the reservoir varies from 1500 to 2200 m and it's thickness is between 60 to 90 m. The reservoir temperature ranges from 64 to 78°C. Twenty three successful wells have been drilled in an area exceeding 300 km^2. A simple model, which simulates the geology of the reservoir, as well as it's reponse to production, has been developed. The principal result of the reservoir evaluation for the Tanggu geothermal reservoir is that it's production potential is about twice the current production. This study also resulted in several recommendations regarding the future management of the reservoir, listed below:

- A comprehensive reservoir management programme must be designed and implemented for the Tanggu geothermal reservoir. This should, of course, be a cooperative undertaking of the different companies utilizing the field.

- Even though this evaluation indicates that the production potential of the Tanggu reservoir is about twice the current production, the production from the field should be increased slowly in steps. At each step the response of the reservoir should be evaluated and it's potential revised.

- The most important reservoir management action which can be taken in Tanggu would be to improve the energy efficiency of the space heating as already discussed. The resulting reduction in hot water consumption would result in some water level recovery and reduced operational costs, if the heating area remains constant. It may also make it possible to double the present heating area, without surpassing the production potential of the geothermal reservoir, and hence double the revenue from space heating. Such improvements constitute, of course, a major undertaking for the companies involved, but this may be carried out in small steps during a longer period.

- The combined yield of the 23 wells, drilled so far in Tanggu, exceeds the estimated production potential of the reservoir. It is therefore recommended that no new wells be drilled in the area. If the separate district heating systems are integrated into one system, some of the existing wells may be used as re-injection or back-up wells. If more production wells are nevertheless drilled in the area, they should be located more than 2 km away from other production wells.
- Re-injection is potentially a very important management operation in the Tanggu field, since it will counteract the water level decline. The re-injection test currently under way in Tanggu must be continued. A tracer test should be carried out concurrently with the re-injection, principally to confirm the current model of the reservoir (Axelsson et.al., 1995).
- Monitoring in Tanggu needs significant improvement, particularly in view of the foreseeable increase in production during the next few years. Monitoring data is the basis of modeling studies, and evaluations, such as the one presented here.
- Since the two simple models, used in the reservoir evaluation, simulate the geothermal reservoir fairly accurately, they should suffice as management tools for the Tanggu reservoir in the coming years. In the future, however, as more data become available, a detailed numerical model for the Tanggu reservoir should be developed.

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