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POWER GENERATION POTENTIAL AT CHINGSHUI GEOTHERMAL FIELD, TAIWAN

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ABSTRACT

Chingshui geothermal field is one of the promising geothermal prospects in Taiwan because of its relatively high resource temperature and available geological and reservoir studies. During its development phase, numerous shallow and deep wells were drilled for exploration and production, and reservoir flow and storage capacities were estimated from flow tests in some wells. From earlier studies, we concluded that the major reasons for the relatively low level of power generated in the 1980s were the high skin factor in the wells drilled with mud and the lack of produced water reinjection. In this study, the power capacities of wells and recoverable geothermal reserves at the Chingshui field were re-assessed based on the current availability of advanced binary-cycle power plants and downhole pumping technologies. Given (a) the reservoir properties of Chingshui as penetrated by the wells, (b) a minimum fluid temperature of 180°C, (c) the range of skin factor (6.6 to -2) achievable by the present drilling technology, and (d) the present state of binary plants and downhole pump technologies, we estimated conservatively that the net generation capacity per well achievable by pumping would range from 2 to 7 MW. From a probabilistic volumetric approach, the total recoverable geothermal reserve estimated in the area is sufficient for a plant capacity of at least 22 MW, and most-likely 32 MW. These results suggest the possible number of wells needed for developing the power capacity specified. All these analyses indicate that it is possible to develop a 20 to 30 MW, binary-cycle power plant at the Chingshui field provided the skin effect in current wells can be reduced or new production wells are drilled.

1. INTRODUCTION

Taiwan, an island in west pacific "ring of fire", is a country with abundant hydrothermal resources. Chingshui geothermal field, located in northeastern Taiwan, was first developed in the 1970s by governmental institutes in Taiwan. Unfortunately, the development plan was abandoned in the late 1980s due to the rapid pressure decline in reservoir where no produced water was reinjected. Geologically, the Chingshui area is located at the northeastern end of the submetamorphic zone. The reservoir rock is the fractured submetamorphic slate of the Miocene Lushan formation, which is the predominant rock widely cropping out all over this area (Chiang et al., 1979). Detailed geological and geophysical studies can be referenced to Tseng (1978), Su (1978), and Lee et al. (1980). The reservoir type in Chingshui is moderate-temperature, liquid-dominated reservoir with high gas contents. From 1970 to 1985, major studies and drilling activities were conducted by the Chinese Petroleum Corporation and Taiwan Industrial Technology Research Institute. During that period, ten deep wells were drilled at the Chingshui field by the Chinese Petroleum Corporation. Among them, seven wells tapped potential feed zones and flowed successfully. Figure 1 shows the inferred reservoir temperature distribution at 1500m depth and well locations at the Chingshui field. Several flow tests were conducted to estimate the capacity of the reservoir in the 1970s. Completion tests of well 4T were conducted by Chiang et al. (1979) and interference tests were conducted and analyzed by Chang and Ramey (1979), and recently reanalyzed by Fan et al. (2005). These results provided possible reservoir performance parameters. However, no systematic studies of recoverable reserves and commercial power generation potential were conducted.

The major reservoir-related factors controlling power generation potential are: reservoir temperature, pressure, and hydraulic characteristics. Reservoir temperature and pressure can be readily measured and monitored once a well is completed. Reservoir hydraulic characteristics depend primarily on the following parameters: porosity (ϕ), permeability (k), formation thickness (h) and skin factor (s). The product of reservoir permeability and thickness, kh, is referred to here as "reservoir flow capacity"; the

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product of reservoir porosity and thickness, ϕh, is referred to as "reservoir storage capacity". Skin factor is a dimensionless parameter indicating the magnitude of the well damage due to drilling fluid invasion, mechanical damage and chemical precipitation. A zero skin factor means an undamaged well. The larger the positive skin factor, the more a well is damaged, whereas a negative skin factor implies a stimulated well.

Chang and Ramey (1979) conducted an interference test by flowing well 16T and observing the pressure response in 5 other wells (4T, 5T, 9T, 12T and 14T). The data from well 5T were believed to be less reliable, and hence not considered in subsequent studies. From the radial flow model, the values of reservoir flow capacity estimated were moderate in general, as were the values of storage capacity. Fan et al. (2005) reanalyzed those test data using both radial and linear flow models. Though they concluded that the linear flow model fits the interference test data better, analysis of the interference data using the radial flow model was adopted in our study to compare with earlier results. Table 1 summarizes the possible reservoir properties obtained from these analyses. As shown in Table 1, the results from shallowest well 4T indicate promising reservoir parameters; however, further pressure drawdown tests of this well indicated a high skin factor ranging from 6.6 to 12.6 (Shen and Chang,1979). Some surprisingly high skin factors (s > 40) were even reported from other wells in the field (Ramey and Chang, 1979). This implies serious well damage and might be the major factor leading to the low production rate experienced in the 1980s when a 1.5 MW back-pressure power plant was installed. With the improvement of drilling technique, it is not difficult to drill a well with zero skin factor, even with a negative skin factor due to the well's intersecting open fractures. Based on these historical data, we considered the Chingshui field to be a good candidate for re-assessment of the power generation potential.

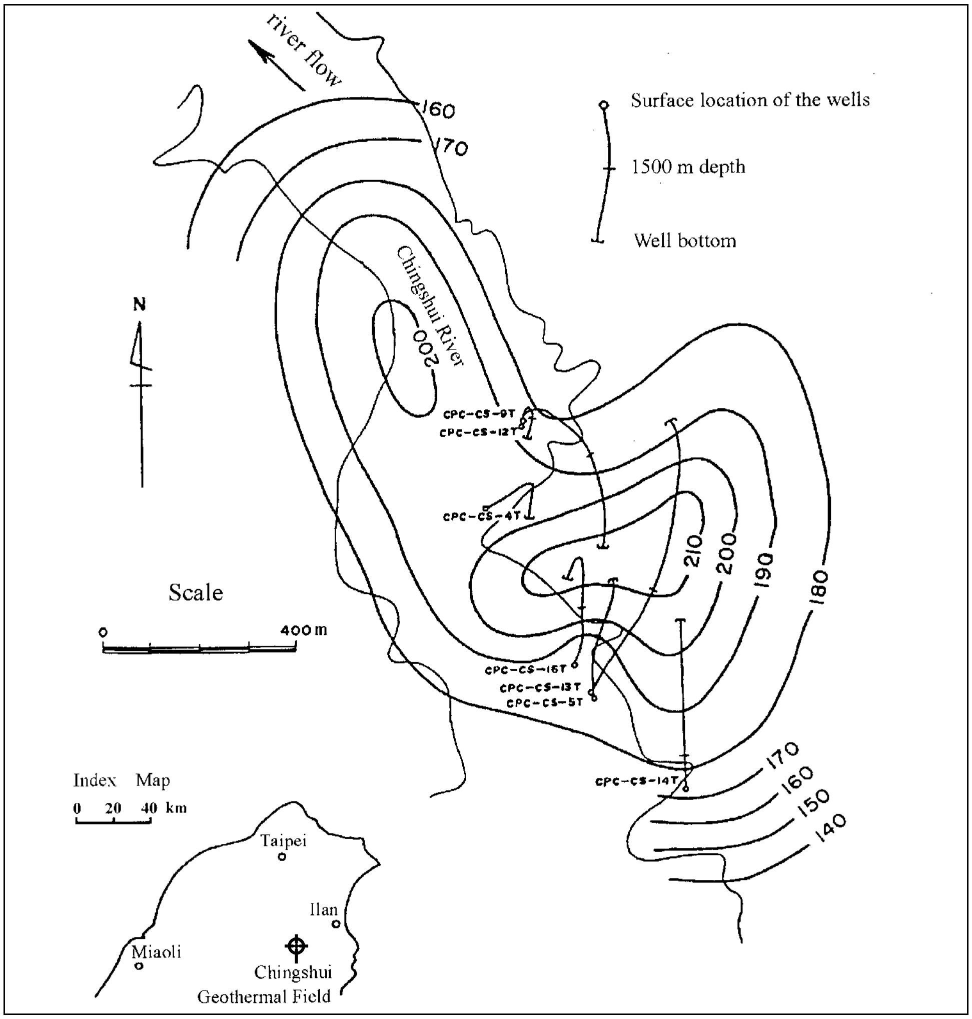

Figure 1. Well locations and inferred temperature distribution (in degree Celsius) at 1500 m depth in the Chingshui geothermal area (after Chang and Ramey, 1979).

Table 1. Reservoir properties estimated from wells at the Chingshui Geothermal field.

Well	Total Depth (m)	T at TD (^{o}C)	ϕh (m) [a]	ϕh (m) [b]	kh (darcy-m) [a]	kh (darcy-m) [b]
4T	1505	201	160	425	8.8	9.24
5T	2005	220	790	NA	2.5	NA
9T	2079	205	60	185	7.8	7.49
12T	2003	223	120	1650	8.8	7.59
14T	2003	215	200	108	4.3	4.18

[a] from Chang and Ramey (1979)
[b] from Fan et al. (2005)

2. METHODOLOGY

As shown in Table 1, the ranges of reservoir temperature, flow capacity and storage capacity at the Chingshui field were moderate. To maximize energy recovery, the installation of a binary-cycle power plant and well production with downhole pumps is suggested. Therefore, all discussion hereafter is based on this development plan. Sanyal et al. (2005) proposed an approach to optimizing the power capacity of pumped wells from moderate temperature geothermal systems by utilizing the well productivity characteristics and present pumping technology. This approach serves as the main framework of our study of the well productivity at Chingshui.

2.1 Productivity Characteristics of a Geothermal Well

Most of the discovered geothermal reservoirs worldwide are fractured reservoirs. To apply the pressure transient theory developed for petroleum and groundwater fields (Earlougher, 1977), we have treated the fractured rocks as equivalent homogeneous porous media. The basic equation for the radial flow of a single phase fluid in homogeneous porous media is derived as:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{k\rho}{\mu} r\frac{\partial p}{\partial r}\right)=\phi c_t\rho\frac{\partial p}{\partial t} \tag{1}$$

where p is pressure; k is reservoir permeability; r is radius; t is time; ρ is fluid density and c_t is total compressibility (of rock plus fluids). All symbols used in this paper are defined in the Nomenclature section below.

For a production well, the wellbore pressure transient between the early time wellbore-dominated response and the late time boundary-dominated response is called the “infinite acting period” (Horne, 1998). In the radial flow model, the fluid flow during this period is called “infinite acting radial flow” (IARF). In liquid-dominated geothermal reservoirs, which are of vast extent compared to well spacing and are subject to natural recharge of fluids from outside the reservoirs, the late-time boundary-dominated response is rarely experienced. Therefore, we consider the IARF only in the analysis below. Utilizing the Line-Source Solution (Earlougher, 1977) of Equation (1), the mass production rate from a single well in IARF is given as:

$$w=\frac{2\pi(kh)\rho(\Delta p)}{\mu\, p_D}, \tag{2}$$

In equation (2), p_D is given by:

$$p_D=-\frac{1}{2}Ei\left(\frac{-r_D^{\,2}}{4t_D}\right), \tag{3}$$

where t_D is a dimensionless time function and r_D is a dimensionless function of radius, as described below:

$$t_D=\frac{(kh)t}{(\phi h)c_t\mu r_w^{\,2}},\quad \text{and}\quad r_D=\frac{r}{r_w}$$

In equation (3), Ei is the Exponential Integral function. In the wellbore ($r_D = 1$), equation (3) can be approximated by:

$$p_{wD}=\frac{1}{2}(\ln t_D+0.80907) \tag{4}$$

Equation (4) is valid for $t_D/r_D^{\,2} > 10$. Productivity Index (PI) is defined here as the total mass flow rate (w) per unit pressure drop (Δp), that is,

$$PI = w/\Delta p\,, \tag{5}$$

where $\Delta p = p_i - p_{wf}$. From equations (2) and (5), *PI* for a single, undamaged well can be expressed as:

$$PI = \frac{2\pi(kh)\rho}{\mu\, p_D} \tag{6}$$

For a damaged or stimulated well, the additional pressure loss or gain caused by skin effect is given as:

$$\Delta p_{skin} = \frac{w\mu}{2\pi(kh)\rho} \cdot s \tag{7}$$

and the dimensionless skin factor (s) can be added to p_D in equation (6), that is:

$$PI = \frac{2\pi(kh)\rho}{\mu\,(p_D + s)} \tag{8}$$

If the subject well is surrounded by other production wells tapping the same reservoir, the interference caused by these wells producing simultaneously has to be considered. The pressure interference can be calculated using the method of superposition in space (Earlougher 1977; Horne 1998). Assuming all wells are produced at the same rate simultaneously, the *PI* of the subject well considering the interference among n production wells is given by:

$$PI = \frac{2\pi(kh)\rho}{\mu\left[\sum_{i=1}^{n} p_{Di}(t, r_i) + s\right]} \tag{9}$$

and, from equation (3),

$$p_{Di}(t, r_i) = -\frac{1}{2} Ei\left(\frac{-(\phi h)c_t \mu r_i^2}{4(kh)t}\right), \tag{10}$$

where r_i is the distance from well i to the subject well. Equation (9) is the form of *PI* considering skin effect and interference from neighboring wells. In actual fields, all parameters in equation (10) are obtained from well tests. Given p_{Di} and skin factor, *PI* can be calculated.

2.2 Power Available from a Pumped Well

With the development of downhole pumping technology, electrical submersible pumps (ESP) and line-shaft pumps can vastly enhance the production rate of a well in a reservoir with poor flow capacity. As described by Sanyal et al. (2005), for any given pump setting depth, the maximum available pressure drop in a pumped well without the risk of cavitation is estimated from:

$$\Delta p = p_i - (h_z - h_p)G - (p_{sat} + p_{gas} + p_{suc} + p_{fr} + p_{sm}) \tag{11}$$

The frictional pressure loss (p_{fr}) is calculated by:

$$p_{fr} = \frac{f\rho v^2}{2 g_c d}\left(h - h_p\right) \tag{12}$$

where f is Moody friction factor; v is fluid velocity in well; d is internal diameter of the wellbore, and g_c is gravitational unit conversion factor. At the present state of downhole pump technology, the pump can be set as deep as 1100 m if an ESP is used and as deep as 500 m if a line-shaft pump is used. From the calculated value of the *PI* from equation (9) and maximum allowable pressure drawdown from equation (11), the maximum available production rate can be calculated using the equation:

$$w = (PI)(\Delta p) \tag{13}$$

Therefore, the available production rate for different time periods can be estimated. Given the fluid temperature, the production rate is next converted to the well's power capacity. To estimate power generation, the fluid requirement per megawatt generation capacity can be expressed by:

$$\dot{w}_{mw} = \frac{1}{E_u W_{\max}} \tag{14}$$

$W_{\max}$ in equation (14) is derived from the First and Second Laws of Thermodynamics:

$$dq = C_f\, dT \tag{15}$$

$$dW_{\max} = dq\left(1 - \frac{T_o}{T}\right), \tag{16}$$

For a binary-cycle power plant, T_o is assumed to be the average ambient temperature, and a value of 0.45 is assumed for utilization efficiency (E_u) based on empirical data on the performance of modern binary power plants. The gross power capacity of the well is $w/\dot{w}_{mw}$. The net power capacity (j_{net}) at the wellhead is then calculated by subtracting from the gross power capacity the parasitic power (j_{esp}) needed for pumping. The power required by operating an ESP at the maximum available drawdown condition is given by:

$$j_{esp} = \frac{1}{E_m}\left(\frac{wH}{E_p} + h_p L\right) \qquad (17)$$

In equation (17), the total delivered head (H) is given by:

$$H = (p_d - p_{sat} - p_{gas} - p_{sm})/G + h_p, \qquad (18)$$

where p_d is the pump discharge pressure. From equations (14) and (17), the net power available from a pumped well is:

$$j_{net} = wE_u W_{\max} - \frac{1}{E_m}\left(\frac{wH}{E_p} + h_p L\right) \qquad (19)$$

We have used the data summarized in Tables 2 and 3 to evaluate the range of production rate and power capacity of wells at the Chingshui field. Then, we have evaluated the possible recoverable energy reserves field-wide by volumetric estimation of the stored heat using Monte Carlo simulation. From the estimated net power capacity per well and the recoverable reserves, we have estimated the minimum number of wells needed to recover the geothermal reserves at the Chingshui field.

3. RESULTS OF WELL CAPACITY ANALYSIS

Most parameters used in this analysis were taken either from the literature or from the original technical reports for the Chingshui field, except for some hypothetical and generalized parameters mentioned below. Since the bottom locations of seven producible wells were distributed unevenly (Figure 1), to simplify the well interference effects, we assume so-called five-spot well patterns with 300m spacing; that is, four surrounding wells with 300 m distance to the subject well, all wells producing at the same rate. According to Chang and Ramey (1979), the bottomhole temperature of these wells ranges from 201 to 225°C. Considering future expansion of the wellfield to surrounding cooler locations and the optimal inlet temperature of the downhole pumps, we used 180°C as reservoir temperature. Table 2 lists the fixed parameters used for pumped wells at the Chingshui field. Judging from earlier technical reports and from Table 1, we tabulated the possible best and worst reservoir capacities and well efficiencies at the Chingshui field (Table 3). The value of skin factor of 6.6 reported by Shen et al. (1979) indicates considerable well damage, which is less likely to occur with modern geothermal drilling practices.

To evaluate the range of available production rates, the *PI* is calculated first using equation (9). Figure 2 compares *PI* of a single production well to that of a production well surrounded by four wells produced simultaneously as described before. Parameters from the best case scenario were used in this illustration. For a single well, *PI* decreases with time, for p_D increases with time (equation 3) in IARF behavior. For multiple wells, *PI* decreases more steeply due to the additional increment of p_D contributed by surrounding wells (equation 10). After applying the values in Tables 2 and 3, the maximum pressure drop and production rates were calculated from equations (11) and (13). Subsequently, the net power available per well for the scenarios listed in Table 3 was computed using equation (19).

Table 2. Fixed parameters used for analysis of pumped flow, Chingshui geothermal field[*]

Number of neighboring wells and spacing :	Four wells, with 300 m spacing
Reservoir temperature:	180° C
Static reservoir Pressure	133 barg@1500m
Gas partial pressure:	0
Pump suction pressure:	3.75 bar
Pressure safety margin:	0.68 bar
Relative roughness:	0.018 cm
Casing diameter:	8-1/2 inches
Pump discharge pressure:	7.2 barg
Pump efficiency:	0.75
Motor efficiency:	0.88
Rejection temperature:	25° C
Utilization factor:	0.45
Thermal conductivity of rock:	3.1 W/m/°C
Rock compressibility	0.000133 bar^{-1}
Specific heat of rock:	2,700 kJ/m^3/°C

[*] Power loss per unit length of pump shaft = 0 for an electric submersible pump.

Table 3. Scenarios used for analysis of pumped flow, Chingshui geothermal field

Scenario	Worst case	Best case
Reservoir flow capacity (d-m):	4.18	9.24
Reservoir storage capacity (m):	108	425
Skin factor:	6.6 [a]	-2.0

[a] Data from Shen et al. (1979)

Although the wells at Chingshui can be self-flowed rather than pumped, this option was not considered for two reasons: (a) the net power capacity per well if self-flowed would be substantially lower given the moderate reservoir flow capacity, and (b) selfflowing wells will produce steam-water mixture with the associated problem of wellbore scaling. Therefore, the use of downhole pumping technology, which assures a higher net well capacity and single-phase water production, was assumed in this study. The maximum capacities of present ESPs can, in theory, allow an output rate of about 200 liter/second, operation depth of up to 1100 m and operation at temperature of nearly 200°C. Figures 3 and 4 show the available production rate and net power capacity, respectively, of a well versus the ESP setting depth for a range of production time in the best case scenario. The representative well for this case is well 4T (with improved skin factor) which was the major producer during pilot run of power generation in the 1980s. As shown in Figure 3, with the expected reservoir parameters, achievable improvement in skin factor, and optimal pumping technology, this well is capable of the production at the upper limit of rate an ESP can reach (640 ton/hr). The corresponding power capacity is about 9.5 MW. To prevent pump damage and the risk of pump block-off, we considered 700 m as the safety margin of the ESP setting depth even though it can be set as deep as 1100 m. As shown in Figure 4, to maintain a 7 MW capacity, the pump has to be set at 420 m depth initially and gradually deepened to 700 m at the end of 20 years of production. Figures 5 and 6 show the available capacities versus the ESP setting depth for the worst case scenario. The representative well for this case is well 14T. As shown in Figure 5, even under such lower limits, the pumped well can still produce more than 200 ton/hr by using adequately deep pump setting depths during 20 years of production. Conservatively, if a minimum acceptable capacity of 2 MW/well is specified, the pump has to be set at a depth range of 500 to 700 m during 20 years of production. This parametric analysis indicates that the power capacity of current wells with ESPs installed should easily exceed 2 MW/well. However, the total installable power capacity depends on the extent of recoverable heat reserves at the Chingshui field. In next section, a probabilistic analysis is performed to estimate the recoverable reserves.

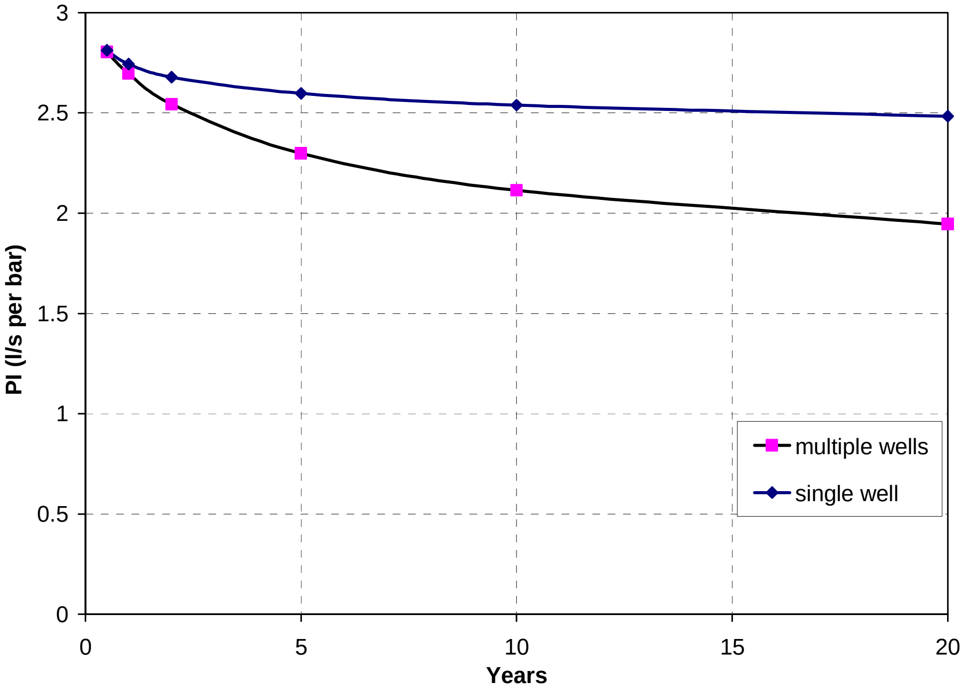

Figure 2. Productivity index with single well production and multi-well interference at the Chingshui field, best case.

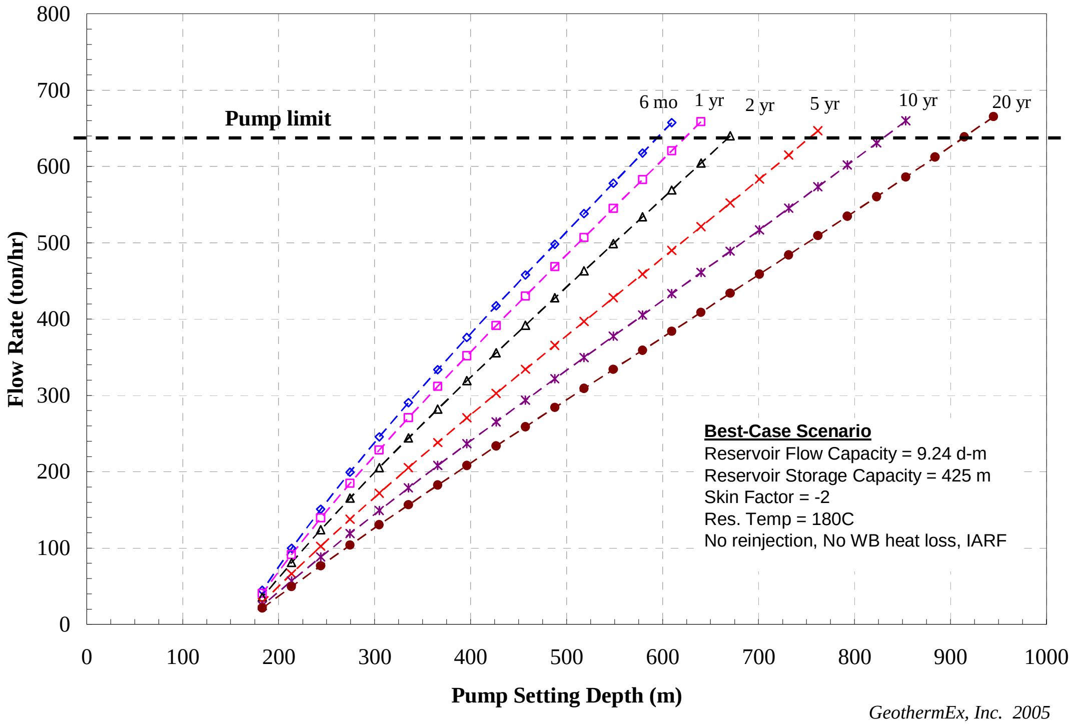

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Figure 3. Production rate available vs. pump setting depth at the Chingshui field, best case.

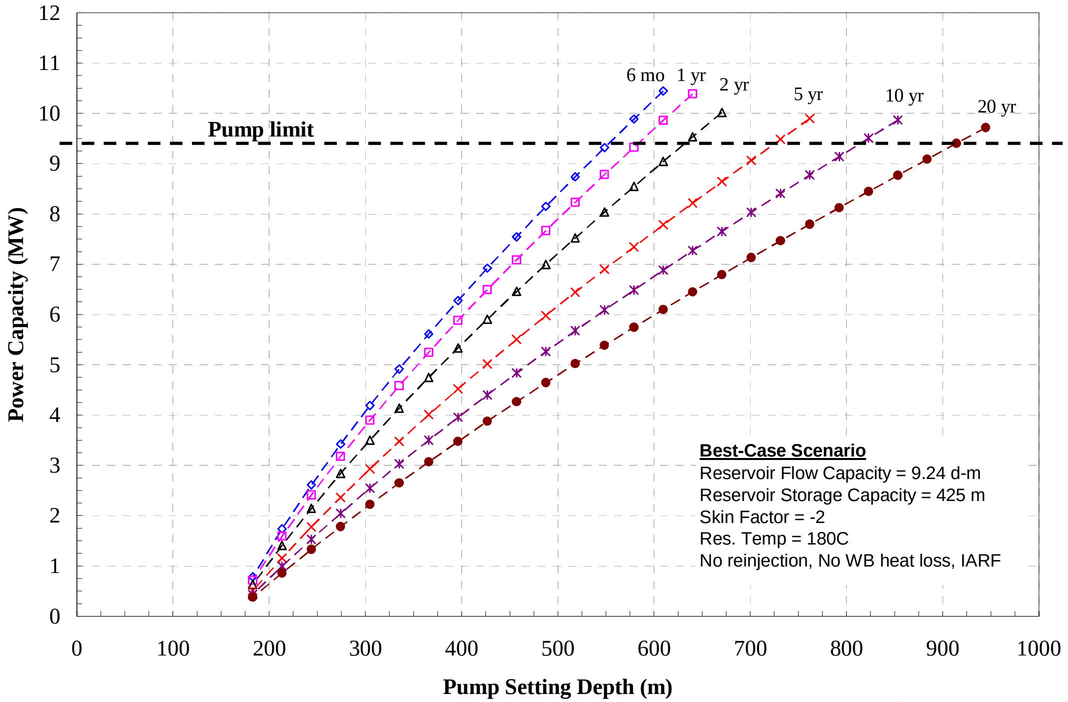

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Figure 4. Net power capacity available vs. pump setting depth at the Chingshui field, best case.

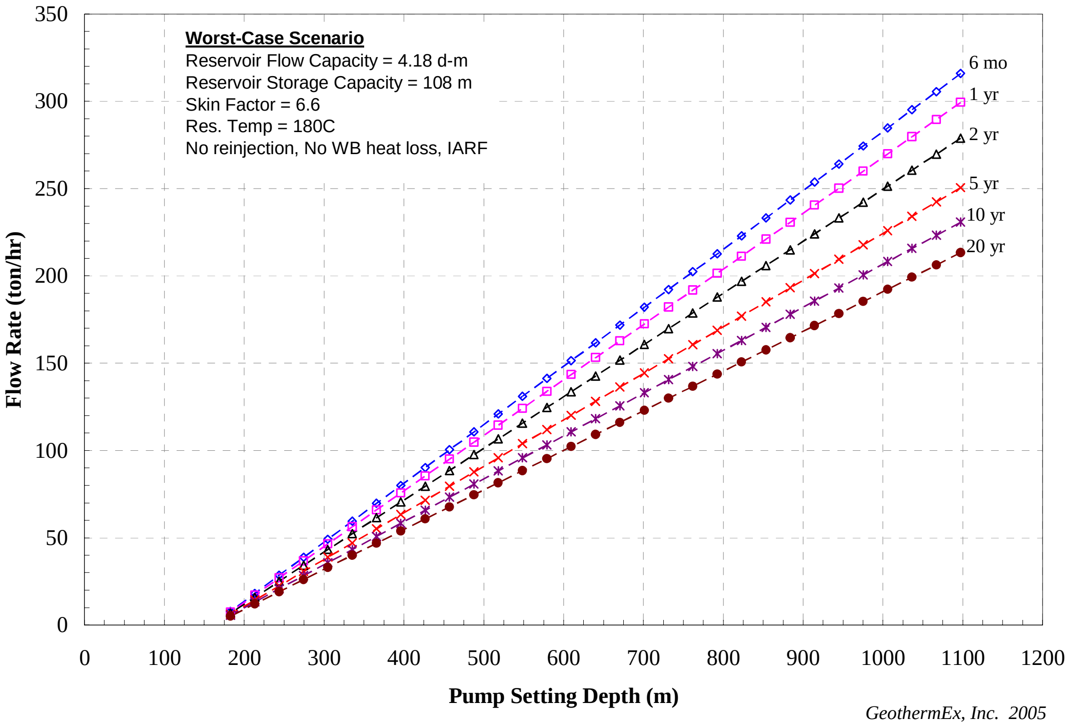

Figure 5. Production rate available vs. pump setting depth at the Chingshui field, worst case.

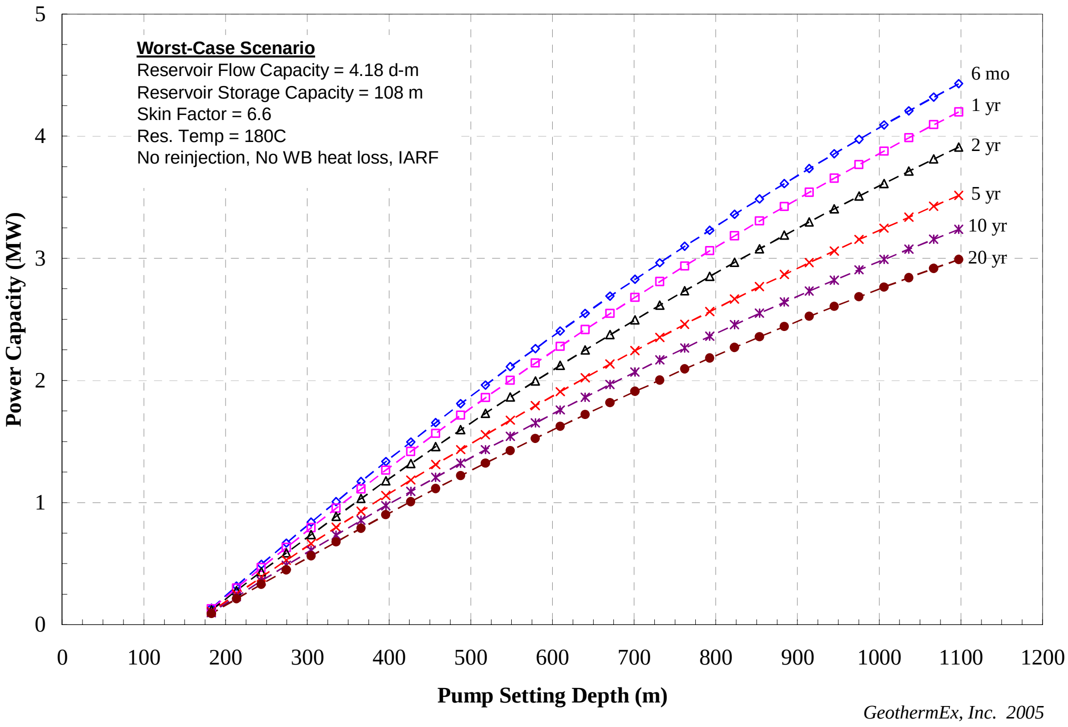

Figure 6. Net power capacity available vs. pump setting depth at the Chingshui field, worst case.

4. PROBABILISTIC ANALYSIS OF RECOVERABLE RESERVES

Unlike the oil and gas industry, there has been no universal approach in defining geothermal reserves or power capacities in geothermal reservoirs (Sanyal, 2004). Therefore, it is worthwhile describing the terminology and methodology used in this reserve analysis. In this study the term “reservoir” represents a subsurface body of rock at a temperature of 180°C or greater and the fluid it contains in the pore space. This is a fairly conservative definition, since (a) geothermal power can be generated from water at temperatures as low as 100°C nowadays, and (b) this approach ignores any natural recharge of hot water from depth into the reservoir. Here we also define 90% cumulative probability of recoverable reserves as “proven generating capacity”, and most likely (“modal”) recoverable reserves as “probable generating capacity”.

The adopted methodology of assessing geothermal power capacity of the Chingshui field is the U.S. Geological Survey approach (Muffler, 1979), where the total power capacity of a geothermal field is defined as:

$$j_t = \frac{VC_v(T_{avg} - T_o)R}{FL_p}, \tag{20}$$

where V is volume of the reservoir; T_{avg} is average temperature of the reservoir; F is the power plant capacity factor (the fraction of time the plant produces power on an annual basis), and L_p is power plant life. The volumetric specific heat (C_v) of the reservoir and overall recovery efficiency (R) are determined as:

$$C_v = \rho_f C_f \phi + \rho_r C_r (1 - \phi) \tag{21}$$

$$R = \frac{W \cdot \varepsilon \cdot E_u}{C_f \cdot (T - T_o)}, \tag{22}$$

The parameter W in (22) is derived from the first and second laws of thermodynamics and was defined previously in equations (15) and (16). According to Sanyal et al. (2004), a recovery factor (ε) in the range of 0.1 to 0.2 with 0.15 being most likely is appropriate for such reserve estimation. The bulk volume of the reservoir is defined as the volume within which temperature is equal to or greater than 180°C. Prior to computing V, the reservoir area and thickness have to be estimated. In this preliminary study, we used the equation below to estimate the reservoir volume:

$$V = A_{\geq 180} h_{avg} \tag{23}$$

Similar to the volumetric definition above, the reservoir area $A_{\geq 180}$ means the area within which temperature is equal to or greater than 180°C. From the temperature profile in Figure 1, the reservoir area of the Chingshui field is about 2 km^2 (also see Hsiao and Chiang, 1979; Fan et al., 2005). We have considered a range of 1.4 to 2.6 km^2 for the reservoir area with a most likely value of 2 km^2. The reservoir thickness was the major uncertainty in reserve estimation, because there exists no direct way to measure how thick the “reservoir” is. Hsiao and Chiang (1979) constructed a conceptual model of the Chingshui field based on geological, geophysical and well information. The average thickness of the Chingshui reservoir was suggested to be 2km according to the microseismic survey conducted by Taiwan Academia Sinica (Yu et al., 1977). Therefore, 2 km was taken as the most likely value of thickness within an estimated range of 1.5 to 2.5 km. The most likely average reservoir temperature (T_{avg}) at the Chingshui field is conservatively assumed to be 190^{o}C, the overall range of reservoir temperature being 180 ^{o}C to 200 ^{o}C. The range of porosity was taken as 7.2% to 17% with equal probability. Table 4 shows these uncertain parameters as well as the fixed parameters used for power capacity calculation at the Chingshui field. The probabilistic method of Monte Carlo simulation was used to assess the power generation potential at the Chingshui field.

Table 4. Input parameters for power capacity calculation at the Chingshui field.

Variable Parameters	**Minimum**	**Most Likely**	**Maximum**
Reservoir Area (km^2)	1.4	2	2.6
Reservoir Thickness (m)	1500	2000	2500
Rock Porosity ^{b}	7.2%		17.0%
Reservoir Temp. (°C)	180	190	200
Recovery Factor	10%	15%	20%

Fixed Parameters	
Rock Vol. Heat Capacity (kJ/m^3-°C)	2,700
Rejection Temp. (°C)	25
Utilization Factor	45%
Plant Capacity Factor	90%
Power Plant Life (years)	30

^{b} inferred from thickness and storage capacity.

Using the parameters listed in Table 4, the result of probabilistic analysis of geothermal energy reserves at the Chingshui field is shown in Figure 7. The corresponding statistics is shown in Table 5. It should be emphasized that all of the assessments were based on limited data from rather old literature. The quality and certainty of these data remain questionable until further research and project development are conducted. Therefore, in order to lower the development risk, the proven power capacity (90% probability) is suggested to be used as the recoverable reserves in this preliminary stage. From both illustrations, the range of recoverable reserves is between 13 to 73 MW. The proven power capacity is about 22 MW, and the probable capacity is about 30 MW. From this probability assessment, we considered a field-wide power capacity of 22 MW as a good goal for initial development plans at the Chingshui field if no further data become available.

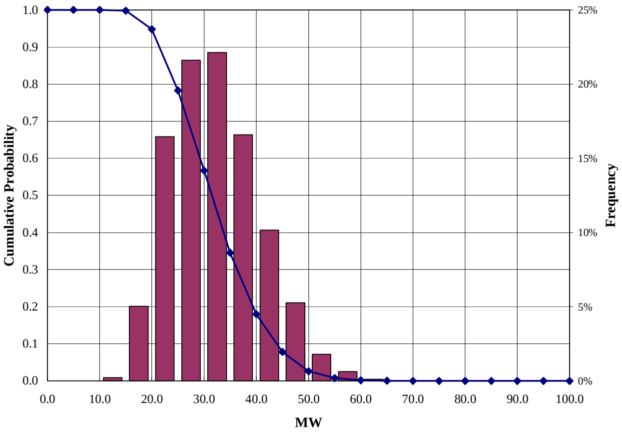

Figure 7. Probabilistic analysis of geothermal energy reserves at the Chingshui field.

Table 5. Statistics of recoverable geothermal energy reserves at the Chingshui field.

	MW	MW/km^2	Recovery Efficiency
Proven capacity (90% prob.)	**21.81**	**11.43**	**1.03%**
Most-likely capacity (Modal)	29.35	15.60	1.41%
Standard Deviation	8.37	3.67	0.27%

Considering the power capacity available for a pumped well and power capacity available for the whole Chingshui field (22 MW), the minimum number of wells needed to sustain a 22 MW binary-cycle power plant was estimated, assuming a conservative 70% success rate in drilling. For the best case in Figure 4, at least five wells with the capacity of 7 MW per successful well need to be drilled. On the other hand, at least fifteen wells with capacity of 2 MW per successful well need to be drilled for the worst case. The wellbore heat loss is ignored in current study; however, it is expected to be insignificant due to the high flow rate in pumped wells. Furthermore, once the pressure transient passes the IARF period, the inflow boundary or nature recharge effect may affect the production rates shown in Figures 3 and 5. The reinjection of produced fluid is an effective way to resolve the problems of waste fluid disposal as well as pressure decline. To this end, good reservoir management has to be performed to avoid cooling front breaking through to the production wells.

5. CONCLUSIONS

Based on the literature data, the power capacity per pumped well ranges from 2 MW to 7 MW at the Chingshui field provided the skin factor ranges from 6.6 to -2, and maximum pump setting depth is 700m. The result of probabilistic analysis indicated that the geothermal reserves at the Chingshui field ranges from 13 to 72 MW. The proved reserve capacity is 22 MW which could be a good initial goal for future development plan. Considering the power capacity per well, the number of wells needed to be drilled is 5 and 15 for the best scenario and worst scenario, respectively (with 70% success rate). All these analyses indicate feasible conditions for future development at the Chingshui field if the skin effect in current wells can be improved or new production wells are drilled. To confirm these assessments, working over, stimulating, and retesting the damaged wells are recommended.

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NOMENCLATURE

C_f = specific heat capacity of fluid, for water C_f = 4.19 kJ/kg^{o}C.
C_r = specific heat capacity of rock matrix.
C_v = volumetric specific heat of the reservoir.
c_t = total compressibility of rock and fluid.
d = internal diameter of the wellbore.
E_u = utilization efficiency factor to account for mechanical and other losses that occur in a real power cycle.
E_p = pump efficiency.
E_m = motor efficiency.
F = power plant capacity factor (the fraction of time the plant produces power on an annual basis).
f = Moody friction factor.
G = hydrostatic gradient at production temperature.
g_c = gravitational unit conversion factor.
H = total delivered head.
h = net reservoir thickness.
h_{avg} = average reservoir thickness.
h_p = pump setting depth.
h_z = depth to production zone.
j_{esp} = power required by operating a downhole pump in a well.
j_{net} = net power available from a pumped well.
j_t = total power capacity of a geothermal field.

L = shaft horsepower loss per unit length.
L_p = power plant life.
p_D = a dimensionless variable that is a function of time.
p_d = pump discharge pressure.
p_{fr} = pressure loss due to friction in well between h_z and h_p.
p_{gas} = gas partial pressure.
p_i = initial static reservoir pressure.
p_{sat} = fluid saturation pressure at production temperature.
p_{sm} = additional safety margin to ensure cavitation does not occur at pump intake.
p_{suc} = net positive suction head required by the pump.
p_{wf} = flowing wellbore pressure.
R = overall recovery efficiency (the fraction of thermal energy in the reservoir that is converted to electrical energy at the power plant).
r = distance between the "line source" (well center) and the point at which the pressure is being considered.
r_w = wellbore radius.
r_D = dimensionless radius.
T = resource temperature.
T_{avg} = average temperature of the reservoir.
T_o = rejection temperature (equivalent to the average annual ambient temperature).
t = time.
t_D = dimensionless time.
V = volume of the reservoir.
v = fluid velocity in a well.
W_{ma} = maximum thermodynamically available work per lb of fluid.
w = mass flow rate.
$\dot{w}$ = mass flow rate required per megawatt generation capacity.
μ = fluid viscosity.
ϕ = reservoir porosity.
ρ = fluid density.
ρ_f = bulk density of fluid.
ϕ = reservoir porosity.
ρ_r = bulk density of rock matrix.
ε = recovery factor (the fraction of thermal energy in-place recoverable as thermal energy at the surface).

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