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ASSESSMENT OF THE ENERGY POTENTIAL OF THE BEREGOVSKY GEOTHERMAL SYSTEM, UKRAINE

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ABSTRACT

The Beregovsky area is one of the prospective geothermal areas of the Ukraine. It is a typical low-temperature geothermal area with temperatures up to 68°C. About 15 wells have been drilled in this territory for various purposes. In all the boreholes, well logging, well tests and geochemical sampling of thermal water have been carried out. On the basis of these data a geothermal resource assessment for the Beregovsky area is attempted. By using preliminary estimates of reservoir properties, a volumetric assessment and a random distribution study (Monte Carlo method) of the geothermal production capacity were carried out. It is estimated that the energy potential of the Beregovsky geothermal area is 1.23×10^{17} J and the possible direct use potential (e.g. space heating) produced for a 25-year period is estimated to be about 15 MW_t. Analysis of well test data was carried out using graphical methods (Semi-log and Horner methods) and the VARFLOW computer software. The results of this analysis indicates that the average transmissivity of the Beregovsky reservoir is about 0.5×10^{-5} m^3 Pa-s. Finally, a lumped parameter model using the LUMPFIT computer program is used to simulate the Beregovsky geothermal area. The model was, consequently, used for predicting the reservoir response to three constant production rate cases over the next 10 years.

1. INTRODUCTION

The basic tasks of this study are to evaluate the nature, characteristics and the probable production potential of the Beregovsky geothermal system. This is done by determining well producion flow rates, predicting the reservoir response to exploitation and designing a management plan. The main responsibility of the geothermal reservoir engineer is to evaluate the magnitude of the resource and the size of the electrical or thermal power plant that can be supported by the field in question over a designated project life, i.e. the energy reserves of the reservoir.

Assessment of geothermal resources includes a cumulation of actions connected with the estimation of the resource base in a given area that can be recovered under specified economic conditions. Accordingly, geothermal resource assessment depends on geological, physical, technological, environmental and economic factors (Muffler and Cataldi, 1978).

The choice of a method for a reservoir assessment depends on the available data, the purposes of the assessment and the accuracy needed. The three methods usually applied in estimating the potential reserve of a geothermal resource are the volumetric method (stored heat method), simple modelling (analytical or lumped parameter model) and detailed distributed parameter modelling (numerical simulations).

At early stages of a geothermal assessment investigation, when no (or not enough) wells have been drilled and permeability values are not yet available, the volumetric method may be applied. This method involves estimating the static reserve of heat in the reservoir and then applying a recovery factor to estimate the recoverable energy. When several wells have been drilled, pressure-transient data should be available but analysis of the data gives estimates of the reservoir parameters. At this stage a simple model, such as a lumped-parameter model, can be constructed. Finally, when a detailed production and response history is available, the only assessment tool that can incorporate the entire set of available field data is a detailed distributed-parameter model. In this report the first two methods are applied to the Beregovsky area.

2. GENERAL OUTLINE OF THE BEREGOVSKY AREA

The Beregovsky geothermal area was used as an example to test the energy potential assessment techniques for geothermal systems outlined above. The Beregovsky geothermal area is located in the southwest part of the Zakarpatsky internal downfold in West Ukraine. The Zakarpatsky area is an important fuel and energy region of the Ukraine. About 200 petroleum and gas wells have been drilled there. However, some of these wells are no longer profitable for such use. They do provide thermal water and could be used economically for district heating. The temperature of the thermal water is usually within the limits of 45-120°C, and the depth of the productive aquifers ranges from 1000 to 3000 m. Thus, the already existing wells may be used for the purpose of providing the heat supply for this region. The Beregovsky field is also ranked among several prospective geothermal areas of the Ukraine (Zabarny et al., 1997).

From the morphological point of view, the Beregovsky area is a flat plain with an average elevation in the range of 200-206 m a.s.l. The Vishkovsky Mountains, which have an elevation greater than 270 m, form the northern border of the Beregovsky field. Surface geology is characterized by powerful deposition of sedimentary rocks and according to geophysical exploration surveys the crystal basement is located at a depth of 4-6 kilometres. The sedimentary sequence is composed of alternating tuffs, alevrollites, argillites, clays and sandstones. On the boundary of the Vishkovsky structure effusive rocks, such as trachyandesite, andesite and dacite dated from Later Meocene, are found at the surface.

The Beregovsky geothermal area is very complicated tectonically: many NE-SW and NW-SE trending regional faults cross the area. These faults are considered responsible for the geothermal anomalies (temperature, chemistry and isotopes) in the region as they provide flow channels from greater depth up to shallower levels. It should be noted that the main area of the feed-zones of the sedimentary aquifers is the Folded area of the Carpathians, which means that the movement of the water is from northwest to southeast. Recharge occurs in deeper horizons of the valley of the river Òissà. The estimated maximum pressure difference for the Miocene horizon is 10 bar, which indicates slow movement of underground water. The average permeability thickness of the productive aquifer is around 10^{-13} m^3, based on well tests (Lyal´ko, 1974).

The Beregovsky geothermal area is 6 kilometres south of Beregovo. About 15 wells of various purposes have been drilled in this territory. In 1985 investigations started with the purpose of searching for thermal waters for construction of the sanatorium “Beregovo”. Four additional wells were drilled directly for this purpose. The location of the wells is shown in Figure 1 and the schematic cross-section of the Beregovsky geothermal area is shown in Figure 2. In all the boreholes, well logging, well tests and geochemical sampling of the thermal water has been carried out. The results are summarised in Table 1.

In 1986 a long term pressure transient test was initiated in the Beregovsky geothermal area. The duration of the test was about three years. The pressure changes resulting from variable production from wells in the area were monitored in four wells. Well 2-T and well 8-T produced with average flow rates of 4.2 l/s and 3.3 l/s, respectively. Well 15-T was used as an observation well and well 19-T was used for injection. Unfortunately, the result was influenced by flow from surrounding wells used for other purposes, which were not part of the long-term test. As a consequence measured pressure response data from some of the wells was not suitable for further analysis. Data from observation well 15-T is considered to be not seriously affected by wells which were not part of the long-term test. This data-set will, therefore, be used later in the report.

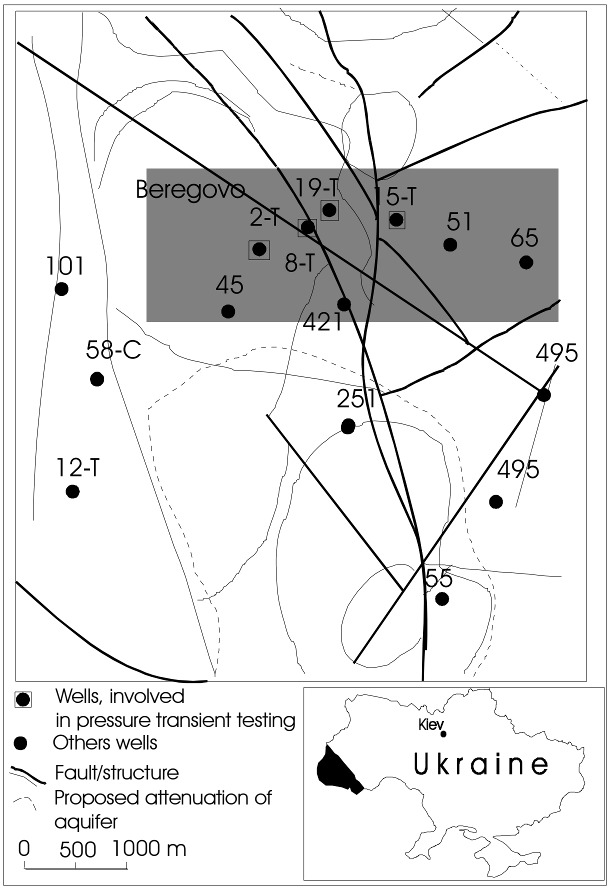

FIGURE 1: A map of the Beregovsky geothermal area showing locations of wells and main geological structures

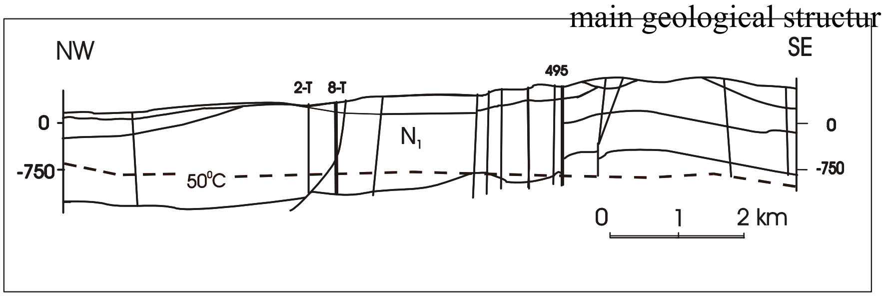

FIGURE 2: A schematic cross-section of the Beregovsky geothermal area

TABLE 1: An overview of wells in the Beregovsky geothermal area

Parameter	Well no.			
	2-T	**8-T**	**15-T**	**19-T**
Year of drilling	1971	1978	1986	1987
Depth (m)	1049.1	1050	1120	1160.1
Age of rock	Miocene	Miocene	Miocene	Miocene
Main rock unit	Tuff	Tuff with argillite	Tuff	Tuff
Temp. of fluid (°C)	68	66	65	
Static water level (m)	13	20	21	8.3
Mineralisation (g/l)	29.2	-	25	25
Status of well	Productive	Productive	Monitoring	Injection

3. THE VOLUMETRIC METHOD

As was mentioned above, the volumetric method is convenient to apply at the first stage of an estimation of the geothermal potential. The base information for this method consists of geological and hydrogeological surveys, geophysical exploration, sampling of surface manifestations, short-term testing, i.e. in general most of the available information. The results obtained by this method are convenient for rough estimates of the resources. This method for assessing geothermal resource potential is based on the calculation of energy contained in a certain volume of rock, but neglects all recharge to the system.

The governing equation for estimating the total heat, E_{tot}, contained in a reservoir volume is (Gazo, 1992) (nomenclature is given at the end of the report)

$$E_{tot} = V\rho_r c_r (1-\phi)(T-T_{ref}) + V\rho_f c_f \phi (T-T_{ref}) \tag{1}$$

By using Equation 1, the geothermal resource base can be estimated, i.e. the total thermal energy in a volume, V of crust beneath a specified area. The first part of the right hand side of the equation is heat stored in the rock matrix, and the second part is the heat stored in the water in the pores. One of the important parameters in this equation is the reservoir volume. If within the limits of the research area a detailed exploration was carried out, the boundary and thickness of productive horizon can be established, and consequently the definition of the volume is not complex. However, if the subsurface conditions are only known in a small wellfield, it can be difficult to estimate the total volume.

Indeed only a small fraction of the geothermal energy, determined with the help of Equation 1, is useful and can be brought to the surface. The recoverable energy, E_R can be estimated by applying a geothermal recovery factor, R_f, to the total geothermal resource base, such that

$$E_R = R_f E_{tot} \tag{2}$$

The recovery factor depends on the proposed production mechanism, on the effective porosity of the formations and on the temperature difference between the reservoir and the wellhead. Muffler and Cataldi (1978) suggested that for water-dominated geothermal systems the recovery factor depends on the total porosity with values ranging from 0% at $\phi = 0$, to as high as 25% at $\phi = 20$. The recovery factor will then be given by the linear equation

$$R_f = 1.25\phi \tag{3}$$

The next step in the calculations is to estimate how much of the geothermal reserve can be converted into usable energy. This amount depends on the energy losses occurring during conversion and the available energy fraction from the reserve. The economic geothermal resource, E_e , is then defined as

$$E_e = fE_R \tag{4}$$

where f is called the efficiency factor. For space heating 50-90% of the thermal energy brought to the surface can be converted into heat.

The load factor indicates the percentage of time the plant is in operation. Thus, taking into account the above remarks, the following equation applies for converting the estimated energy reserve into power (Sarmiento, 1993):

$$MW_t = \frac{Energy\ available \times Recovery\ factor \times Efficiency\ factor}{Load\ factor \times Life\ time} \tag{5}$$

3.1 Monte Carlo simulation

The Monte Carlo simulation is a modification of the volumetric method that involves the calculation of the heat-in-place in the rock and converting it to equivalent power using recovery factors and conversion efficiencies, assuming a homogenous and closed reservoir (Sarmiento, 1993). However, in contrast to the volumetric method, this technique permits taking into consideration the uncertainty distribution of every parameter and factor which serve as the basis for the computations.

Below, some of the most commonly applied uncertainty distributions are listed. A constant or uniform uncertainty distribution (square) is used when the value of a parameter is possible over a certain range of values (and when any value within a definable limit is considered equally likely). A triangular distribution is used when the minimum and maximum values are not very likely, but the mean value has the highest probability. It is considered a better representation of many natural resources if a standard deviation can be computed. Log-normal distribution is also common and usually fits a series of measurements like porosity and permeability. In our accounts we shall apply constant-, and triangle types of probability distributions. Thus, the constant distribution of parameters is calculated as (using EXCEL):

$$P = P_{\min} + R1 \times (P_{\max} - P_{\min}) \tag{6}$$

And a triangular distribution is calculated accordingly (using EXCEL):

$$P = P_{\min} + (R2 + R3)/2 \times (P_{\max} - P_{\min}) \tag{7}$$

where $R1$, $R2$ and $R3$ are random numbers.

3.2 Results of Monte Carlo calculations for the Beregovsky geothermal system

For the Beregovsky area the reservoir temperature is about 60°C and the thermal energy can be used for space heating only with application of a peak source, i.e. a boiler house using organic fuel. According to the temperature diagram of the network, and the water available for the geothermal space heating systems, the peak source would be switched on when the external air temperature is below 2°C. Above this temperature, the energy of the thermal water is sufficient for maintaining the successful space heating. The difference between the temperature of fluid entering and leaving the installation is equal to 30°C. The reference temperature was, therefore, assumed to be 30°C on average.

The useful geothermal resource was calculated from the total resource using recovery factors based on available information on reservoir porosity. The basic equations for the calculation were Equations 1 and 5. According to Equation 3 and assuming a total porosity of 15%, the recovery factor is 0.2. The efficiency factor and load factor are both supposed to be 0.5, respectively. For the parameters where the exact value was not known, the technique of uncertainty or probability distribution (a random number generator) was used. The result is an overall probability distribution for the reserve estimate that quantitatively incorporates the uncertainties for each parameter. The randomness of certain values was defined either by square or triangular distributions. The square probability distribution was applied to the reservoir area, thickness, average temperature and fluid density, whereas rock density and porosity were determined by the triangular method. The numerical values of the parameters used in the assessment are presented in Table 2.

TABLE 2: Parameters used in the Monte Carlo analysis of the Beregovsky geothermal area, best guess values and probability distribution input

Parameter	**Best guess (model)**	**Probability distribution**		
		Type	**Min.**	**Max.**
Area (km^2)	11	Square	5	17
Reservoir thickness (m)	850	Square	500	1200
Reference temperature (°C)	30	Constant		
Rock density (kg/m^3)	2700	Triangle	2400	3000
Porosity (%)	15	Triangle	5	25
Recovery factor	0.2	Constant		
Rock specific heat (J/kg°C)	1000	Constant		
Average reservoir temperature (°C)	68	Square	65	98
Fluid density (kg/m^3)	980	Square	960	1000
Fluid specific heat (J/kg°C)	4200	Constant		
Conversion efficiency (%)	0.5	Constant		
Plant life (years)	25	Constant		
Load factor	0.5	Constant		

Using the above stated parameters and the Excel function RAND, the energy reserve and energy potential were calculated. The estimated power production capacity was then plotted as a histogram, shown in Figure 3. The following conclusions can be made from the histogram. The probability range of the power production capacity is estimated to be from 0 to 25 MW$_t$ and the most likely value is close to15 MW$_t$. Hence, 15 MW$_t$ can be assumed as a good estimate. This corresponds to a mass flow of the order of 240 l/s (considering the efficiency factor of 0.5).

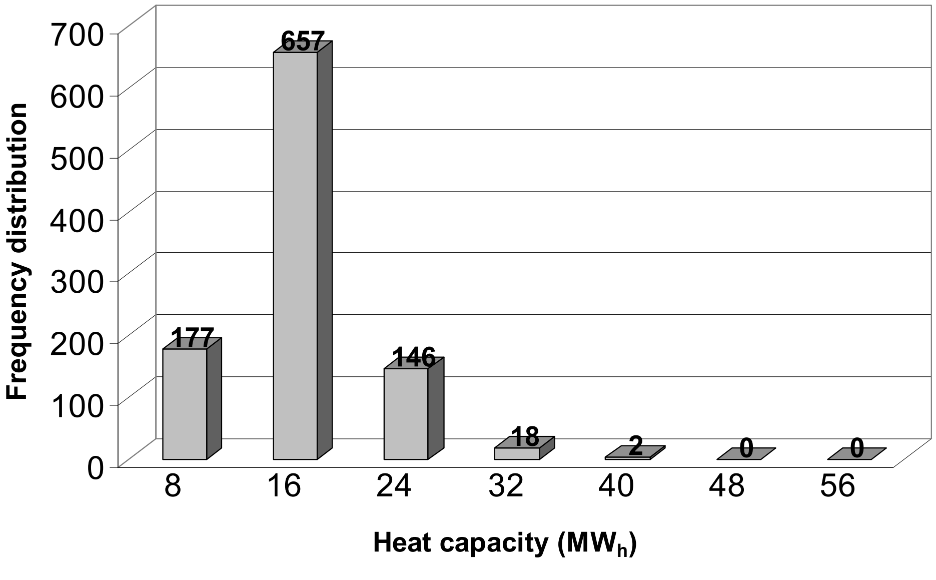

FIGURE 3: Frequency distribution of available heat energy potential in the Beregovsky geothermal area, calculated by the Monte Carlo method

4. ANALYSIS OF PRESSURE TRANSIENT TEST DATA

In an assessment of the energy potential of any geothermal system it is important to obtain representative values for the hydrological and thermal properties of the reservoir (Anderson, 1995). Pressure transient tests involve creating transient conditions in the reservoir by producing from (or injecting into) the formation. The effects of the disturbance are then investigated by measuring the time-dependent pressure changes that occur either at the active well (single well test) or at a nearby shut-in observation wells (interference test). Pressure transient test analysis is based on the choice of an appropriate simple model where the pressure response is given by an analytical function. It is commonly used to estimate the permeability (or transmissivity) and storativity of a geothermal system. When the conditions of well testing are simple, it can be convenient for interpretation to use manual graphical methods. If the structure of a reservoir is complicated and test conditions more complex (variable flow rate instead of constant flow rate) more advanced models must be used with computerized fitting methods (forward or least-squares).

4.1 Semi-log analysis method

The pressure change, Δp, in a reservoir behaving as a Theis-model is represented by the following equation:

$$-\Delta p = \frac{\mu}{4\pi kh}\int_0^t \frac{q(\tau)}{t-\tau}\exp[\frac{-\mu c_t r^2}{4k(t-\tau)}]d\tau \tag{8}$$

which can be approximated by

$$-\Delta p = \frac{Q\mu}{4\pi kh}[2.303\log(\frac{-4kt}{\mu c_t r^2}) - 0.5772] \tag{9}$$

Thus, if the pressure change is plotted against log (t), the slope m of a linear part of the diagram will allow an estimate of the reservoir transmissivity kh/μ

$$m = \frac{2.303\,Q\mu}{4\pi kh} = 0.183\,Q\frac{\mu}{kh} \tag{10}$$

By using the value of the drawdown Δp on the semi-log straight line, at some selected time t the storage coefficient $c_t h$ can be estimated by

$$c_t h = 2.25\frac{kh}{\mu}\frac{t}{r^2}\times 10^{-\frac{\Delta p}{m}} \tag{11}$$

where r is the distance from the production well to observation well (or the radius of a production well if that well is also the observation well).

4.2 The Horner plot method

Very useful, but comparable information can be obtained by analyzing data for the recovery of the water level when pumping tests are discontinued. Usually for this purpose, the so-called Horner method of analysis is used. The advantage of the Horner method is that it is not as sensitive to fluctuations in flow rate.

The end of pumping is considered an independent perturbation comparable to the beginning of pumping. The technique of parameter estimation is similar to the method described above, except for the definition of a correct level of the initial water level. This level takes into account the residual influence of the pumping test. The slope on a semi-log plot is again represented by Equation 9, except for the fact that the slope is defined from a plot of the pressure as a function of the logarithm of $(t_p+\Delta t)/\Delta t$, where t_p is the duration of the pumping test.

4.3 Results of pressure transient analysis for the Beregovsky area

Pumping test data from well 2-T was used as the basis of the well test analysis. The static water level was estimated to be 13 m. Water level changes caused by pumping were observed for six days. The average flow rate was 28.2 l/s and the total drop of the water level was 1.1 m. Water level recovery was observed after the end of the pumping tests. The duration of the pressure buildup test was 5 days and the initial level was practically restored. The weak water level response due to considerable production from of the reservoir, 28.2 l/s, indicates high permeability of the productive aquifer.

The standard procedure of well test analysis was carried out for well 2-T. The test data were plotted on a semi-log graph and the transmissivity was computed by Equation 9. After that the data for the buildup test from well 2-T was plotted by the Horner plot method. Figure 4 illustrates the data of the drawdown part and Figure 5 shows the Horner plot data for water level recovery. For the Horner case, the transmissivity and storativity were also estimated by Equations 9 and 10.

Table 3 shows the calculated reservoir parameters. It can be seen from Table 3 that the transmissivity values calculated from the semi-log analysis and Horner plot method are quite similar.

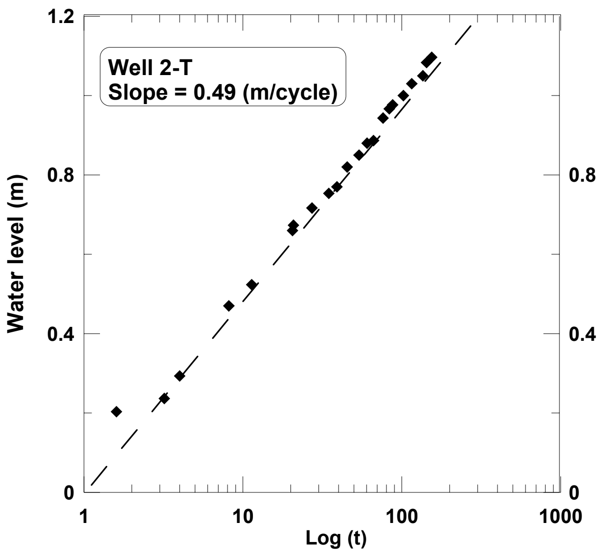

FIGURE 4: Semi-log analysis from well 2-T in the Beregovsky area

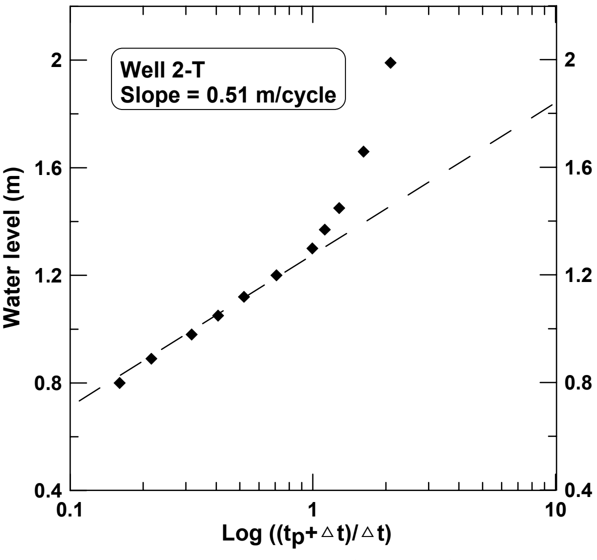

FIGURE 5: A Horner plot for data from well 2-T in the Beregovsky area

TABLE 3: The results of well test analysis for well 2-T in the Beregovsky reservoir

Method	**Initial water level (m)**	**Average production (l/s)**	**Slope (m/cycle)**	**Distance (m)**	**Trans-missivity (m^3/Pa s)**	**Permeability thickness (m^3)**	**Storativity (m/Pa)**
Semi-log	0.2	28.2	0.49	560	0.1×10^{-5}	0.4×10^{-9}	0.6×10^{-7}
Horner	0.8	28.2	0.51	560	0.1×10^{-5}	0.4×10^{-9}	0.4×10^{-7}

4.4 The VARFLOW computer program

The computer program VARFLOW may also be used for analysis of the pressure transient test data (EG&G Idaho, Inc., and Lawrence Berkeley Laboratory, 1982). It can be used to calculate more complicated cases, however, such as for several wells producing at the same time and for variable flow rate. In cases where production is variable, the pressure change due to each production well may be calculated by Equation 8. Flow rates are modelled by superposition of consecutive "production pulses". Within any "production pulse" the flow rate may be constant or vary linearly.

The essence of the simulation technique consists in varying the reservoir parameters (transmissivity, storativity) until the calculated pressure change curve coincides as much as possible with the measured test data. This program calculates drawdown in an idealized reservoir system (Theis model): the productive aquifer is of infinite areal extent, or bounded on one side by a linear constant potential or barrier boundary. It is isothermal, horizontal, with a constant thickness bounded above and below by impermeable layers, and contains anisotropic porous medium. The program is set up to calculate pressure changes at up to 25 observation and 25 production wells. The computer code can also include drawdown due to the skin effect in production wells (EG&G and Lawrence Berkeley Laboratory, 1982)

4.5 Results of the VARFLOW simulation for the Beregovsky area

The pressure changes resulting from the variable production from the Beregovsky area, during the long-term test discussed earlier, were used for the VARFLOW simulation. Unfortunately, pressure data from two production and one injection well were unsuitable for use as already discussed. Therefore VARFLOW was found applicable only to data from observation well 15-T. The simulation was achieved by varying the reservoir parameters (transmissivity, storativity and initial water level) until a good fit between observed and calculated data was obtained. The results are shown in Figure 6.

The following parameters gave the best results: initial pressure = 4.7 m, transmissivity = 0.1×10^{-5} m^3/Pas, and storativity = 0.6×10^{-7} m/Pa. These parameters are quite similar to other estimates presented previously.

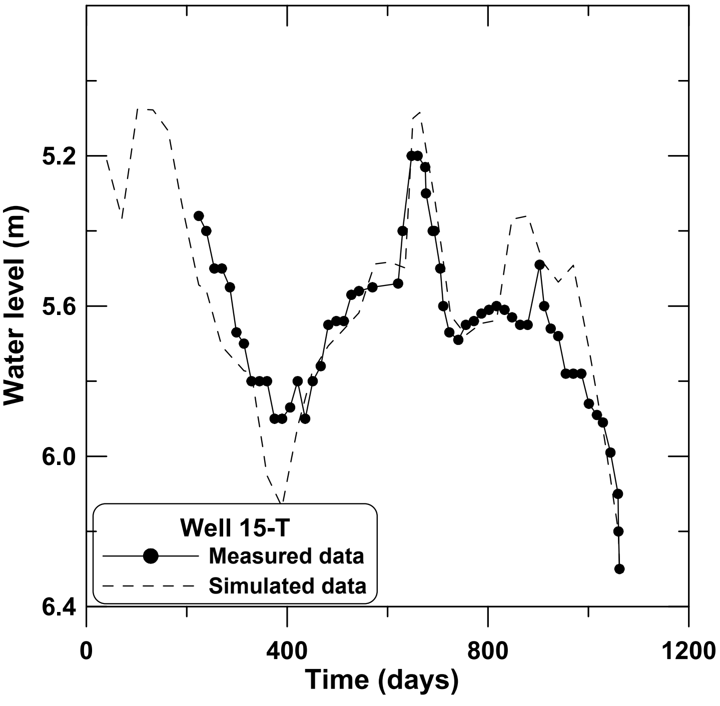

FIGURE 6: Simulation by VARFLOW of water level variations in well 15-T during long-term testing of the Beregovsky geothermal area in 1986-1989

5. LUMPED PARAMETER MODELLING

The resource calculated by the volumetric method represents the static geothermal reserve. This is not enough for development of an optimal production strategy of geothermal utilization. Such a strategy can be achieved by creating a model of the system with parameters that adequately describe the reservoir. Modelling studies are carried out to accurately analyse data from geothermal wells and estimate the generating potential of a system. The lumped modelling method is appropriate in the first stage of a modelling study when data on the nature of a reservoir or the time available for calculations are limited.

The computer code LUMPFIT is used here for lumped parameter modelling (Axelsson and Arason, 1992). It tackles the simulation problem as an inverse problem. It automatically fits analytical response functions of lumped models to the observed data by using a non-linear iterative least-squares technique for estimating the model parameters. Axelsson (1989) gives the theoretical background of this method.

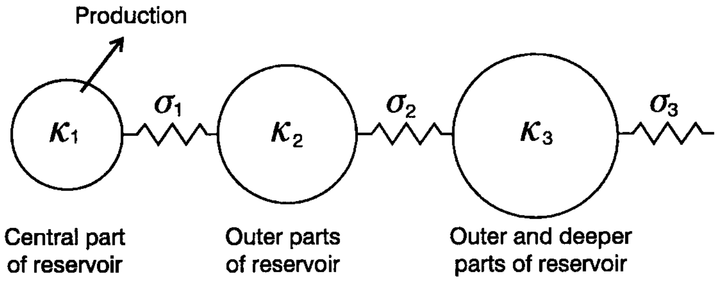

FIGURE 7: Example of a lumped parameter model of a hydrological reservoir (Axelsson, 2000)

The principal idea of lumped modelling consists in replacement of the real reservoir with tanks or boxes with capacitances (storage). The number of tanks depends on the complexity of the reservoir being modelled. Most such models use two or three tanks to represent the entire system. Figure 7 shows an example of a lumped parameter model of a hydrological reservoir.

One of the tanks represents the innermost part of the reservoir and the others act as recharge parts either at depth or outside the main reservoir. Each tank simulates storage in the appropriate part of the reservoir but ignores its geometry. A tank has mass capacitance κ when it responds to a load of liquid mass m with a pressure increase $p = m/\kappa$. The tanks are connected by means of conductors that simulate flow resistance (permeability) in a reservoir with the conductance $\sigma_{ik} = q_{ik}/p_k - p_i$, where q_{ik} is mass flow from tank k to tank i and p_i is the pressure in tank i. If the reservoir is open it means that one of the tanks is connected to a system with a constant pressure: if it is closed, the tanks are not connected to an outside recharge system and the pressure of the system declines continuously as production proceeds. A closed model is, therefore, more pessimistic than an open one.

Lumped-parameter modelling is used to simulate pressure response data based on production from a reservoir. The basic equation describing the pressure response p of an open lumped model with N tanks, to a constant production Q since time $t = 0$ is the following (Axelsson and Arason, 1992):

$$p(t) = -\sum_{i=1}^{N} Q\frac{A_i}{L_i}(1 - e^{-L_i t}) \tag{12}$$

The pressure response of an equivalent N tank closed model is given by the equation

$$p(t) = -\sum_{i=1}^{N-1} Q\frac{A_i}{L_i}(1 - e^{-L_i t}) + QBt \tag{13}$$

The coefficients A_i, L_i and B are functions of the storage coefficients of the tanks κ_I and the conductance coefficients of the resistors σ_I of the model. The storage coefficient of a tank is defined by the following equation:

$$\kappa_i = V_i s \tag{14}$$

where s is the storativity ($s = \rho_f \times (\phi c_w + (1-\phi) c_r)$ and V_i the volume of a tank.

For one-dimensional flow the average permeability, k, can be estimated by using the following equation:

$$k = \sigma \frac{L\nu}{A} \tag{15}$$

For two-dimensional flow the average permeability, k, can be estimated by using the equation:

$$k = \frac{\sigma \ln(r_2/r_1)\nu}{2\pi h} \tag{16}$$

From Equation 14, we can estimate the volume of the reservoir (storage due to compressibility). Equation 15 or 16 provides a method to estimate reservoir permeability. The lumped model can be used to assess the production potential of the reservoir. This can be done by using the lumped-parameter model to predict the pressure changes in the reservoir for different cases of future production. The maximum allowable drawdown in the area can be used for estimating the maximum potential of the system. At this stage the allowable drawdown will be set at 100 m, later that may be increased.

5.1 Modelling results

To obtain information about reservoir properties of the Beregovsky area, predict the system response to future production and estimate production potential of the system, a lumped parameter model was used. The basis for modelling were the pressure changes resulting from variable production from the Beregovsky area, earlier used in the simulation by VARFLOW. The simulation process was carried out automatically by using the LUMPFIT computer program (Axelsson and Arason, 1992). In the first step a closed one-tank model was used, which represents the simplest model possible. After that the model was consistently made more complex, first a one open-tank model, and finally a closed two-tank model. The results of the simulation are shown in Figure 8. The parameters of the models are shown in Table 4.

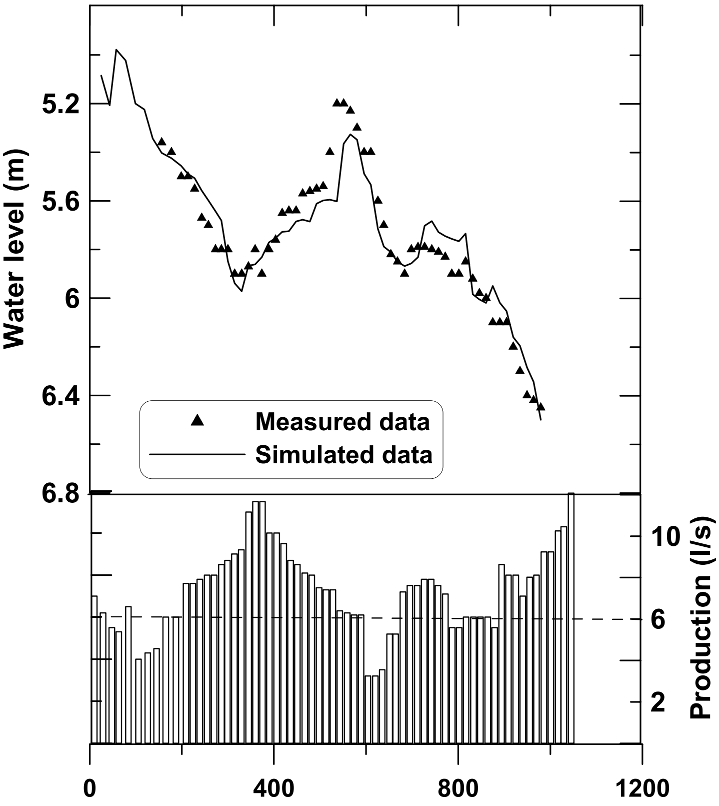

FIGURE 8: Data for three years production in the Beregovsky geothermal area simulated by a lumped parameter model

TABLE 4: Parameters of the lumped models for the Beregovsky area

Parameter	Open one-tank	Closed two-tank
A_1	0.013	0.013
L_1	0.083	0.081
B		0.0013
κ_1 (kg/Pa)	666.9	606.3
κ_2 (kg/Pa)		6062.7
σ_1 kg/Pa)	0.6×10^{-3}	0.52×10^{-3}
Coeff. of determinat. (%)	32.3	87.1

Using a closed two tank lumped model resulted in a satisfactory fit between observed and calculated pressure. In this model the fluid is produced from the first tank and the pressure is monitored in the same tank. The first tank can be considered as the main production reservoir and the other acts as the surrounding recharge area of the entire geothermal system. As can be seen from Table 4, the reserves (volume) of the recharge area are an order of magnitude greater than the reserves of the well area.

The best fitting lumped model reveals storage coefficient of the main area, κ_1, and the recharge area, κ_2, as 606.3 and 6062.7 ms^2, respectively. The high mass conductivity, $\sigma = 0.52\times10^{-3}$ ms reflects the high permeability of the system. Using the parameters presented in Table 4, and Equation 14, the volume of the first tank is estimated at 5.5 km^3 and the volume of the second tank at 55 km^3.

Assuming one-dimensional flow and a reservoir thickness of 1 km, the cross-sectional area of the system perpendicular to the direction of a flow, A, will be about 2.3 km^2. The distance between the centres of the two tanks, L, is about 13 km. The permeability is by Equation 15 estimated at 1.2×10^{-12} m^2.

Assuming two-dimensional flow and a reservoir thickness of 1 km, the radius of the first tank equals 1.3 km and the radius of the second tank equals 4.4 km. Therefore, r_1 = 0.65 km and r_2= 2.9 km. Based on these values and Equation 16 the permeability is estimated at 5.2×10^{-14} m^2. This may be compared with the results of well-test analysis and the VARFLOW simulation, a transmissivity of 0.1×10^{-5} m^3/Pas, which corresponds to a permeability-thickness of 4.2×10^{-10}. and a permeability value $k = 4.2\times10^{-13}$ m^2 assuming a reservoir thickness of 1000 m.

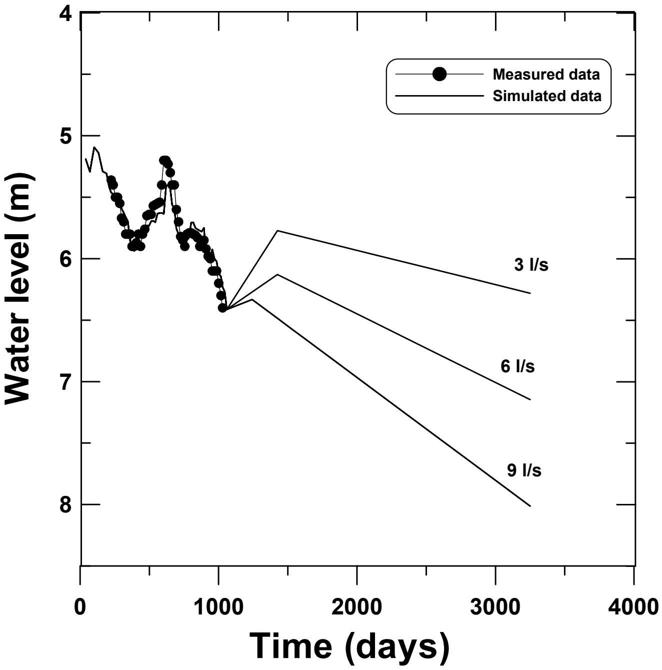

FIGURE 9: Predictions of the lumped parameter model for Beregovsky geothermal area

5.3 Future predictions and reservoir potential

Based on the maximum drawdown of 100 m the system should be able to sustain production at the order of 100-200 l/s. Lumped-parameter modelling was used to predict reservoir pressures for 3, 6 and 9 l/s net production rates in the Beregovsky area. The best fitting lumped model (a closed two-tank) was used for the calculations, which were made for the next 10 years. Figure 9 shows the results of these calculations. It reveals that the system can clearly sustain net production rates considerably higher than 9 l/s.

6. CONCLUSIONS

The main purpose of the present work was to review geothermal resource assessment methods and to consider the basic strategy for choosing such a method. This, of course, depends on the available input data and the requested accuracy of the results. The Beregovsky geothermal area in Ukraine was taken as an example and used to evaluate the different methods. Consequently, the assessment of the Beregovsky area resulted in estimates of the geothermal reservoir properties and estimates of production potential.

The main conclusions of the assessment are as follows:

1. The energy potential of the Beregovsky geothermal area estimated by the volumetric method is 1.23×10^{17} J, and the most likely direct-use power potential, as estimated by the Monte Carlo probability method, is on the order of 15 $\mathrm{MW_t}$.
2. The results of pressure transient test analysis and reservoir modelling indicate that the average transmissivity of the Beregovsky reservoir is 0.1×10^{-5} $\mathrm{m^3}$ /Pas, corresponding to a permeability thickness of $4.0 \times 10^{-10}\,\mathrm{m^3}$.
3. Predictions by a lumped parameter model indicate that over the next 10 years the water level will reach a depth of 6, 7 and 8 m for 3, 6 and 9 l/s average production, but this geothermal system could sustain much more production (100-200 l/s).

The following is recommended for future management of the Beregovsky geothermal area:

1. Long-term monitoring of the Beregovsky geothermal area must be implemented.
2. Tracer tests should be conducted in order to establish flow paths and possible cooling resulting from injection.
3. In the future when production is increased from the field the present modelling and predictions should be revised. When sufficient data becomes available, numerical modeling of the Beregovsky system should be considered.

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NOMENCLATURE

A = Area ($\mathrm{m^2}$);
C_r = Rock specific heat (J/kg°C);
c_t = Compressability ($\mathrm{Pa^{-1}}$);
$E_{s,r,f}$ = Stored heat in the system, rock and fluid, respectively (kJ);
h = Thickness (m);
h, h_t = Enthalpy of fluid at initial and reference reservoir temperature (kJ/kg);
k = Permeability ($\mathrm{m^2}$);
L = Length of resistor (m);

$P_{min,max}$ = Parameter of the distribution;
p = Reservoir pressure(bar);
Q = Flow rate (m^3/s);
R = Random value;
r = Radial distance (m);
s = Storativity (kg/Pa m^3);
T, T_{ref} = Temperature, reference temperature (°C);
t = Time (s);
V_i = Tank volume (m^3);

ϕ = Rock porosity;
κ = Storage coefficient (kg/pa);
$\rho_{r,f}$ = Density of rock and fluid, respectively (kg/m^3);
μ = Dynamic viscosity (Pa s);
ν = Kinematic viscosity (Pa s);
σ = Mass conductivity (m s);

REFERENCES

Anderson, E.B., 1995: Geothermal data management case studies: Resource assessment. In: Arason, P., and Björnsson, G., 1994, *ICEBOX.* 2nd edition, Orkustofnun, Reykjavík, 38 pp.

Axelsson, G., 1989: Simulation of pressure response data from geothermal reservoir by lumped parameter models. *Proceedings of the 14th Workshop on Geothermal Reservoir Engineering, Stanford University, California,* 257-263.

Axelsson, G., 2000: Sedimentary geothermal systems in China and Europe. In: *Long-term monitoring of high- and low-enthalpy fields under exploitation.* World Geothermal Congress 2000, pre-congress short courses, Kokonoe, Japan, May, 203-221.

Axelsson, G., and Arason, P., 1992: *LUMPFIT, automated simulation of pressure changes in hydrological reservoirs. Version 3.1, user´s guide.* Orkustofnun, Reykjavík, 32 pp.

EG&G Idaho, Inc., and Lawrence Berkeley Laboratory, 1982: *Low to moderate temperature hydrothermal reservoir engineering handbook.* Idaho Operations Office, USA, report IDO-10099, Appendix E, 40 pp.

Gazo, F.M. 1992: *Reservoir assessment of the Mak-Ban geothermal field, Luzon, Philippines.* UNU G.T.P., Iceland, report 6, 32 pp.

Lyal´ko, V., 1974: *Calculation of heat and mass transfer in the earth's crust* (in Ukrainian). Ukrainian Academy of Sciences, Kiev, 271 pp.

Muffler, P., and Cataldi, R., 1978: Methods for regional assessment of geothermal resources. *Geothermics, 7*, 53-89.

Sarmiento, Z.F., 1993: *Geothermal development in the Philippines.* UNU G.T.P., Iceland, report 2, 99 pp.

Zabarny G., Shurchkov A., and Zadorozhnaja A., 1997: *Resources and thermal potential of the prospective geothermal areas of Zakarpatsky region,Ukraine* (in Ukrainian). Ukrainian Academy of Sciences, Kiev, 150 pp.