

Assessment of Probability of Success for Hydrogeothermal Wells

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ABSTRACT

The quantification of geological risks, respectively the estimation of probability of success is one of the most important factors for investors and decision makers. Although the data base is often not optimal because of nonexistent comparing objects, a good quantitative assessment of the geological risks is required. We have gained experience by writing some expert reports about geological risks for geothermal wells for insurance companies and investors.

In this paper a concept of the assessment of probability of success (POS) will be discussed. Data base for the estimation of POS is the information about the water productivity, the drawdown of the water level and the aquifer temperature. The depth of the aquifer has to be determined as exactly as possible by seismic measurements. The project manager has to declare, at which flow rate and at which temperature the geothermal well will be (partly) successful. Then the POS can be calculated.

Information about the hydraulic parameters of the aquifer can mostly be determined in a regional scale only. Information from boreholes nearby or other boreholes having similar conditions can be weighted in a suitable manner. For the temperature prognosis, local conditions must be considered besides regional trends. An area of 1000 km² was normally chosen in the previous studies. Because of the small data base the simplest way to calculate the POS of a project is to multiply the single POS of flow rate and temperature.

The POS was calculated in this manner for a geothermal well drilled in 2004 in the south of Munich (Bavaria). This POS was the base for a private insurance contract. To our state of information, this is worldwide the first hydrogeothermal borehole which is insured by an assurance company.

1. INTRODUCTION

Hydrogeothermal energy in the low-enthalpy range up to 150 °C can be used for heat purposes, but also for electric power generation, and heat and power cogeneration. Both on the European and the global scale, a significant volume of generated energy can be implemented technologically in this way. A study by the Office for Technology Impact Assessment of the German Parliament (Paschen et al. 2003) estimated the geothermal power generation potential in Germany as 10²¹ J. Only around 1 % of this potential involves hot-water aquifers. Despite this low percentage, geothermal power plants in the short to medium term in Germany will primarily involve the use of hot water from aquifers. Some central barriers hinder the industrial

integration of geothermal energy use into energy supplies. Basically, the high investment risk for the first geothermal well is the most important obstacle. Therefore, the quantification of geological risks is the central question for investors and decision makers, which has to be answered by geoscientists. Although the data base is often insufficient because of nonexistent comparing objects, a good quantitative assessment of the geological risks is required.

Extensive investigations and methods for the assessment of exploration risks are known in the oil and gas industry (e.g. Rose 1987, Lerche 1998). The data base in oil and gas exploration is much greater than in geothermal exploration, so the sophisticated methods of oil and gas exploration are not applicable in geothermal energy. Some public insurance proceedings were implemented for geothermal wells on national levels as Rybach et al. (2000) and Partowidagdo (2000) reported, but private insurance contracts covering geological risks have been unknown until now.

2. GEOLOGICAL SITUATION AT THE MODEL LOCATION

We have gained experience by some expert reports about geological risks for geothermal wells, worked out for insurance companies and investors. Our concept of the assessment of probability of success (POS) will be discussed in this paper based on a model case with real background. A geothermal plant located south of Munich, the capital of Bavaria (South Germany, cf. Fig. 3), is intended to demonstrate the possibilities of generating power in the 1-3 MW_{el} range from groundwater at temperatures of 100-130 °C. Production requires the drilling of an extraction and an injection well (doublet) in the Malm karst. The location of both boreholes was constrained by the requirements for the surface facilities such as available land for drilling and the power plant control room, as well as customers for the district heating system using the hot water.

2.1 Geothermal Resources

The Malm karst of the Southern German / Upper Austrian Molasse basin is one of the most important hydro-geothermal energy reservoirs in Central Europe. The Malm (Upper Jurassic) which is present throughout almost the whole of the area is a highly-productive aquifer which dips from north to south to increasing depths and temperatures. The geothermal resources of the Malm for thermal extraction total 53.6*10¹⁸ J (billion GJ) (Frisch et al. 1992). Resources are classified as that part of the geothermal energy potential which could be extracted underground using current technology and which could also potentially be of economic value (Muffler and Cataldi 1978). A minimum temperature of 100 °C is required for power generation. This considerably reduces the geothermal power generation potential compared to the thermal extraction resources. Only around 20 % of the geothermal resources have temperatures exceeding 100 °C. Making allowance for a reinjection temperature of 70 °C and an

estimated energy conversion efficiency of approx. 10 %, the geothermal resources of the Malm suitable for power generation are estimated at $0.5 \cdot 10^{18}$ J (Schulz 2002), i.e. 1% of the resources for heat production.

2.2 Determining the Depth of the Aquifer

The Upper Bavarian Alpine margins were the focus of intensive oil and gas exploration from 1952 to 1988 (Lemcke 1988). Information from boreholes in the eastern Molasse basin indicate that the most prospective sites for high water production are in the immediate vicinity of faults. Optimal development therefore requires exploration of the geological structure, as well as information on the karstification of the Malm.

The nearest deep boreholes are 10-16 km from the planned well location (see Fig. 2). The most important nearby boreholes are at Oberdill (2879 m, Purbeck), Pöding (2825 m, Lower Cretaceous) and Hofolding (max. 3494 m, Malm) (see table 1). One of the main objectives of seismic reprocessing was to determine the depth of Top Malm. The Top Malm at the planned drilling location is at a depth of slightly over 3000 m (Schulz et al. 2004). The thickness of the Malm in the study area is estimated at 500 m to 550 m.

Fault zones with small throws (decameters) can be identified in seismic lines running to the east of the planned borehole and particularly, in the line running to the north of the borehole. Their dip is steep; their strike direction cannot be specified. Making allowance for other factors, the preferred deviation direction of the well is NNW.

2.3 Essential Parameters

In addition to high temperatures, the critical factor for the economic efficiency of geothermal energy utilization is primarily the production rate achievable during continuous operation. The project manager has to declare, at which flow rate (with which drawdown) and at which temperature the geothermal well will be (partly) successful. For economic reasons, production in our case must lie within the 50 to 100 l/s range with temperatures of at least 100 °C.

The parameters for the assessment of probability of success (POS) in this model example are

- temperature of 100 °C (the POS should also be calculated for higher temperatures),
- flow rate of 50 l/s with a drawdown of 150 m (or 300 m) (the POS should also be calculated for flow rates of 65 l/s and 100 l/s).

3. TEMPERATURE PROGNOSIS

The GGA Institute database was used to assess the temperature. This database contains information on around 10,000 boreholes and their temperatures throughout Germany. In addition to temperature logs, the analysis mainly used bottom hole temperatures (BHT). These BHT logs are made in almost all industrial wells at the deepest part of the well immediately after the end of each drilling phase and are thermally disturbed by the drilling activity (mud circulation). It is possible to correct (extrapolate) these BHT figures to calculate the undisturbed temperatures because the disturbance caused by mud circulation on the temperature field is lowest in the deepest part of the borehole. Different extrapolation methods can be used depending on the time since the end of drilling, the mud circulation period and the number of BHTs measured in the well (Schulz et al. 1992). In addition, the figures are

compared with a statistical evaluation of all available borehole data in the study area. Unlike undisturbed temperature logs, the results still have an error of approx. ± 5 K despite the corrections.

Because the beds of the South German Molasse basin dip southwards from the Danube in the direction of the Alps, temperatures in the Malm also generally increase southwards. However, the average temperature gradient (determined from Top Malm to the surface) decreases in this direction. This general trend is superimposed by local temperature anomalies thought to be attributable to convection systems. Underground temperature distribution overall is very complex (see Frisch et al. 1992).

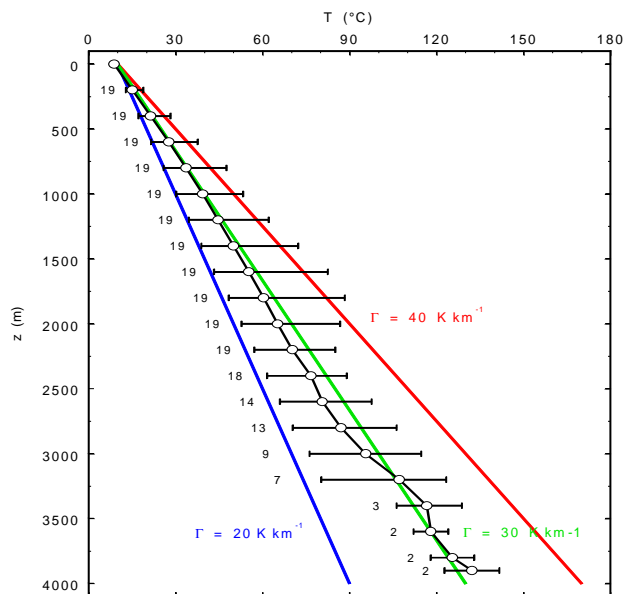


Figure 1: Temperature depth profile in the study area (approx. 1000 km²) with details on observed minimum and maximum temperatures. The figures next to the observed minimum values show how many measurements exist for each depth; the averages are calculated with a weighting function taking into account the different reliability and accuracy of the data. The lines correspond to temperature gradients of 20, 30 and 40 K/km.

An aquifer depth of 3000 m (see above) is used for a conservative temperature forecast. No significant increase in temperature within the Malm karst is expected even if a high degree of karstification is present because of the good vertical mixing of the thermal water. The study area encompassed nine TK25 sheets, i.e. 33 km x 33 km, around the location (see Fig. 2). BHT measurements from only 19 boreholes are available in the study area; these have been compiled within a temperature depth profile in Fig. 1. No wells with temperature information exist in the immediate vicinity of the planned borehole.

Data availability decreases sharply below 2500 m (Fig. 1). A depth of 2500 m was therefore selected for the temperature isolines (Fig. 2). The isolines were mapped using the GMT program package (Wessel & Smith 1995); the “continuous curvature splines in tension” interpolation method was used (Smith & Wessel 1990). 15 boreholes (white dots) with temperature information are available for a depth of 2500 m.

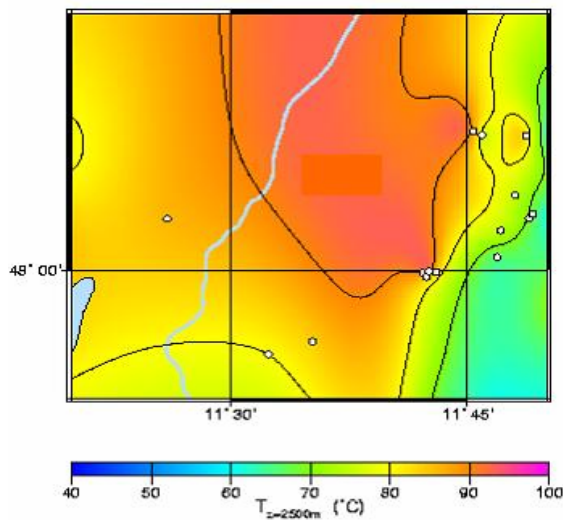


Figure 2: Temperature isolines at 2500 m depth in the study area; the planned borehole site is located in the centre of the map. The white dots mark boreholes with temperature data.

Table 1: Temperature at 3000 m depth in the vicinity (1000 km²) of the planned borehole.

Range / Borehole	Depth (m)	grad T (K/km)	Calculation	Temp. (°C)	Dir
Unterschleißheim Th 1	1570	40.7	extrapolation	131.4	N
Oberdill 1	2800	29.0	extrapolation	96.2	W
Endlhausen /Thanning (2 boreholes)	2000 3800	28.3 30.6	interpolation (2-3.8 km) (0-3.8 km)	95.5 101.1	S
Hofolding (4 boreholes)	2200	30.9	interpolation (2.2-3.3 km)	107.3	SE
Hofolding (4 boreholes)	3300	33.9	interpolation (0-3.3 km)	110.9	SE
Hofolding 3	3380	35.2	interpolation (2.2-3.4 km)	115.0	SE
Vaterstetten(1+2) Vatterstetten 2	2500 2540	29.9 31.9	extrapolation extrapolation	99.1 105.0	NE

Depth: Mean measuring depth for existing temperature measurements.

grad T: Mean temperature gradient between temperatures averaged in the quoted depth and the Earth's surface ($T_0 = 9.3$ °C).

Dir.: direction.

The temperature range in Fig. 1 does not reflect a statistical distribution, but depends on the local subsurface situation as Fig. 2 shows. The borehole site lies within the 90 °C isoline at a depth of 2500 m, i.e. in a zone of elevated

temperatures. This zone is highlighted by high temperatures to the N of Munich and the temperatures in the four Hofolding boreholes (SE). Much lower temperatures have been measured to the E. However, the boreholes to the SE and NE exclude the possibility of these low-temperature conditions existing in the drilling site. In line with the overall trend, lower temperatures exist to the S. The nearest temperature data point to the N is in the Unterschleißheim Th 1 well drilled in 2002, for which an undisturbed temperature log is available: the temperature of the Top Malm aquifer (approx. 1570 m) was 73.2 °C; the gradient is 41 K/km.

The available figures were extrapolated or interpolated to a depth of 3000 m for the temperature prognosis of the planned borehole. All of the figures lie between 95-115 °C (Tab. 1), only the extrapolation of the temperature in the Unterschleißheim borehole (N of Munich, outside of Fig. 2) yields a significantly higher temperature. The temperatures of Tab. 1 are the base for calculating the possibility of success (POS, Tab. 2). Decreasing temperature gradient to the S (i.e. lower temperature in the S in the same depths) has to be assumed according to the regional temperature distribution. That is why only the higher value in the S (Endlhausen / Thanning) is taken into account. The local temperature distribution (Fig. 1) shows that the temperature in the planned borehole is to be assumed to be higher than to NE (Vaterstetten): therefore the condition is fulfilled at 100 °C and partly fulfilled at 105 °C. As we have only 7 temperature data points to our disposal, the statistical weight of each data point is 14 %! The POS for 100 °C is diminished to 86 % by the data point in the W. A probable figure of 107-110 °C (median value) would be interpreted for the temperature isoline map at 3000 m depth in the study site. Temperatures of 120 °C are also possible; temperatures above 130 °C can be excluded.

Table 2: Possibility of success (POS) for reaching the quoted temperature at 3000 m depth (see Tab. 1).

Temp. (°C)	90	95	100	105	110	115	120
Number	7	7	6	4.5	3	2	1
POS	100%	100%	86%	64%	43%	29%	14%

Number: number of used temperature data of Tab. 1, respectively number of data reaching the quoted temperature.

4. HYDRAULIC PARAMETERS

It is difficult to estimate the expected production rates because of the strong local variability in thermal water flow typical for karst aquifers. The borehole might for instance penetrate a highly productive karst cavity whilst another borehole drilled close by could miss the cavity completely. In addition, there are also regional differences reflecting facies and tectonics. The Helvetic facies of the Malm karst has much lower hydraulic permeability than the Swabian or Franconian facies. Because of the higher density of tectonic faults in the eastern Molasse basin, it is possible that this area has a higher probability of success.

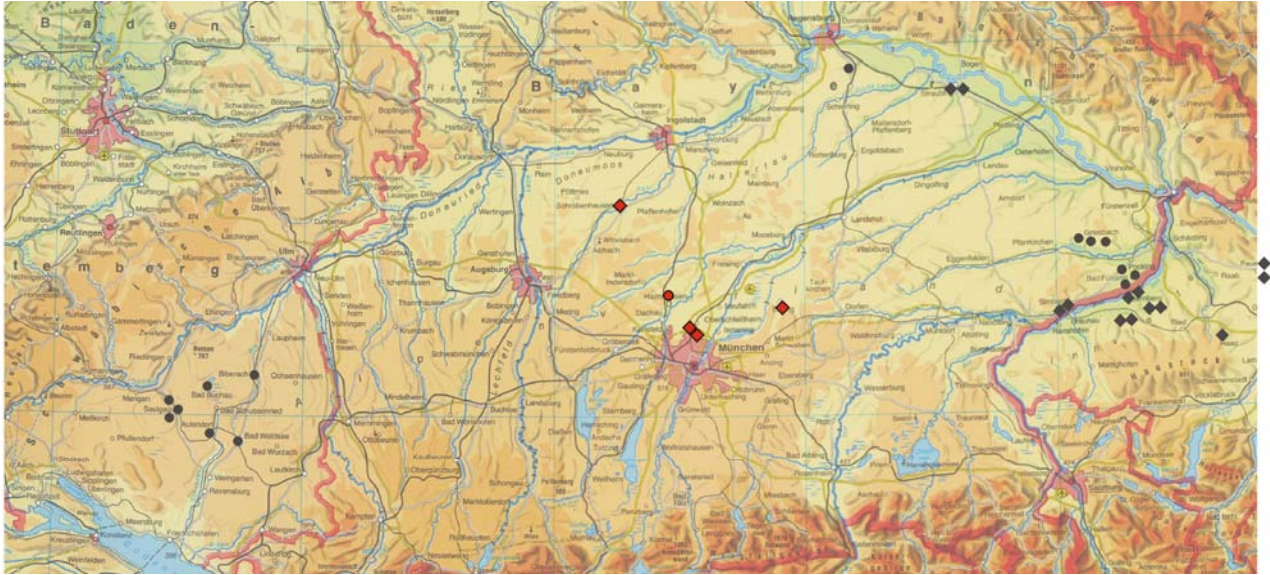


Figure 3: Borehole locations in the South German / Upper Austrian Molasse basin with hydraulic parameters in the Malm (cf. Fig. 4); rectangles: geothermal wells, circles: other wells, in red: wells in the central basin).

(With thanks to Westermann Schulbuchverlag for their approval for the map.)

Reliable conclusions about the prospectivity are only possible when data is available from a large number of boreholes in a specific region. To gain a handle on the probability of success, the data on thermal water flow rates and drawdowns from boreholes, drilled into the Malm in the South German / Upper Austrian Molasse basin (Fig. 3), were compiled (Schulz et al. 2003). These 32 boreholes indicate a wide range of flow rates (mostly production flow rates, in a few cases, also injection flow rates) and drawdowns (also rises in water level in the case of injection wells), as Fig. 4 shows. There is also some information available on transmissivity – the product of permeability coefficient and thickness.

To use these details to estimate the probability of success, the expected drawdowns s_i were calculated for the specified production flow rates Q' . Three cases were assumed:

laminar flow (best case),

$$(1) \quad s_1 = s \cdot Q' / Q$$

pure turbulent flow (conservative case, but not realistic),

$$(2) \quad s_2 = s \cdot Q'^2 / Q^2$$

laminar-turbulent flow (most probable case).

$$(3) \quad s_3 = a' \cdot Q' + a' \cdot (b/a) \cdot Q'^2$$

with Q : measured flow rate [m^3/s], s : measured drawdown [m] and $a' = s / (Q + b/a \cdot Q^2)$. The coefficients a [s/m^2] and b [s^2/m^3] are determined by interpretation of multi level production tests in existing geothermal wells. The newest value of the coefficients was determined in the Unterschleißheim Th1 well: $b/a=11.8$ (Struffert, pers. comm. 2002); this well is also the closest geothermal well to the study area. This value shows that the turbulent part of the flow is relatively small; the case of pure turbulent flow can be excluded. Secondary effects, like temperature dependency or friction losses, are overlooked; they would yield a little higher POS.

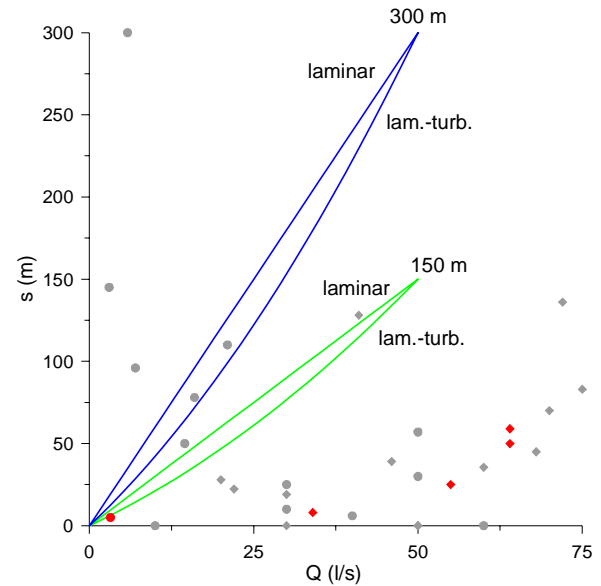


Figure 4: Production rates Q with drawdown s for wells in the Molasse basin (rectangles: geothermal wells, circles: other wells, in red: wells in the central basin). Theoretical curves for production rates of a max. drawdown of 300 m (blue) and 150 m (green); straight line: laminar flow, parabola: laminar-turbulent flow.

The expected drawdown for a production rate of 50 l/s is less than 300 m for 29 (of 32) boreholes as laminar flow and for 27 boreholes as laminar-turbulent flow is assumed (Tab. 3). The data points of the successful boreholes are located below the blue curves in Fig. 4: in the laminar case below the linear line, in the laminar-turbulent case below the parabola. If a drawdown of only 150 m can be realized, the green curve in Fig. 4 and the first line in Tab. 3 are valid.

Table 3: Number of successful wells in the Malm karst and deduced possibility of success for a flow rate $Q = 50$ l/s at a drawdown $s = 150$ m (300 m); s_1 laminar flow, s_2 turbulent flow, s_3 laminar-turbulent flow.

Q	s	s_1	s_2	s_3	
32		32	31	32	Total
50 l/s	150 m	25	23	24	successful
		78%	74%	78%	%
50 l/s	300 m	29	25	27	successful
		91%	81%	84%	%

There are wells for water demand and balneology as well as for geothermal utilization among the 32 boreholes considered here. It is apparent that the productivity of geothermal wells is higher than that of wells drilled for other purposes. The reason is that geothermal wells which were dry were stimulated for instance with acid treatment. This fact should be taken into account in the assessment of POS. Therefore using of weight factors is suggested: Wells drilled for geothermal utilization are doubled weighted. Additionally, the spatial distance (this means also the geological similarity) to the planned well can be considered: The success values a_i of the wells drilled in the central Molasse basin are also doubled. With these constraints, the POS are calculated as follows:

$$(4) \quad POS = (\sum u_i w_i a_i) / (\sum u_i w_i)$$

with \sum : sum $i = 1 \dots N$; u_i , w_i : weight factors ($w_i = 2$ for wells in the central basin; otherwise 1; $u_i = 2$ for geothermal wells, otherwise 1); $a_i = 1$ for successful wells (i.e. $s \leq 150$ m, 300 m), otherwise 0.

Table 4: Weighted number of successful wells in the Malm karst and possibility of success (POS) for a flow rate $Q = 50$ l/s at a drawdown $s = 150$ m (300 m); s_1 laminar flow, s_2 turbulent flow, s_3 laminar-turbulent flow.

Q	s	s_1	s_2	s_3	
58		58	56	58	Total
50 l/s	150 m	50	46	50	successful
		86%	82%	86%	POS
50 l/s	300 m	55	50	53	successful
		95%	89%	91%	POS

For a production rate of 50 l/s and a drawdown of 300 m the probability of success is estimated at 95 % (Tab. 4). This figure changes minimally (91 %) when making allowance for laminar-turbulent flow. If a drawdown of 150 m is assumed, the probability of success is still 86 %. The POS for a flow rate of 65 l/s at a drawdown of 300 m (150 m) is still 91 % (85 %). The last figure (85 %) is also achieved with a production rate of 100 l/s and a drawdown of 300 m. These figures are still associated with a degree of uncertainty because the number of boreholes in the central

Molasse basin in particular is insufficient for reliable statistical conclusions to be made.

5. PROBABILITY OF SUCCESS

The probability of success (POS) can be defined in the simplest way by determining the probability of each risk separately and multiplying the single probabilities. But this method is also problematic to use in geothermal exploration assessing quantitatively the probability of each parameter, because the data base is normally very small.

In the case investigated in this paper, the condition of the temperature of 100 °C can be fulfilled with a high probability ($p_1=0.86$). The probability of a production rate of 50 l/s (100 l/s) at a drawdown of 300 m is assessed with $p_2 = 0.95$ (0.85). Stimulation measures to reduce the geological risk such as optimum seismic information, acid treatment or deviation of drilling are presumed.

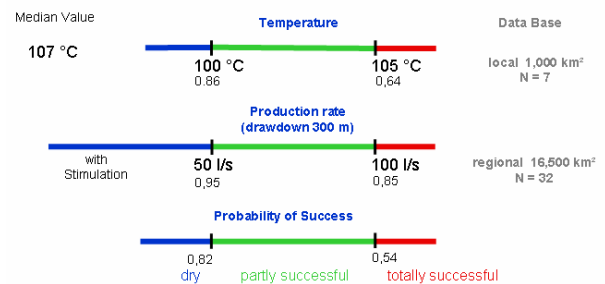


Figure 5: Probability of Success for the model case

A POS for a geothermal well with a production rate of 50 l/s (100 l/s) at a drawdown of 300 m and a temperature of minimum 100 °C is yielded with these figures:

$$p = p_1 \cdot p_2 = 0.82.$$

Such a POS is extremely high, if it was assessed in the oil and gas exploration; it should be considered that the value of a production well in the carbon industry is much higher than in geothermal energy.

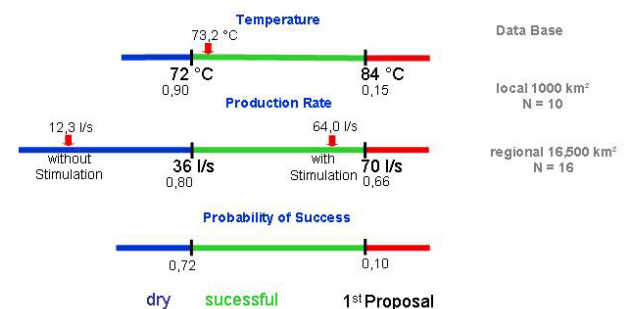


Figure 6: Probability of Success for the Unterschleißheim Th 1 well. The well was successful after stimulation (red arrows); the POS was estimated with 0.72

The POS of the Unterschleißheim Th 1 well was assessed with 0.72 (Jung et al. 2002, unpublished). The probability of the hydraulic parameters (production rate of 36 l/s at 110 m drawdown) was given with 0.80, the data base was smaller than now, and the probability of the temperature of 72 °C was 0.90. The measured temperature at the top Malm is 73.2 °C, and the first pumping test resulted 12.3 l/s at a drawdown of 162 m. after acid treatment the production

rate was 64 l/s at a drawdown of 59 m. This result shows that the method for assessing the POS is very realistic; it seems that the assessment underestimates the real value, particularly if stimulation measures will be carried out.

6. CONCLUSIONS

A concept of the assessment of probability of success for a geothermal well was discussed for a specific location. The structural interpretation of the seismic lines reveals that the Top of the aquifer lies at a depth of slightly more than 3000 m at that location. Local analysis (study area approx. 1000 km²) indicates that there is a good probability that the expected temperatures will be 107-110 °C. A temperature of 100 °C minimum required for power generation is expected with a probability of 0.86. Because of the karstification, estimating the potential production rates proved to be problematic. Regional analysis for the whole Molasse basin (16,500 km²) reveals that production rates of 50 l/s with a maximum drawdown of 300 m can be achieved with a probability of approx. 90 %. This may involve stimulation measures such as acid treatment and drilling deviation. The overall POS of the geothermal well is 0.82.

The project design included geoscientific prospect evaluation with a special seismic reprocessing and interpretation, a local analysis of the temperature distribution and a regional assessment of the hydraulic parameters. Stimulation measures as deviation and acid treatments are an integral part of the financial design for the geothermal plant. Drilling the first well began in spring 2004. The borehole is privately insured against the risk of non-discovery. This was based on the estimated probability of success outlined here. According to our information, this is the first geothermal borehole in the world which has been privately insured against failure.

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