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APPROPRIATE USE OF USGS VOLUMETRIC "HEAT IN PLACE" METHOD AND MONTE CARLO CALCULATIONS

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ABSTRACT

The USGS volumetric estimation method together with Monte Carlo simulations is often used to provide estimates of the probable electrical generation capacity of a geothermal system. The methodology consists of combining probability density functions for uncertain estimates of the temperature, area, and thickness of a geothermal reservoir to obtain the probability distribution function for the stored energy ("heat in place") and the resulting electrical capacity of the potential geothermal reservoir. Taken at face value, the methodology is deceptively simple. However, geothermal reservoir assessment and the prediction of the electrical capacity should be regarded as a continuing process – from the early exploration phase to the time when the reservoir becomes depleted. The key to a proper use of the technique is the specification of the probability distributions of the reservoir parameters. The data acquired during each phase of the reservoir development and production provides continuing refinement of reservoir parameters and, therefore, the electrical capacity. Very often, these parameters are designated based on data from other geothermal reservoirs. Conditions vary widely between and within the various geothermal provinces around the world. Thus, it is essential that, as far as possible, actual field data should be used when prescribing reservoir parameters. Without data-driven reservoir parameters, use of Monte Carlo simulations is liable to generate unreliable estimates of reservoir capacity for electrical generation.

INTRODUCTION

In the early stage exploration of geothermal resources associated with an identified hydrothermal convection system, it is necessary to obtain an estimate of the potential electrical energy that might be produced from the delineated geothermal system. In the 1970s, researchers at the United States Geological Survey (USGS) developed a methodology to quantify the uncertainty of estimates of the geothermal resources associated with an identified hydrothermal convection system (e.g., Nathenson, 1975a; 1975b; Nathenson and Muffler, 1975; Muffler and Cataldi, 1978; Brook, et al., 1979). The USGS volumetric estimation methodology consists of combining estimates with uncertainties for the temperature, area, and thickness of a geothermal reservoir into an estimate of the stored energy ("heat in place") with uncertainty. Probability density functions for temperature, area, and thickness are assumed based on uncertain estimates in order to calculate the probability distribution function for the stored "heat in place". The probability distribution function for the stored energy can be obtained using a Monte Carlo approximation. Thus, the USGS volumetric estimation method together with Monte Carlo simulations is often used to provide estimates of the probable generation capacity of a geothermal resource. Taken at face value, the method is deceptively simple.

The parameters required for the computation of electric capacity of the "heat in place" are provided in Table 1.

Table 1. Parameters required for the calculation of the electric generation capacity using the USGS volumetric "heat in place" method.

Group 1 Parameters:
Reservoir Area (km^2)
Reservoir Depth (m)
Reservoir Thickness (m)
Reservoir Temperature (°C)
Thermal Recovery Factor (%)
Group 2 Parameters:
Volumetric Heat Capacity (kJ/m^3-K)
Rejection Temperature (°C)
Conversion Efficiency (%)
Plant or Project Life (years)
Plant Load Factor (%)

The parameters in Table 1 can be divided into two groups. The second of these groups (*Group 2 Parameters*) contains parameters whose value does not either vary substantially from case to case (volumetric heat capacity, power plant or project life, power plant load factor) or can be specified sufficiently accurately using available engineering data (rejection temperature, conversion efficiency). The situation is completely different as far as the first group (*Group 1 Parameters*) of parameters is concerned.

Specification of statistical distributions for the parameters in the first group (reservoir area, reservoir depth, reservoir thickness, reservoir temperature, thermal recovery factor) is at best a difficult task and as demonstrated below is highly dependent on the stage of development of a geothermal system. Reservoir area, thickness, and temperature are required to compute the "heat in place". Reservoir depth, often ignored in Monte Carlo simulations, is important in that it determines the depth to which the wells must be drilled in order to access the geothermal resource.

Thermal recovery factor is needed to compute the fraction of "heat in place" that may be recovered using a system of production and injection wells. The latter parameter depends on the permeability structure (fracture vs. matrix, permeability anisotropy, faulting, etc.), production and injection well depths and patterns, and the thermal (heat and fluid recharge from depth) and hydraulic boundary conditions (recharge/discharge along the ground surface, and assumed lateral boundaries for the geothermal reservoir). Since many of the reservoir properties that affect the thermal recovery factor are likely to be poorly known until the reservoir has been produced for several years, specification of the thermal recovery factor for a specific reservoir is more often than not a matter of conjecture. A major goal of reservoir engineering- including well drilling and testing, data collection and synthesis, and detailed reservoir modeling – is to obtain reliable estimates of the thermal recovery factor for a particular reservoir.

EXPLORATION PHASE

Prior to deep well drilling and testing, data that may be used to estimate reservoir parameters include shallow temperature gradient surveys (temperature data from heat flow holes usually less than 100-200 m in depth), chemical geothermometer values for fluid samples from any hot springs/fumaroles, and surface alteration (e.g., sinter, carbonate) surveys. Surface alteration if present can provide an indication of probable reservoir temperatures; as an example, presence of sinter indicates fluid temperatures in excess of about 175°C. Chemical geothermometer data, if available, provide a reasonable first estimate of the reservoir temperature.

Extrapolation of the high shallow temperature gradient data to great depth should be done with considerable care since the relatively high permeability associated with a geothermal reservoir will tend to produce a near isothermal (and low temperature gradient) zone. Temperatures at depth, obtained by extrapolating shallow gradient data and not supported by any other evidence, should be regarded as an estimate of maximum reservoir temperature; a first estimate of the minimum temperature may be computed using the average regional temperature gradient.

During the exploration phase, chemical geothermometers provide the best estimate of the possible range for reservoir temperatures. Shallow temperature gradient data, in conjunction with chemical geothermometers, may then be used to estimate the depth range for the geothermal reservoir. A minimum estimate of possible reservoir area may be obtained from the distribution of hot springs/fumaroles and high temperature gradient areas. Geophysical data (e.g., resistivity surveys) or geological mapping (e.g., surface alteration, faulting, etc.) may be useful for estimating the probable maximum geothermal reservoir area.

Prior to geothermal well drilling and testing, it will not in general be possible to obtain any reliable estimates of reservoir thickness and thermal recovery factor. Since it may eventually prove impossible to produce fluids from a geothermal reservoir, the possibility of the thermal recovery factor being zero cannot be discounted during the exploration phase; therefore, the proper range for thermal recovery factor is from 0 to 0.20 (the latter value is believed to be the maximum credible value based on world-wide experience with production from liquid-dominated reservoirs). Unfortunately, in most instances prior to geothermal well drilling and testing, the minimum thermal recovery factor is chosen to be 0.05, rather than 0. For example, in Table 2, the GeothermEx (2004) parameters for Silver Peak, Nevada, are presented in Case 1. GeothermEx (2004) provides values for rock matrix volumetric thermal capacity and rock porosity. The volumetric heat capacity for Case 1 was calculated using the GeothermEx values and the volumetric heat capacity for water. A triangular probability distribution is assumed for parameters for which maximum, median, and minimum values are given in Table 2. If only estimates of minimum and maximum values are available, then a rectangular (i.e. uniform) probability distribution is used. It should be pointed out that any particular choice or prescription of the distribution of parameter probability over the postulated range (minimum to maximum) will also impact the cumulative results, and that this issue is not well-studied. Presumably, different distributions (uniform vs. triangular vs. Gaussian vs. log-normal, etc.) will give different answer; thus, providing additional uncertainty in the estimation process.

Since the volumetric heat capacity does not vary significantly, it is assumed to be constant for Cases 2 through 5 (Table 2). Case 2 differs from Case 1 only in that a constant volumetric heat capacity is used in the former case. In Cases 3 through 5, minimum value of thermal recovery factor is assumed to be zero. The rejection temperature (Cases 4 and 5) is taken to be 40°C; the latter temperature is a typical value for the condenser temperature. The depths used in Cases 4 and 5 were calculated using minimum and maximum reservoir temperatures, an average thermal gradient of 10.3°C/100m, and an average surface temperature of 27.8°C. The minimum and maximum reservoir temperatures for Cases 4 and 5 are based on the reported geochemical temperatures from a single fluid sample. The maximum reservoir area for Case 5 corresponds to the entire area explored by shallow temperature gradient wells.

Unlike oil reservoirs, a geothermal well does not penetrate a region of uniform permeability. Very often a geothermal well is completed with a large open-hole section (100 to 1,000 or more meters); actual production usually comes from one or more feed zones with a thickness of the order of (1-100) meters. In any event, during the exploration phase, the reservoir thickness should be assumed to vary within a rather wide range (say between 100 and 2,000 meters). Therefore, for Case 5, the minimum reservoir thickness is reduced to 305 m. In Table 3, it can be seen that the megawatt capacity values as a function of probability for the Silver Peak geothermal prospect given in the GeothermEx (2004) report vary over a very narrow range compared to the megawatt capacity predicted under Case 5. The cumulative probability distributions for Cases 1, 3 and 5 are shown in Figures 1-3. A comparison of Figure 1 with 2 and 3 (see also Table 3) demonstrates that the assumed value for the minimum thermal recovery factor has a major influence on the predicted electrical power capacity at the 90% confidence level. On the other hand, the power capacity at the 10% confidence level remains more or less unaffected by the changes in the minimum values for the recovery factor and the reservoir thickness.

Adoption of the above procedure for specifying parameter values during the exploration phase is liable to yield a wide distribution for estimated electrical capacity with a relatively large ratio between the capacity at 10% confidence level and that at 90% confidence level. The estimated capacity at 10% level would almost certainly be higher than what will ultimately prove to be the case. Similarly, the estimated capacity at the 90% confidence level will go up as we learn more about the geothermal reservoir. The major goal of the resource estimation at this stage should be to determine whether a geothermal resource exists and if it may be economically worthwhile to undertake a program of geothermal well drilling and testing to reduce the uncertainty in the geothermal reservoir parameters and thus obtain a more reliable estimate of the probable resource megawatt capacity.

Table 2. Parameters for Silver Peak, Nevada, Geothermal Prospect. Case 1 parameters are reproduced from GeothermEx (2004).

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
Area (km^2)	Min: 5.4 Med: 11.1 Max: 16.8	Same as Case 1	Same as Case 1	Same as Case 1	Min: 5.2 Med: 10.4 Max: 31.1
Thickness (m)	Min: 762 Med: 1067 Max: 1676	Same as Case 1	Same as Case 1	Same as Case 1	Min: 305 Max: 1676
Depth (m)	0	Same as Case 1	Same as Case 1	Min: 1250 Max: 2042	Min: 1250 Max: 2042
Temperature (°C)	Min: 154 Med: 174 Max: 227	Same as Case 1	Same as Case 1	Min: 150 Max: 232	Min: 150 Max: 232
Volumetric Heat Capacity (kJ/m^3-K)	Min: 2655 Max: 2704	2700	2700	2700	2700
Thermal Recovery Factor	Min: 0.05 Max: 0.20	Same as Case 1	Min: 0.00 Max: 0.20	Min: 0.00 Max: 0.20	Min: 0.00 Max: 0.20
Rejection Temperature (°C)	10	Same as Case 1	Same as Case 1	40	40
Conversion Efficiency (%)	0.45	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1
Plant Life (years)	30	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1
Plant Capacity Factor (%)	0.90	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1

Table 3. Megawatt Capacity Values as a Function of Probability for the Silver Peak, Nevada, Geothermal Prospect.

Minimum MW Capacity with a Probability >	Case 1	Case 2	Case 3	Case 4	Case 5
90%	41	41	13	9	8
50%	82	82	64	44	44
10%	146	150	140	102	137
10%MW/90%MW	3.6	3.7	10.8	11.3	17.1

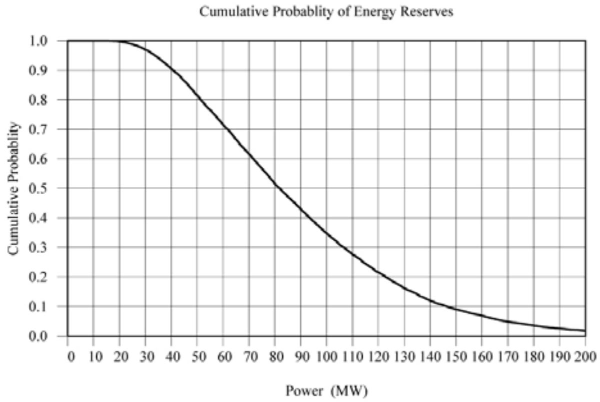

Figure 1: Predicted cumulative probability of energy reserves - Case 1. Predicted electrical capacity is 41 MW at 90%, and 146 MW at the 10% level.

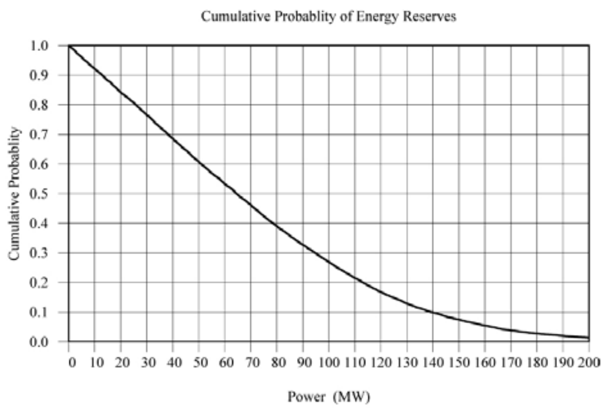

Figure 2: Predicted cumulative probability of energy reserves - Case 3. Predicted electrical capacity is 13 MW at 90%, and 140 MW at the 10% level.

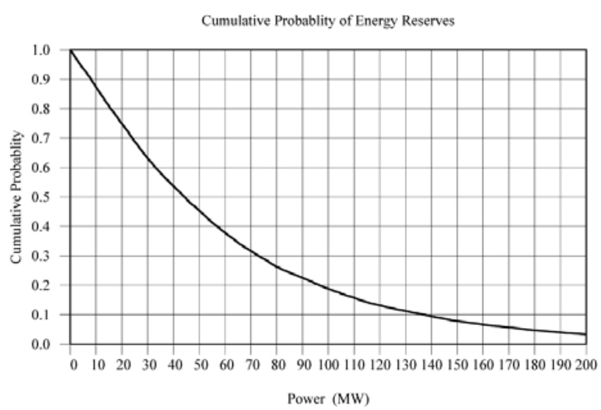

Figure 3: Predicted cumulative probability of energy reserves - Case 5. Predicted electrical capacity is 8 MW at 90%, and 137 MW at the 10% level.

WELL DRILLING AND TESTING PHASE

Drilling and testing of geothermal wells is essential for obtaining reliable estimates of important reservoir parameters. Downhole temperature and pressure surveys in deep wells can be used to establish (1) depth to the top of the geothermal reservoir (defined here as the transition from the linear conductive thermal gradient interval in the well to either a near isothermal or low thermal gradient interval), (2) formation temperature, and (3) formation pressure. Fluid samples from discharging geothermal wells may be used to obtain chemical geothermometers temperatures; generally speaking, different chemical geothermometers yield a range of temperatures. Pressure transient tests (and in particular pressure interference tests) and tracer tests can be used to establish reservoir continuity in the region penetrated by the wells, and to obtain the probable area of the permeable zone. Drilling records ("mud losses") are also helpful in determining depths of permeable horizons. Note that the permeable zone does not necessarily equate to the hot reservoir zone. At the end of the initial well drilling and testing phase, it should be possible to define the following parameters with a high degree of confidence:

1. Reservoir depth: Temperature profiles in wells (i.e., transition from conductive to convective profiles) should be used to estimate the minimum and maximum depths to the top of the permeable zone.

2. Reservoir temperature: Measured temperatures in wells together with chemical geothermometry may be employed to define the range of probable temperatures for the "hot region" of interest in the geothermal system.

3. Reservoir area: Since it is unlikely that the entire reservoir area with elevated temperatures has been penetrated by the geothermal wells, it is almost certain that the minimum reservoir area is greater than that investigated by drilling. Estimates of maximum reservoir area may be obtained from pressure transient data, geophysical surveys (e.g., electrical resistivity), and geological mapping (e.g., alteration surveys).

4. Reservoir thickness: Estimates of minimum and maximum geothermal reservoir thickness may be obtained by examining the convective zone from downhole temperature surveys.

Provided geothermal well drilling and testing has shown adequate well productivity, it is justified at this stage to assume a non-zero minimum value (say 0.05) for the thermal recovery factor.

At the end of geothermal well testing, it should thus be possible to place much closer limits on reservoir parameters (i.e., Group 1 Parameters) than those in the exploration phase. It need hardly be stressed that even after initial geothermal well drilling and testing, it will only be possible to narrow (but not eliminate) the uncertainty in reservoir properties. Use of these "parameter ranges" in the USGS volumetric estimation will result in a considerably narrower distribution of probable electric megawatt capacity than that obtained in the exploration phase. A measure of the success of the geothermal well drilling and testing would be a reduction in the ratio of the estimated electric megawatt capacity at the 10% confidence level to that at the 90% confidence level.

PRODUCTION/INJECTION PHASE

Following a positive outcome from the initial geothermal well drilling and testing program, the production and injection wellfield must be developed. The knowledge of reservoir parameters increases with each new geothermal well that is drilled and tested. However, a production/injection history (and consequent changes in reservoir temperature, pressure, and fluid state) is essential for understanding important geothermal reservoir processes such as boiling due to a reduction in pressure, recharge from the boundaries, and possible short-circuiting between production and injection wells.

At this stage, a detailed geothermal reservoir model may be constructed by calibrating model predictions with available measurements (e.g., temperature and pressure measurements, surface heat and mass flows, production/injection induced changes in the reservoir, etc.). The calibrated model may then be used to forecast the electrical megawatt capacity of the reservoir. The current practice in the geothermal industry is to develop "deterministic" reservoir models. In large part, this practice is driven by the "expert" time required to construct a geothermal reservoir model that is in accord with most of the known facts.

Although Sanyal and Sarmiento (2005) postulated that while numerical simulation is more sophisticated than the volumetric method, the latter can be readily conducted in a rigorously probabilistic way while the former cannot; in principle, however, there is no reason why a Monte Carlo process cannot be used in conjunction with "detailed numerical reservoir model" to assess the impact of uncertainty in reservoir parameters on the probable electrical megawatt capacity. Presently, such a procedure is being used to assess the future productivity of oil and gas fields. However, because of both technical (e.g., computational load) and cost considerations, it may be some time before this becomes a standard practice in the geothermal industry.

Availability of production and injection history as well as detailed reservoir modeling are essential for narrowing the possible ranges for important reservoir parameters, and in turn for obtaining a well-constrained estimate of the future electrical megawatt capacity of the geothermal reservoir.

SUMMARY AND CONCLUSIONS

Geothermal reservoir assessment and the resulting prediction of its electrical megawatt capacity should be regarded as a continuing process – from the early exploration phase to the time when the reservoir becomes depleted. During the early exploration phase, estimates of important reservoir parameters are poorly constrained; application of the USGS "heat in place" evaluation method along with Monte Carlo simulations yields a rather wide distribution for the probable electrical megawatt capacity. As initial deep geothermal wells are drilled and tested, it becomes possible to refine estimates of reservoir parameters (i.e., narrow down the range of possible values), and in turn obtain a much narrower probability distribution for the electrical megawatt capacity. After the start of large-scale production and injection operations and the availability of data on production-induced changes in the geothermal reservoir, it should in principle be possible to further constrain the range of probable electrical megawatt capacity.

To summarize, the USGS volumetric "heat in place" method together with Monte Carlo simulations is an important tool for assessing the electrical capacity of a geothermal reservoir. The secret to a proper use of the technique is the specification of the probability distributions of the reservoir parameters. Very often, these parameters are prescribed based on data from other geothermal reservoirs. At present, there exist insufficient data in the public domain to specify probability distributions for most reservoir parameters. Moreover, conditions vary widely between and within the various geothermal provinces around the world. For this reason, it is essential that as far as possible, actual field data should be used when prescribing reservoir parameters. Without data-driven reservoir parameters, use of Monte Carlo simulations is liable to generate only unreliable estimates of reservoir megawatt capacity.

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