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A REEXAMINATION OF USGS VOLUMETRIC "HEAT IN PLACE" METHOD

Sabodh K. Garg

Science Applications International Corporation
10260 Campus Point Drive
San Diego, CA, 92121, USA
e-mail: gargs@saic.com

Jim Combs

Geo Hills Associates LLC
1950 Champion Hills Drive
Reno, NV, 89523-3886, USA
e-mail: jimjeany@ix.netcom.com

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, thickness, and thermal recovery factor of a geothermal reservoir to obtain the probability distribution function for the stored energy ("heat in place") and the recoverable heat. The electrical capacity of the potential geothermal reservoir is then computed using a conversion (or utilization) efficiency. In a previous paper, we discussed the importance of choosing the probability distributions of the reservoir parameters based on actual field data. Herein, we examine the specification of the reference temperature and the conversion efficiency. We show that the conversion efficiency depends on both the reference temperature and the power cycle (flash, binary). A proper understanding of the latter relationship is essential for obtaining estimates of reservoir capacity for electrical generation.

INTRODUCTION

During 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, thickness, and thermal recovery factor of a geothermal reservoir into estimates of the stored heat ("heat in place") and the recoverable energy with uncertainty. An estimate of the recoverable energy together with a conversion efficiency (or utilization factor) is then used to compute the electrical capacity. The parameters required for the computation of electric capacity of the "heat in place" are indicated 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. 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 is highly dependent on the stage of exploration of a geothermal system. In a previous paper (Garg and Combs, 2010), we remarked 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 megawatt capacity. 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). In this paper, we consider the specification of rejection temperature (sometimes called reference temperature or dead-state temperature), and conversion efficiency (utilization factor). Estimates of the recoverable heat depend directly on the choice of the rejection temperature. Furthermore, the conversion efficiency is seen to be a function of both the rejection temperature and the power cycle (e.g., flash or binary) used to generate electrical power. Stated somewhat differently, conversion efficiency cannot be prescribed independently of the rejection temperature and the power cycle.

STORED HEAT AND AVAILABLE ENERGY

Consider a geothermal reservoir containing single-phase liquid. Heat stored in the geothermal reservoir, q_R , is given by:

$$q_R = V\overline{\rho c}(T_R - T_r) \quad (1)$$

where

$c_w(c_r)$ = Heat capacity of water (rock grains)
A = Reservoir area
H = Reservoir thickness
T_r = Reference (or rejection) temperature
T_R = Average reservoir temperature
V = Reservoir volume (=*AH*)
ϕ = Porosity
$\overline{\rho c}$ = Volumetric heat capacity of fluid-saturated rock $[=\phi\rho_w c_w + (1-\phi)\rho_r c_r]$
$\rho_w(\rho_r)$ = Density of water (rock grains)

The choice of the reference (or rejection) temperature is very important since it has a large effect on the computed value for the available energy and the conversion efficiency (or utilization factor). As noted by Brook et al. (1979), two likely choices for T_r are the ambient (say ~15 °C) and the condenser (~40 °C) temperatures.

A geothermal recovery factor R_g is defined as the ratio of the heat recovered at the wellhead, q_w, to the heat stored in the reservoir, q_R.

$$R_g = q_w / q_R \quad (2)$$

Assuming isenthalpic flow in the wellbore and neglecting the work required to raise water to the wellhead, the enthalpy of produced fluid at the wellhead, h_w, is equal to that of liquid water at the reservoir temperature. Thus

$$h_w = h_R(T_R) \quad (3)$$

The amount of fluid produced at the wellhead, m_w, is given by:

$$m_w = q_w / (h_w - h_r) \quad (4)$$

where h_r is the enthalpy of liquid water at the reference temperature, T_r. Substituting from Eqs. (1)-(3) in to Eq. (4), there follows:

$$m_w = \alpha(T_R - T_r) / (h_w - h_r) \quad (5)$$

where

$$\alpha = R_g V \overline{\rho c} \quad (6)$$

Since the enthalpy of liquid water along the saturation line varies almost linearly with temperature, m_w is only a weak function of the reference temperature.

The concept of availability plays a central role in the USGS volumetric heat in place method. Availability may be defined as the maximum work (or power) output that can theoretically be obtained from a substance (water) at specified thermodynamic conditions (wellhead) relative to its surroundings. DiPippo (2008) observes:

"To achieve this ideal outcome, there are two thermodynamic conditions that must be met:

1. All processes taking place within the system must be perfectly reversible.

2. The state of all fluids being discharged from the system must be in thermodynamic equilibrium with the surroundings."

The first of these conditions amounts to neglecting losses due to friction, turbulence, and other sources of irreversibility. The second condition requires that any fluids discharged from the system - are in temperature equilibrium with the surroundings (i.e., reference temperature). None of the real power cycles can meet these conditions, and the "electrical energy" that is generated is always less than the "available work". The conversion efficiency (utilization factor) is the ratio of the "actual electrical energy" to the "available work".

Neglecting kinetic or potential energy effects, the maximum energy output per unit mass of the substance e is given by (DiPippo, 2008):

$$e = h - h_r - T_{rk}(s - s_r) \quad (7)$$

where h and s denote the enthalpy and entropy of the substance (e.g., steam or hydrocarbon vapor) at turbine inlet conditions with temperature T, T_{rk} is the absolute reference temperature (Kelvin), and s_r is the entropy of liquid phase (water or hydrocarbon liquid) at the reference temperature. For mass m of the substance, the available work is therefore given by:

$$W_A = me = m[h - h_r - T_{rK}(s - s_r)] \qquad (8)$$

The available work, as used in the USGS method (Brook et al., 1979), is computed by replacing mass m in Eq. (8) by m_w from Eq. (5).

To estimate the conversion efficiency (utilization factor), it is necessary to consider the power cycle that will be used to generate electrical energy. Note that in general, mass m_t that enters the turbine is not the same as m_w computed from Eq. (5). In single (or dual) flash systems, liquid brine (and the energy contained in it) is rejected at the separator temperature; only the separated steam is used to generate power. The binary technology involves the use of a secondary fluid (e.g., isobutane), heated by the brine, to generate power; the brine is in any event rejected at a higher temperature than the reference number. For a real power cycle, m, h and s in Eq. (8) should be evaluated at the turbine inlet conditions, and the most appropriate reference temperature (Eq. 8) is the condenser temperature.

ILLUSTRATIVE EXAMPLES

We consider two typical geothermal resources with temperatures of 150 °C and 250 °C. The lower temperature resource is suitable for binary applications while the higher temperature resource will most likely be exploited using flash technology. Before embarking on an analysis of power cycles, it is useful to evaluate available work using the USGS methodology (see e.g., Brook et al, 1979). In our notation, Equation (10) of Brook et al. (1979) can be rewritten as follows:

$$W_{A(USGS)} = m_w[h_w - h_r - T_{rk}(s_w - s_r)] \qquad (9)$$

where m_w is given by Eqs. (5) and (6), and $h_w(=h_R)$ and s_w $(=s_R)$ are evaluated at the reservoir temperature, T_R. Available work computed from Eq. (10) for the two resource temperatures (150 °C and 250 °C) and two reference temperatures (15 °C and 40 °C) is presented in Table 2. All the water properties were evaluated along the saturation line. It is apparent from Table 2 that the computed values for the available work are a strong function of the reference temperature. As expected, the available work increases with a decrease in the reference temperature. For the higher temperature resource, the difference between computed values (Table 2) is about 22 %. The percentage difference (~35 %) is much greater for the lower temperature resource.

Table 2: Computation of Available Work. For sake of simplicity W_A/α instead of W_A is given.

Resource Temperature $T_R(^oC)$	Reference Temperature $T_r(^oC)$	Available Work W_A/α	
		Eq. (9)	Power Cycle
150	15	24.47	-
	40	15.89	10.51
250	15	64.91	-
	40	50.91	29.05

As discussed earlier, specific power cycles must be considered in order to estimate conversion efficiency (utilization factor). In the following, we consider two relatively simple power generation schemes, i.e., single flash and basic binary cycles.

Single Flash

It is assumed that the produced fluid, with enthalpy equal to that of the water at 250 °C (i.e., reservoir temperature), is separated at 5 bars (saturation temperature: 151.831 °C). The separated brine is injected into the reservoir, and the steam is used to generate power. The turbine inlet pressure is set equal to the separator pressure, and the condenser temperature is assumed to be 40 °C. The mass of the fluid produced at the wellhead is given by Eq. (5) with T_r = 151.831 °C. The steam fraction of the produced fluid at a separation pressure of 5 bars is:

$$x = (h_R - h_l)/h_{gl} = 0.2114 \qquad (10)$$

where h_l and h_{gl} denote the enthalpy of liquid water and heat of vaporization at 5 bars, respectively. Combining Eqs. (5) and (10), the mass of separated steam, m_t, entering the turbine is:

$$m_t = 0.2114\alpha(T_R - T_{sep})/(h_R - h_l) \qquad (11)$$

Substituting from Eq. (11) into Eq. (8), evaluating h and s for saturated steam at 5 bars, and putting T_r equal to 40 °C, we finally obtain:

$$W_{Aturbine} = 29.05\alpha \qquad (12)$$

From the data presented in Table 2, it is apparent that the available work given by Eq. (12) is only ~45 % (~57%) of that computed using the USGS methodology and a reference temperature of 15 °C (40 °C). Because of mechanical and other losses in the turbo-generator, only about 70% of the available work given by Eq. (12) is converted to electrical energy (see also Nathenson, 1975a). Thus, if the available work is computed using equation (9) and a reference temperature of 15 °C (40 °C), the overall conversion efficiency (utilization factor) is only ~32% (~40%) for the single flash cycle considered here.

Binary Cycle

The produced brine at a wellhead temperature of 150 °C is used to heat the working fluid (e.g., isobutane), and the spent brine is injected back into the reservoir. The turbine inlet pressure is assumed to be 20 bars; the saturation temperature for isobutane at the latter pressure is 100.36 °C (NIST, 2010). Isobutane is assumed to be saturated at the turbine inlet. With a temperature differential of 5 °C at the pinch point (i.e., the point in the heat exchanger with the least temperature difference between the primary and secondary fluids. The pinch point corresponds to the bubble point for the secondary fluid.), the temperature of the brine at the pinch point is 105.36 °C. The amount of isobutane vaporized by heat exchange with 1 kg of brine is given by:

$$m_{iso} = (h_R - h_{wb}) / h_{isogl} \tag{13}$$

With

h_R (enthalpy of liquid water at 150 °C)
= 632.179 kJ/kg
h_{wb} (enthalpy of liquid water at 105.36 °C)
= 441.795 kJ/kg
h_{isogl} (heat of vaporization of isobutane at 100.36 °C)
= 219.15 kJ/kg

there follows:

$$m_{iso} = 0.90594 \text{ kg} \tag{14}$$

Thermal energy required to heat 0.90594 kg of isobutane from 40 °C to 100.36 °C at a constant pressure of 20 bars is:

Thermal energy = 0.90594
$[\, h_{iso}(20bars, 100.36^o C) - h_{iso}(20bars, 40^o C)\,]$
= 0.90594 (467.07-296.85) = 154.21 kJ

The above thermal energy is supplied by 1 kg of brine as its temperature declines from 105.36 °C to the rejection temperature T_{rej}. Assuming a specific heat of 4.197 kJ/kg °C for water, we have:

$$154.21 = 4.197\,(105.36 - T_{rej})$$

Solving for T_{rej}, we obtain:

$$T_{rej} = 68.62 \text{ °C} \tag{15}$$

With $T_r = T_{rej} = 68.62$ °C, Eq. (5) yields

$$m_{wrej} = 2.3595x10^{-4}\alpha$$

Therefore, the amount of isobutane that flows through the turbine is:

$$m_{tiso} = 0.90594 m_{wrej} = 2.1376x10^{-4}\alpha \tag{16}$$

The work required to pressurize 1 kg of isobutane from 5.31 bars (saturation pressure at 40 °C) to 20 bars at a constant temperature of 40 °C is:

Work = $V_{iso}(40^o C, 20bars)(20 - 5.31)x10^5$ J
= 2.7456 kJ

The available work for the binary cycle is then given by:

$$W_{Aturbine} = m_{tiso}\{h_{giso}(100.36^o C) - h_{liso}(40^0 C)$$
$$-313.15[s_{giso}(100.36^o C) - s_{liso}(40^0 C)] - 2.7456x10^3\}$$
$$= 10.51\ \alpha \tag{17}$$

The available work given by Eq. (17) is only about 43 % (~66 %) of that computed using the USGS methodology and a reference temperature of 15 °C (40 °C). Assuming a turbo-generator efficiency of 70% and a reference temperature of 15 °C (40 °C), the overall conversion efficiency (utilization factor) is thus only ~30 % (~46 %) for the binary cycle considered here.

DiPippo (2004) has analyzed the conversion efficiency for several operating ORC power plants. Although second law efficiencies of over 40% (referred to ambient temperature) have been reported for a couple of power plants utilizing advanced power cycles, most operating ORC power plants have relatively low (less than 25 %) second law efficiencies. GeothermEx (2004) used a utilization factor of 0.45 (referred to 15 °C) in a resource assessment of several low temperatures geothermal fields in Nevada and California. Although the latter utilization factor appears to be theoretically possible, resource characteristics (e.g., change in resource temperature over time) and economic considerations will usually dictate a much lower utilization factor.

CONCLUSIONS

The USGS volumetric “heat in place” method together with Monte Carlo simulations is a widely used tool for assessing the electrical capacity of a geothermal reservoir. The method is deceptively simple and is often misused. In a previous paper, we conclude that the probability distributions of the reservoir parameters must be based on actual field data. Herein, we have examined the specification of a reference temperature, and its relation to available work and the utilization factor (or conversion efficiency). The “available work” is a strong function of the reference temperature. The utilization factor (i.e., ratio of electric energy generated to available work) depends on both the power cycle and the reference temperature. Thus, a proper understanding of the interrelationship between the reference temperature, power cycle, and the utilization factor is critical if valid results are to be obtained using the USGS “heat in place” method.

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