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UPDATED METHODS FOR ESTIMATING RECOVERY FACTORS FOR GEOTHERMAL RESOURCES

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ABSTRACT

An important aspect of geothermal resource assessment methodology is the development of geothermal resource models consistent with the production histories of exploited geothermal fields. The primary method applied in past United States Geological Survey (USGS) assessments was the volume method, in which the recoverable heat is estimated from the thermal energy available in a reservoir of uniformly porous and permeable rock using a constant recovery factor, R_g, of 0.25 for the producible fraction of a reservoir's thermal energy. More recent analyses of data from the fractured reservoirs commonly exploited for geothermal energy indicate that R_g is closer to 0.1, with a range of approximately 0.05 to 0.2. In general this apparent discrepancy in R_g reflects the contrast in thermal energy recovery from complex, fracture-dominated reservoirs compared to the uniform, high-porosity reservoirs considered in the early models. Models for the recovery of heat from heterogeneous, self-similar, fractured reservoirs predict variations in R_g that provide a physically realistic basis for evaluating the production potential of both natural geothermal reservoirs and reservoirs that may be created through the application of EGS technology.

ASSESSMENT METHODOLOGIES – HISTORY, DEVELOPMENT, CHALLENGES

Background

Under the mandate of the Energy Policy Act of 2005, the United States Geological Survey (USGS) is conducting a new assessment of the moderate- and high-temperature geothermal resources of the United States. The new assessment will present a detailed estimate of the geothermal electrical power generation potential and include an evaluation of the major technological challenges of increased geothermal development. It will also introduce significant changes in the models for geothermal energy recovery factors, estimates of reservoir dimensions, limits to temperatures and depths for electric power production, and include the potential impact of evolving Enhanced Geothermal Systems (EGS) technology.

The last national assessment of moderate (90-150 ^oC) and high-temperature (greater than 150 ^oC) geothermal resources, USGS Circular 790 (Muffler, 1979), estimated the potential for approximately 22,000 MWe of power generation from identified high-temperature (>150 ^oC) geothermal systems at depths less than 3 km in the western United States. Estimates of potential power production from undiscovered resources ranged from 72,000 to 127,000 MWe. Since the publication of Circular 790, ongoing reservoir definition and development activities have augmented the information available on identified systems, which have been studied in detail and drilled at a number of locations. Relevant data and conceptual models from these studies will be used in the assessment to better constrain true reservoir geometries. In addition, advances in power production technology and the scientific understanding of geothermal systems indicate that some important elements of geothermal assessment methodology require detailed examination and revision. For example, the 150 ^oC lower limit for electric power production applied in Circular 790 must be revised downward to include power production from moderate-temperature systems using binary technology.

Although Circular 790 was the last national geothermal resource assessment to address both identified and undiscovered moderate- and high-temperature resources, a number of subsequent studies have provided regional assessments of identified resources. Most recently, Lovekin (2004) presented the results of a new assessment of geothermal resources in California and Nevada, with the average estimated power production potential for California equaling approximately 5000 MWe, only 40% of the estimated potential in Circular 790 (see also Sanyal et al., 2004). The reasons for the difference in the estimates are varied, and in order to understand both these reasons and the potential implications for new resource assessments, it is necessary to examine geothermal resource assessment methodologies in greater detail.

The Volume Method and Recovery Factors

Muffler and Cataldi (1978) identified four methods for assessing geothermal resources: surface heat flux, volume, planar fracture and magmatic heat budget. The volume method as developed by Nathenson (1975), White and Williams (1975), Muffler and Cataldi (1978) and Muffler (1979) was quickly established as the standard approach, and recent assessments of geothermal resources in parts of the United States rely on a version of the USGS volume method (e.g., Lovekin, 2004). This method, in which the recoverable heat is estimated from the thermal energy available in a volume of porous and permeable rock, has been discussed in detail elsewhere (Nathenson, 1975; Muffler and Cataldi, 1978; Muffler, 1979; Lovekin, 2004; Williams, 2004), so only a brief summary of the relevant aspects is presented here.

The electric power generation potential from an identified geothermal system depends on the thermal energy, q_R, present in the reservoir, the amount of thermal energy that can be extracted from the reservoir at the wellhead, q_{WH}, and the efficiency with which that wellhead thermal energy can be converted to electric power. Once the reservoir fluid is available at the wellhead, the thermodynamic and economic constraints on conversion to electric power are well known. The challenge in the resource assessment lies in understanding the size and thermal energy of a reservoir as well as the constraints on extracting that thermal energy. In the volume method, the reservoir thermal energy is calculated as

$$q_R = \rho C V (T_R - T_{ref}) \qquad (1)$$

where ρC is the volumetric specific heat of the reservoir rock, V is the volume of the reservoir, T_R is the characteristic reservoir temperature, and T_{ref} is a reference temperature. The thermal energy that can be extracted at the wellhead is given by

$$q_{WH} = m_{WH}(h_{WH} - h_{ref}) \qquad (2)$$

where m_{WH} is the extractable mass, h_{WH} is the enthalpy of the produced fluid, and h_{ref} is the enthalpy at some reference temperature (15 ^{o}C in Circular 790). The wellhead thermal energy is then related to the reservoir thermal energy by the recovery factor, R_g, which was defined in Circular 790 for liquid-dominated systems as

$$R_g = q_{WH} / q_R \;\sim 0.25 \qquad (3)$$

This value for R_g came from an analysis by Nathenson (1975) of the factors influencing the extraction of heat from a geothermal reservoir through a “cold sweep” process, in which the hot reservoir fluid is gradually replaced by colder water through natural or artificial injection. According to this analysis the quantities in equations (1), (2) and (3) are determined by a geometrical concept of the “reservoir” that allows calculation of a volume and an estimate of the ability to extract hot fluid from the volume. In the actual implementation of this approach the mean values for the input variables are replaced with a range of values corresponding to estimated uncertainties, and these values are then used in Monte Carlo simulations to define the most likely reservoir properties and productivity, along with the associated uncertainties (e.g., Muffler, 1979; Lovekin, 2004). This discussion focuses on the mean values for simplicity.

As noted by Williams (2004), for a constant R_g the values for m_{WH} and q_{WH} follow as simple functions of reservoir temperature, pressure, composition and volume. However, analyses of data from fractured reservoirs at The Geysers, Coso and Dixie Valley indicate that R_g in those fields is closer to 0.1 and varies depending upon the assumed reservoir size and geometry (Williams, 2004). The recent Geothermex evaluation of identified geothermal resources in California and Nevada incorporates a range for R_g from 0.05 to 0.2, which yields results consistent with observed production histories in geothermal fields in the United States and overseas but also leaves a large uncertainty regarding potential geothermal power production (Lovekin, 2004).

UPDATED APPROACHES IN THE NEW GEOTHERMAL RESOURCE ASSESSMENT

Reservoir Volume and Permeability

Hydrothermal systems capable of generating electrical power require the presence of both high temperatures and locally high permeabilities (e.g., Bjornsson and Bodvarsson, 1990). Although the volume method provides a means of estimating the heat content of a geothermal reservoir, it does not explicitly predict the reservoir permeability. The presence of permeability adequate for production is based on the existence of a geothermal anomaly (e.g., hot springs, flowing wells, anomalously high heat flow) and the assumed recovery factor, which incorporates an estimate of effective reservoir porosity. Reservoir models and production histories are generally consistent with the predictions of the volume method when the reservoir volume and the spatial distribution of permeability are well-constrained (e.g., Parini and Riedel, 2000; Williams, 2004). Potential problems arise when both the volume of a reservoir and its flow properties must be estimated. Many geothermal reservoirs are dominated by fracture porosity, which can be characterized by high permeabilities but relatively low fluid volumes. In addition, fracture permeability is sensitive to relatively rapid (in geologic time) temporal variations in the state of stress and fluid chemistry.

In the USGS national assessment of low-temperature geothermal resources, Reed (1983) applied models for the recovery of heat and fluid from low-temperature sedimentary reservoirs using constraints on drawdown at production wells. Production-related pressure declines have posed significant problems in geothermal reservoirs, and, despite the risk of thermal breakthrough, injection has become a common procedure for sustaining production (Axelsson, 2003). Consequently, any estimate of reservoir production potential should evaluate longevity from the perspective of injection and eventual thermal breakthrough.

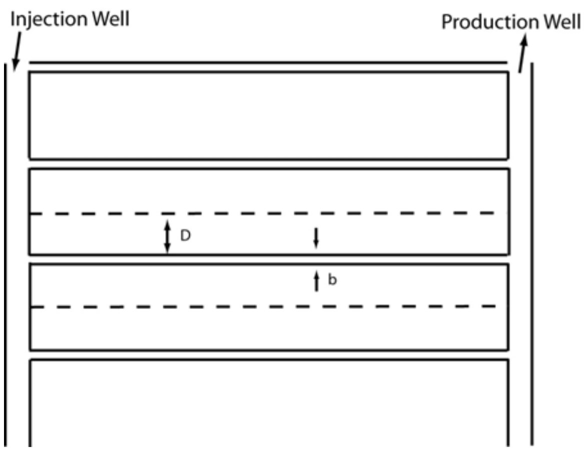

Figure 1. Schematic section through the horizontal fractured reservoir model of Bodvarsson and Tsang (1982).

Thermal Energy Recovery in Fractured Reservoirs

A number of models have been developed to consider the effects of cooling in a geothermal reservoir due to reinjection or natural inflow of water colder than pre-existing reservoir temperatures. With realistic values for the relevant variables, R_g for uniformly porous, homogeneous, and single-phase reservoirs can reach values of 0.5 or higher (e.g., Nathenson, 1975; Gringarten, 1978; Garg and Pritchett, 1990; Chetveryk, 2000, Sanyal and Butler, 2005). The challenge is to extend these results to evaluate the thermal effects of injection and production in reservoirs ranging from those containing a few isolated fracture zones to those that are so pervasively fractured as to approach the idealized behavior of uniformly porous reservoirs. The first step in the transition from these uniform reservoirs to fractured reservoirs is managed through implementation of the fracture flow model of Bodvarsson and Tsang (1982) (Figure 1). This model provides a means of predicting the propagation of a thermal front for liquid-dominated reservoirs with different rates of production and fracture spacing. In the analysis below, the thermal recovery models assume the availability of liquid water for reinjection and evaluate the propagation of cold thermal fronts from injection wells to production wells over a period of 30 years.

For a reservoir with horizontal fractures of aperture b, spacing D (b<<D), and volumetric flow rate $\dot{V}$, Bodvarsson and Tsang identify three time periods in which a different equation describes the rate of movement for the cold front. The first, "early time" behavior is only significant in the vicinity of the injection well and is not relevant for a recovery factor analysis. The second, "intermediate time" behavior is described by

$$t = 4.396 \frac{\lambda \rho_r c_r}{(\rho_w c_w)^2} \left(\frac{\pi r^2}{\dot{V}} \right)^2 \qquad (4)$$

Where t is time, r is radial distance, λ is the formation thermal conductivity, $\rho_r c_r$ and $\rho_w c_w$ are the products of density and heat capacity for the rock and water, respectively. As the thermal front propagates through the formation and recovers heat from the rock matrix between fractures, there is a transition to "late time" behavior which is described by

$$t = \left(\frac{2\pi \rho_r c_r D}{\rho_w c_w \dot{V}} \right) r^2 \qquad (5)$$

Equation (5) represents conditions of uniform energy sweep through the rock between the fractures and corresponds to the homogeneous porous medium models describe by Garg and Pritchett (1990) and others. By contrast, under the conditions described by equation (4), substantial thermal energy in the formation is bypassed by cooler water moving along fast fracture paths. The transition from intermediate to late-time behavior occurs at a critical time given by

$$t_c = \frac{4 \rho_r c_r D^2}{4.396 \lambda} \qquad (6)$$

If the aim of reservoir production is to avoid thermal breakthrough for a period of t=30 years, late-time behavior of uniform energy sweep predominates for fracture spacing D less than or equal to approximately 30 meters with values of $\rho_r c_r$ = 2.6×10^6 J/m.K and λ = 2.5 W/m.K. For fracture spacing significantly greater than 30 meters, the energy sweep is less than complete over the same 30 year period.

This property of the Bodvarsson and Tsang model can be used to estimate R_g for fractured reservoirs of the type shown schematically in Figure 1. Figure 2 shows the variation in R_g for a range in fracture spacing for a horizontal reservoir 500 meters thick with a constant flow rate at the injection and production wells. For comparison purposes the results for a homogeneous porous reservoir (fracture spacing less than 30 meters) have been normalized to the R_g of 0.25 used in Circular 790. With increasing fracture spacing the recovered thermal energy drops dramatically, reaching a minimum of $R_g \sim 0.02$ for a single permeable fracture (or fracture zone) passing through the middle of the reservoir and intersecting both wells.

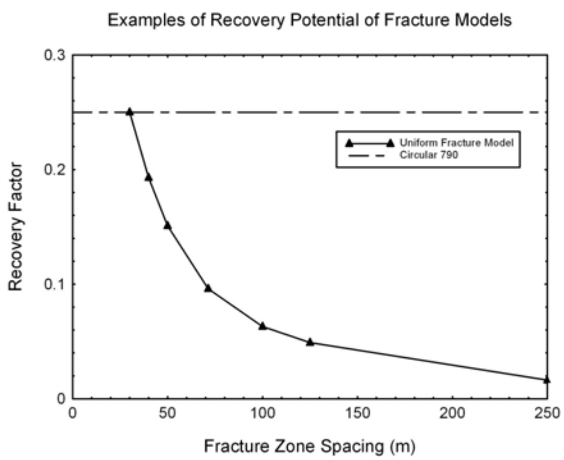

Figure 2. Variations in recovery factor with fracture spacing for model incorporating planar fractures with uniform flow properties.

Although the results shown in Figure 2 are suggestive of how less heat may be recoverable from naturally-fractured reservoirs, the Bodvarsson and Tsang model fails to replicate other important features of geothermal production from fractured reservoirs. In particular, analyses of tracer tests in active geothermal fields, as well as variations in recorded flow rates from producing fractures, clearly indicate significant variation in permeability and path length among fractures connecting injection and production wells (Shook, 2005; Reed, 2007). The chemical tracer tests yield information on the variability of flow in a reservoir that can be plotted as a curve relating flow capacity to storage capacity, or the productivity of each portion of the reservoir. Examples for the Beowawe and Dixie Valley geothermal fields are shown in Figure 3. In the Beowawe field approximately 50% of the flow comes from the most productive 10% of the permeable fractures, and in the Dixie Valley field approximately 35% of the flow comes from the most productive 10% of the permeable fractures. By contrast, the uniform fracture model requires an equal distribution of flow across the entire permeable fracture network (Figure 3).

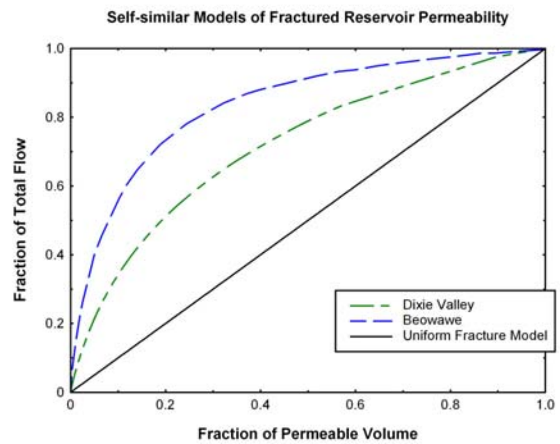

Figure 3. Distribution of flow capacity across the reservoir permeable volume for the fractured reservoir model of Bodvarsson and Tsang (black) and the Beowawe (Shook, 2005) and Dixie Valley (Reed, 2007) geothermal fields.

Thermal Energy Recovery from Self-similar Fractured Reservoirs

Given that the spatial distributions and hydraulic properties of real fracture networks are highly heterogeneous, any accurate characterization of injection and production from fractured reservoirs must be able to account for this heterogeneity. One simple and effective way of characterizing this heterogeneity has been through the use of models that characterize fracture properties such as permeability through a self-similar distribution (e.g. Watanabe and Takahashi, 1995). If, for example, the productivity of fractures intersecting a production well follows a self-similar distribution, this distribution is described by

$$N_k = C_k k^{-d_k} \quad (7)$$

where k is a reference permeability, N_k represents the number of fractures intersecting the well with permeability greater than or equal to k, C_k is a constant, and d_k is the fractal dimension. Although there is some direct evidence for fractal dimensions of properties that are relevant to permeability, such as fracture aperture, fracture length, and fracture density, the fractal dimensions for permeability may vary over a wide range (Watanabe and Takahashi, 1995; Dreuzy et al., 2001; Figure 4). For the purpose of this analysis, the fractures of interest are those that contribute significant volume to flow in the well and thus span a permeability range of approximately two orders of magnitude (Bjornsson and Bodvarsson, 1990). These will be a relatively small subset of the total population of fractures with measureable permeability. This analysis also equates the productivity of individual fracture sets with their permeability, an approach consistent with observations in producing geothermal fields (e.g., James et al., 1987).

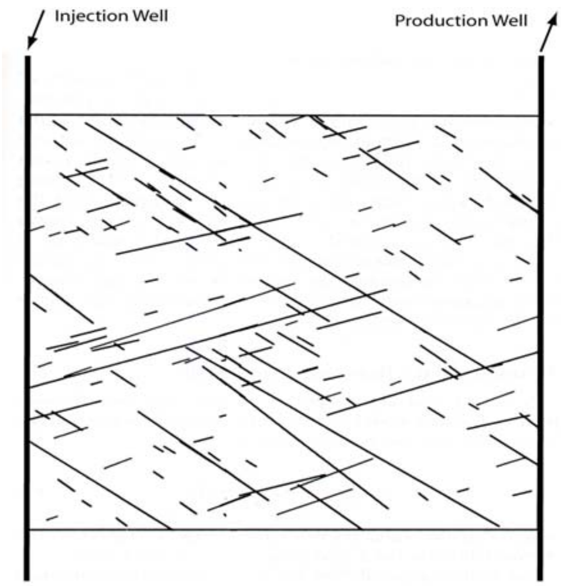

Figure 4. Schematic of self-similar fracture distribution in an idealized geothermal reservoir modified from Watanabe and Takahashi (1995).

Given a value for d_k, the R_g calculations derived from the Bodvarsson and Tsang (1982) model can be repeated for a set of N fractures following the distribution of permeability specified by equation (7) and summing to the same total flow rate delivered by the same number of uniform fractures. The results for a fractal model with $d_k \sim 1$ are shown in Figure 5. The higher value of R_g for the single fracture case (~0.06) is due to the longer path followed by the typical non-planar fracture. The lower value of R_g for the average productive fracture spacing of 30 meters is due to the varied permeabilities of the fractures, since thermal breakthrough will occur at a time determined by the flow properties of the most productive fracture rather than at a time defined by the average fracture productivity.

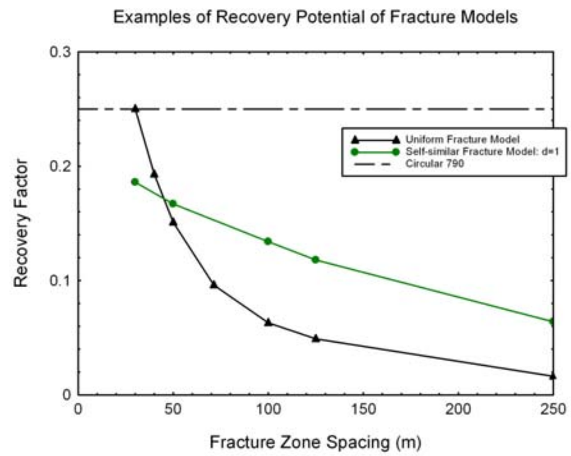

Figure 5. Variations in recovery factor with fracture spacing for example models incorporating planar fractures with uniform flow properties (black) and a fractal distribution of flow properties among the producing fractures (green).

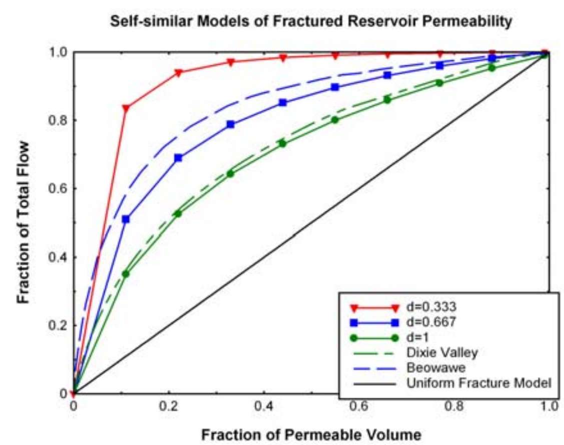

Figure 6. The fraction of flow in a producing well contributed by each fractional portion of the permeable reservoir volume. In the uniform fracture model (green), flow is distributed equally among the producing fractures. In the fractal model (blue), a significant fraction of the flow is delivered by a relatively small fraction of the reservoir. This is consistent with observed reservoir behavior (e.g., Shook, 2005).

An important test of the relevance of the self-similar model to actual geothermal reservoir performance is shown in Figure 6 with a comparison of the flow capacity/storage capacity curves for three different fractal dimensions with the Beowawe, Dixie Valley and uniform fracture model curves from Figure 3. The distribution of flow for the Dixie Valley field is consistent with the modeled distribution for d=1, and the distribution for the Beowawe field is consistent with the modeled distribution for d=0.667. The smaller value for d in the Beowawe field reflects the predominance of a single fracture or fracture system in the permeability tapped by the production and injection wells included in the chemical tracer test. These results indicate that the self-similar models for fracture permeability reproduce the behavior of producing geothermal reservoirs and provide a physically-based justification for the observed variation in R_g.

SUMMARY

The United States Geological Survey (USGS) is conducting an new assessment of the moderate- and high-temperature geothermal resources of the United States. The new assessment will present a detailed estimate of electrical power generation potential and an evaluation of the major technological challenges and environmental impacts of increased geothermal development. A number of changes are being incorporated in the new resource assessment of identified geothermal systems, and among these is an adjustment in expected R_g to account for the behavior of heterogeneous fracture-dominated reservoirs. Models for the effects of injection within reservoirs of self-similar distributions of fracture permeability reproduce both the observed range of R_g and the flow capacity/volume capacity characteristics of producing fractured geothermal reservoirs. Although these analytical models are not intended as replacements for detailed numerical reservoir models, they do provide a physically realistic justification for applying a range of potential recovery factors to a unexploited reservoir in order to reflect the heterogeneous character of fracture permeability. Because EGS technology depends on developing a reservoir through the creation and stimulation of fractures, a similar recovery factor analysis may be applicable to evaluating the EGS resource.

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