A Review of Methods Applied by the U.S. Geological Survey in the Assessment of Identified Geothermal Resources

By Colin F. Williams, Marshall J. Reed, and Robert H. Mariner

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Abstract

The U. S. Geological Survey (USGS) is conducting an updated assessment of geothermal resources in the United States. The primary method applied in assessments of identified geothermal systems by the USGS and other organizations is the volume method, in which the recoverable heat is estimated from the thermal energy available in a reservoir. An important focus in the assessment project is on the development of geothermal resource models consistent with the production histories and observed characteristics of exploited geothermal fields. The new assessment will incorporate some changes in the models for temperature and depth ranges for electric power production, preferred chemical geothermometers for estimates of reservoir temperatures, estimates of reservoir volumes, and geothermal energy recovery factors. Monte Carlo simulations are used to characterize uncertainties in the estimates of electric power generation. These new models for the recovery of heat from heterogeneous, fractured reservoirs provide a physically realistic basis for evaluating the production potential of natural geothermal reservoirs.

Introduction

Under the mandate of the Energy Policy Act of 2005, the United States Geological Survey (USGS) is conducting a new assessment of the moderate-temperature (90 to 150^{o}C) and high-temperature (>150^{o}C) geothermal resources of the United States. The assessment is focused on the western United States, including Alaska and Hawaii, and is highlighting geothermal energy resources located on public lands. It will be the first comprehensive national geothermal resource assessment since 1979 (USGS Circular 790; Muffler, 1979). In the new assessment the USGS will provide estimates of the geothermal electrical power generation potential from identified and undiscovered resources, and evaluate the potential impact of evolving geothermal production technology. An important component will be a provisional estimate of the power production potential of Enhanced Geothermal Systems (EGS) techniques, which involve the creation of producing geothermal reservoirs in low permeability rock units.

As described by Williams and Reed (2005), Williams and others (2007), and Reed and Mariner (2007), a number of changes are being incorporated in the new resource assessment. Changes to the evaluation of identified hydrothermal systems include: (1) a minimum temperature for electric power production of approximately 90°C (75°C in Alaska), (2) a maximum depth extent for selected geothermal reservoirs of as much as 6 km, (3) a change in the preferred geothermometers used for estimating reservoir temperatures, (4) a revised method for determining recovery factors, and (5) independent evaluations of reservoir permeability using reservoir models, production histories, and chemical tracer tests. This report provides a summary of USGS techniques used to evaluate the electric power production potential of identified geothermal resources.

Background

Comprehensive efforts to assess the geothermal resources of the United States began after passage of The Geothermal Energy Research, Development and Demonstration Act of 1974, which assigned responsibility for the evaluation and assessment of geothermal resources to the USGS through the U.S. Department of the Interior (DOI). The USGS produced three national geothermal resource assessments in the eight years following, USGS Circular 726, *Assessment of Geothermal Resources of the United States-1975* (White and Williams, 1975), USGS Circular 790, *Assessment of Geothermal Resources of the United States–1978* (Muffler, 1979) and USGS Circular 892, *Assessment of Low-temperature Geothermal Resources of the United States–1982* (Reed, 1983). These reports evaluated various methodologies for geothermal resource assessments and provided estimates of potential electric power generation that continue to guide long-term geothermal planning (for example, Green and Nix, 2006).

The last national assessment of moderate (90 to 150°C) and high-temperature (greater than 150°C) geothermal resources, USGS Circular 790 (Muffler, 1979), estimated the potential for approximately 23,000 Megawatts-electric (MWe) of electrical power generation from identified high-temperature (>150°C) 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. Circular 790 listed nine western states (Alaska, Arizona, California, Hawaii, Idaho, Nevada, New Mexico, Oregon and Utah) with the potential for at least 100 MWe of electrical power generation per state from identified geothermal systems.

Geothermal Resource Terminology

This report follows other USGS geothermal resource studies in using the terminology adopted by Muffler and Cataldi (1978) for the subdivision of the geothermal resource base. These subdivisions are easily illustrated through a modified McKelvey diagram (fig. 1), in which the degree of geologic assurance regarding resources is set along the horizontal axis and the economic feasibility (effectively equivalent to depth) is set along the vertical axis (Muffler and Cataldi, 1978). USGS geothermal assessments consider both identified and undiscovered systems and define the "resource" as that portion of the accessible resource base that can be recovered as useful heat under current and potential economic and technological conditions. Similarly, the "reserve" is the identified portion of the resource that can be recovered economically using existing technology.

Within this framework, identified hydrothermal systems are divided into three temperature classes: low-temperature (<90^{o}C), moderate-temperature (90 to 150^{o}C), and high-temperature (>150^{o}C). High-temperature systems include both liquid- and vapor-dominated resources. Moderate-temperature systems are almost exclusively liquid-dominated, and all low-temperature systems are liquid-dominated. All three temperature classes are suitable for direct use applications, but in general only moderate- and high-temperature systems are viable for electric power generation. Systems at the upper end of the low-temperature range can be exploited for electric power generation if sufficiently low temperatures are available for cooling the working fluid in a binary power plant. These conditions are found at Chena Hot Springs in Alaska (Holdman, 2006).

In the new USGS geothermal assessment, identified geothermal systems are also categorized as producing (the reservoir is currently generating electric power), confirmed (the reservoir has been evaluated with a successful commercial flow test of a production well), and potential (there are reliable estimates of temperature and volume for the reservoir but no successful well tests to date). Reservoir thermal energy and electric power production potential are estimated for all producing, confirmed, and potential geothermal systems above 90^{o}C in the contiguous United States and Hawaii, and above 75^{o}C in Alaska.

The Volume Method

An important component 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 USGS assessments for evaluating the production potential of identified geothermal systems was the volume method (Nathenson, 1975; White and Williams, 1975; Muffler and Cataldi, 1978; Muffler, 1979), in which the recoverable heat is estimated from the thermal energy available in a reservoir of uniformly porous and permeable rock using a thermal recovery factor, R_g, for the producible fraction of a reservoir's thermal energy. These studies established the volume method as the standard approach, and recent assessments of geothermal resources in parts of the United States rely on modified versions of the USGS volume method (for example, Lovekin, 2004). The basics of the volume method have been discussed in detail (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 (for example, DiPippo, 2005). The challenge in the resource assessment lies in quantifying 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

$$q_R = \rho C V (T_R - T_0), \quad (1)$$

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_0 is a reference, or dead-state, temperature. The thermal energy that can be extracted at the wellhead is given by

$$q_{WH} = m_{WH}(h_{WH} - h_0), \quad (2)$$

where m_{WH} is the extractable mass, h_{WH} is the enthalpy of the produced fluid, and h_0 is the enthalpy at some reference temperature (15°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 as

$$R_g = q_{WH} / q_R \quad (3)$$

Inherent in equations (1) and (2) is 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 general it is possible to produce many times the original volume of fluid from the reservoir in order to recover the thermal energy from the reservoir rock. Because The Geysers vapor-dominated field in northern California was the only producing geothermal reservoir in the United States at the time, the mean value for R_g of 0.25 used in Circular 790 was derived 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. Analyses of production data from fractured reservoirs at The Geysers, Coso in California, and Dixie Valley in Nevada, 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 most likely values closer to observed values but also leaves a large uncertainty regarding potential geothermal power production (Lovekin, 2004).

From estimates of R_g and measurements of reservoir volume and properties, the exergy, E, (DiPippo, 2005), referred to as the available work, $W_{A,}$ in Circular 790, for a geothermal reservoir can be determined as

$$E = m_{WH}[h_{WH} - h_0 - T_0(s_{WH} - s_0)], \tag{4}$$

where s_{WH} is the entropy of the produced fluid and s_0 is the entropy at the reference temperature. 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 reservoir properties and productivity, along with the associated uncertainties (for example, Muffler, 1979; Lovekin, 2004; Williams and Reed, 2007). The electric energy, $\dot{W}_e$, for a given period of time (typically 30 years) is then determined through multiplying the exergy over the same period of time by a utilization efficiency, η_u, which is generally well-constrained for a reservoir of a specified fluid state and temperature (Muffler and others, 1979).

$$\dot{W}_e = \dot{E}\eta_u \tag{5}$$

For power generation above 150°C, Muffler and others (1979) used a constant value for η_u of 0.4 down to the minimum reservoir temperature for electric power production of 150°C. Lovekin (2004) increased this to 0.45. A compilation of η_u for existing geothermal power plants producing from liquid-dominated systems over a wide range of temperatures confirms η_u equal to approximately 0.4 above 175°C (fig. 2). There is a linear decline in η_u below 175°C as reservoir temperatures approach the reference state in binary power plant operations. In the new assessment the 150°C lower limit is revised downward to include binary power production from moderate-temperature systems. Developments in binary power plant technology have led to electric power generation from systems with temperatures as low as 94°C in the lower 48 states (Amedee, California) and 75°C in Alaska (Chena Hot Springs), and production from lower temperatures is possible, if not always economically viable at the present time. For geothermal systems in the contiguous United States and Hawaii, the lower limit for electric power generation is set at 90°C, but for Alaska the assessment includes potential power generation from systems with temperatures as low as 75°C, due to the availability of near-freezing cooling water at many sites.

Temperature and Chemical Geothermometers

Geothermal reservoir temperatures can be determined from in situ measurements in exploration and production wells where available. In order to characterize the thermal state of a geothermal reservoir when in situ temperature measurements are not available, chemical geothermometers can be applied as proxies. The calculation of chemical geothermometers rests on the assumption that some relationship between chemical or isotopic constituents in the water was established at higher temperatures and this relationship has persisted when the water cools as it flows to the surface. The calculation of subsurface temperatures from chemical analyses of water and steam collected at hot springs, fumaroles, geysers, and shallow water wells is a standard tool of geothermal exploration and fills the need to estimate the subsurface temperature of a geothermal prospect area before any deep wells are drilled.

The first temperature calculations were based on experimental laboratory studies of mineral solubility at elevated temperature (Kennedy, 1950; Fournier and Rowe, 1966). As geothermal exploration progressed, observed relationships among dissolved chemical constituents at known temperatures in wells were used to calibrate geothermometers from the aqueous species produced at the surface. Experimental and field data from sodium-chloride solutions were used to develop the mathematical equations for several geothermometers, and most of the calculations are suggested only for use with analyses of dilute, sodium-chloride type waters at near-neutral pH. In some geothermal prospect areas, for example the Basin and Range, sodium-bicarbonate type waters predominate, and few systems have sodium-chloride type water. The differences in the types of water chemistry encountered in geothermal systems require extra caution in the application of geothermometers.

Interpretation of the calculated temperatures requires knowledge of the most likely reactions to have occurred between the water and the surrounding rocks. In addition, the charge balance is calculated for every water analysis as a check for the completeness of the analysis and its accuracy. For the USGS geothermal resource assessment, some simple calculations are used to determine the reliability of the chemical analyses of geothermal waters (Reed and Mariner, 1991). Each ion in the analysis is converted to its equivalent concentration, and the charge balance error (CBE) is calculated as 100 times the absolute value of the difference between the summation of equivalent concentrations of cations (Na^+, K^+, Ca^{++}, Mg^{++}) and the summation of equivalent concentrations of anions (Cl^-, F^-, HCO_3^-, SO_4^{--}) divided by the average of the summation of equivalent concentrations of cations and the summation of equivalent concentrations of anions. An error greater than 10 percent in the charge balance is indicative of a problem with the analysis, and analyses that fall into this category are only be used for geothermal calculations in the assessment if no other analyses are available and the associated uncertainties in the calculated temperatures can be quantified.

Most geothermal systems never reach chemical equilibrium because most of the reaction rates are dependent on the concentrations of components in solution (Barton, 1984). The flow of hydrothermal fluids through a geothermal reservoir is constantly changing the concentrations of components in solution, and the geothermometers reflect a steady-state condition that exists at high temperature between the circulating water and enclosing rocks. The reaction rates for mineral solubility are dependent on temperature as well as several other variables in a hydrothermal system. For example, the approximate times to reach equilibrium between the feldspar minerals and fluid for the Na-K-Ca geothermometer varies from tens of hours at 500°C to on the order of 100 years at 150°C, and the solution-mineral equilibrium for quartz takes from tens of hours at

250°C to tens of years at 100°C (Barton, 1984). As the geothermal water cools on its way to the surface, the reaction rates become more sluggish. A secondary assumption is that the flow of hydrothermal water to the surface is rapid with respect to the rates of reactions at near-surface temperatures.

Geothermometer-based temperature estimates in the new geothermal resource assessment rely primarily on silica and cation geothermometers. In natural environments, it is often difficult to choose the correct silica geothermometer because it is not clear which mineral is controlling the dissolved silica concentration. Below 180°C, there is a choice between geothermometers for chalcedony and quartz, since each of these minerals may control the dissolved silica in different rock environments. Giggenbach (1992) developed an equation to approximate the calculated temperature in the transition zone between the chalcedony solubility control at low temperatures and the quartz solubility control at high temperatures (fig. 3). This smoothed curve eliminates the ambiguity of the calculations between 20°C and 210°C. Above 210°C, the quartz geothermometer is representative of the silica solubility in geothermal systems up to about 250°C. Temperatures for waters with dissolved silica concentrations of more than 462 mg/L (250°C) and for silica concentrations in condensed steam are estimated by comparing the analyzed silica concentrations with the quartz solubility determinations in Fournier and Potter (1982).

Silica geothermometers rely on the fact that each of the silica (SiO_2) minerals has its own solubility in water as a function of temperature and pressure, and silica hydrolizes in water to form the neutral silicic acid complex, $H_4SiO_4°$. The silica minerals precipitate from the aqueous solution by the reverse reaction when the silicic acid complex becomes supersaturated, polymerizes, and precipitates as a solid. The rates of dissolution and precipitation are relatively rapid at high temperatures and are rather sluggish at low temperatures. The individual silica mineral that precipitates depends on the temperature and pressure conditions and on the degree of supersaturation.

Fournier (1992) warns that the geothermometers are changed significantly by high concentrations of ions in solution, especially at high temperature (over 300°C). The equations for silica geothermometers work best at pH values between 5 and 7 (Fournier, 1992). In acidic solutions (less than pH = 3) or in alkaline solutions (greater than pH = 8) part of the silicic acid complex ionizes and the precipitation reaction is changed (Busey and Mesmer, 1977). Silica mineral saturation temperatures for high-pH waters are determined using SOLMINEQ88, a solution-mineral equilibrium computer model (Kharaka, 1988). There are few systems encountered with low pH, and the corrections are not considered here.

The cation geothermometers use ratios of cation concentrations to represent the hydrothermal, steady-state reactions that take place within mineral groups such as the feldspars, micas, zeolites, or clays. The use of concentration ratios rather than the actual concentrations makes these geothermometers less sensitive to changes in strength of the solution due either to boiling or to dilution. The cation geothermometers normally use sodium, potassium, calcium, magnesium, and lithium in various relationships that are temperature dependent. For the Na-K-Ca-Mg geothermometer, these relationships are based on several different mineral equilibria, and these different reactions result in a discontinuous function for this geothermometer.

The most commonly used cation geothermometer is the Na-K-Ca-Mg formulations of Fournier and Truesdell (1973) and Fournier and Potter (1979). The Na-K-Ca-Mg geothermometer has two formulations, one for lower (<100ºC) temperature waters and one for higher (>100ºC) temperature waters. This geothermometer was used extensively in the previous USGS geothermal resource assessment (Brook and others, 1979). However, in the western United States (Brook and others, 1979), these two different formulations result in a major discontinuity and an underreporting in the number of systems in the range between 100ºC and 130ºC (fig. 4). There should be a larger number of lower temperature geothermal systems, with a systematic decrease in the number of systems as aquifer temperatures increase (see for example, Reed, 1983, fig. 16).

Although control from calibration well samples is limited, it appears that the K-Mg geothermometer provides estimated temperatures reasonably close to temperatures measured in drilled geothermal systems within the 90ºC to 130ºC range. The potassium-magnesium geothermometer relates temperature to the logarithm of the ratio of potassium concentration squared to magnesium concentration, $c_{(K)}^2/c_{(Mg)}$ (Giggenbach, 1988). Temperatures were calculated for the geothermal systems (with reported Mg concentrations) in the western United States (Brook and others, 1979), using the K-Mg geothermometer (fig. 5), and these K-Mg geothermometer temperatures exhibit a continuous decrease in the number of geothermal systems as higher temperatures are evaluated, regardless of the type of water chemistry. Because the potassium to magnesium ratio is consistently representative of the subsurface temperature, the K-Mg geothermometer is generally the preferred cation geothermometer in this assessment. The Na-K-Ca geothermometer is preferred in Cl-rich waters and used where Mg data are unavailable. The magnesium ion concentration is below the detection limit in many analyses of geothermal waters, and the K-Mg geothermometer cannot be calculated for these waters.

Reservoir Volume

The difficulty of developing accurate estimates for the volumes of unexploited geothermal reservoirs varies depending on the geologic setting and the availability of data from exploration and development drilling. 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, and this can lead to heterogeneous permeability distributions within the fracture-dominated reservoirs (for example, Melosh and others, 2008). Estimates of reservoir volumes in the new assessment are derived from production histories, drilling results, chemical tracer tests, and exploratory geological and geophysical investigations.

In some cases information on a geothermal system is limited to the temperature, flow rate and chemical composition of a thermal spring. Under these circumstances, reservoir volumes are estimated by applying constraints from well-characterized geothermal reservoirs in analogous geologic settings. For example, for hot springs emerging from range-front faults in the Great Basin, the width of the fault damage zone (typically 100 to 500 m) constrains one horizontal dimension of the geothermal reservoir, and the temperature of the reservoir fluid relative to the background geothermal gradient defines the maximum depth of circulation. The greatest uncertainty in the estimated reservoir volume for a range front fault system lies in the lateral extent of the reservoir along strike. In the absence of geophysical or structural constraints, the upper end of possible along-strike extents is defined by the examples of producing geothermal reservoirs and other well-explored geothermal systems. Based on these examples, the default along-strike extent of a fault-hosted geothermal reservoir ranges from 1 to 5 km, with a most likely extent of 2 km. The largest volumes determined from this range of reservoir dimensions are consistent with larger, producing fault-hosted reservoirs such as Dixie Valley and Beowawe. The smallest volumes are consistent with simple vertical conduits of limited spatial extent and doubtful viability for commercial power production.

In Circular 790 the maximum depth extent for geothermal reservoirs was set to 3 km, as a representative limit of the economic and technological constraints of drilling and exploitation (Muffler and others, 1979). Although the maximum depth of geothermal drilling in the United States is approximately 3.5 km, geothermal wells deeper than 4 km have been completed in Italy, and a number of wells for Enhanced Geothermal Systems development have been drilled to depths of approximately 5 km (Kobayashi, 2000; Bertani, 2005). In the case of geothermal systems for which the base of the reservoir has not been defined by drilling, thermal constraints on the vertical extent of fluid circulation or the depth of the brittle-ductile transition are applied, but in no case is the base of the reservoir allowed to extend beyond 6 km.

Studies relating the rate of natural heat loss (both advective and conductive) and the dimensions and rate of fluid flow through a hydrothermal system can also provide a basis for estimating the volume of a geothermal reservoir (Wisian and others, 2001; Williams, 2005). In the new resource assessment, estimates of total heat loss from a geothermal reservoir are determined from heat flow or temperature-gradient measurements, when available, and used as an additional check against the predictions of the estimated reservoir temperatures and volumes.

Geothermal Recovery Factor

Hydrothermal systems capable of generating electrical power require the presence of both high temperatures and locally high permeabilities (for example, 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 (for example, hot springs, flowing wells, anomalously high heat flow) and the assumed recovery factor, which incorporates an estimate of the effective reservoir permeability and 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 (for example, 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. Models for the recovery of heat from uniformly porous, homogeneous, and liquid-phase reservoirs using injection indicate that R_g can reach values of 0.5 or higher (for example, Nathenson, 1975; Garg and Pritchett, 1990; Sanyal and Butler, 2005).

To allow for uncertainties in the distribution of permeability in a producing geothermal reservoir, the resource estimates in Circular 790 were based on a Monte Carlo uncertainty model with a triangular distribution for R_g with a most-likely value of 0.25 and a range from 0 to 0.5 (Muffler et al, 1979). 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 (Lovekin, 2004; Williams, 2004, 2007). 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. The original values for R_g were derived from models of the effects cooling in a geothermal reservoir due to reinjection or natural inflow of water colder than pre-existing reservoir temperatures (for example, Nathenson, 1975; Bodvarsson and Tsang, 1982; Garg and Pritchett, 1990; Sanyal and Butler, 2005). This is consistent with the optimal extraction of thermal energy from a reservoir, as in general it is possible to produce many times the original volume of fluid from the reservoir in order to recover the thermal energy from the reservoir rock. 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). 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 and highlights the sensitivity of thermal energy recovery to average fracture spacing. For representative geothermal reservoir rock and fluid properties, the Bodvarsson and Tsang model predicts that fractured reservoirs approach the uniform energy sweep possible in porous reservoirs when the average fracture spacing is approximately 50 m. As the average fracture spacing grows, a progressively larger fraction of thermal energy in the formation is bypassed by cooler water moving along fracture paths, and the geothermal recovery factor drops (Williams, 2007; Williams and others, 2007).

Although these results are suggestive of the factors that determine why 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 6. In the Beowawe field approximately 50 percent of the flow comes from the most productive 10 percent of the permeable fractures, and in the Dixie Valley field approximately 35 percent of the flow comes from the most productive 10 percent of the permeable fractures. By contrast, the uniform fracture model requires an equal distribution of flow across the entire permeable fracture network (fig. 6). The spatial distributions and hydraulic properties of real fracture networks are highly heterogeneous, and the heterogeneity manifests itself in the fundamental production characteristics yielded by the moment analysis of tracer tests. Any accurate characterization of injection and production from fractured reservoirs must be able to account for this heterogeneity.

Williams (2007) investigated the use of self-similar fracture distributions in a modification of the Bodvarsson and Tsang (1982) model as a means of better representing the actual fracture flow characteristics and variations in R_g observed in producing reservoirs. 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 (for example, 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

$$N_k = C_k k^{-d_k} , \tag{6}$$

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 (for example, Watanabe and Takahashi, 1995; Dreuzy and others, 2001). 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 (for example, James and others, 1987). Records of flow from producing fractures in geothermal wells confirm the varying contribution of individual fractures or fracture sets to geothermal production (fig. 7), and also demonstrate large the range of fractal dimensions necessary to characterize the observed variations in flow.

Figure 8 compares flow capacity/storage capacity curves from self-similar models for three different fractal dimensions with the Beowawe, Dixie Valley and uniform fracture model curves from figure 6. (For details see Williams, 2007.) 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 dominance of a single fracture or fracture system in the permeability tapped by the chemical tracer test. Like the uniform fracture model, the self-similar fracture flow models yield a range of values for R_g that depends both on average fracture spacing and on the dimensionality of the spatial distribution of fractures (fig. 9).

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. Given the observed variability in fracture flow properties, the likelihood that most natural fractures will match these varied flow properties with diverse fracture spacings and orientations, and the range of recovery factors determined from production histories of geothermal reservoirs, it is not possible to assign a single value, or even a narrow range, for R_g for unexploited geothermal systems. Taking the above analysis as a guide, in the new resource assessment R_g for fracture-dominated reservoirs is estimated to range from 0.08 to 0.2, with a uniform probability over the entire range. For sediment-hosted reservoirs this range is increased from 0.1 to 0.25.

Electric Power Estimates and Monte Carlo Uncertainty Analyses

Equations 1 through 5 cover the basic relationships used to estimate electric power generation potential for a given geothermal system. Uncertainties in the estimates are accommodated through a Monte Carlo simulation approach, which is shown schematically in figure 10. For each system, USGS investigators determine most likely, minimum and maximum values for reservoir temperature and volume. These values are used to generate triangular probability distributions for temperature and volume, and the resulting distributions are combined for an estimate of reservoir thermal energy. A uniform distribution for the geothermal recovery factor is introduced in the next step of the Monte Carlo analysis, and the resulting values for wellhead exergy are transformed to electric power estimates using the utilization efficiency relationship shown in figure 2. The final result is a distribution of electric power generation estimates for each geothermal system (fig. 10), which includes values for the most likely, mean, median, 5 percent and 95 percent electric power generation potential.

Summary

The USGS is conducting a new assessment of the moderate- and high-temperature geothermal resources of the United States. This new assessment will present a detailed estimate of electrical power generation potential and an evaluation of the major technological challenges for increased geothermal development. The assessment effort involves partnerships with the Department of Energy, Bureau of Land Management, national laboratories, universities, state agencies and the geothermal industry. The new assessment will introduce significant changes in the models for geothermal energy recovery factors, estimates of reservoir permeability, limits to temperatures and depths for electric power production, and include the potential impact of evolving EGS technology.

Improvements incorporated in the new resource assessment include (1) a minimum temperature for electric power production of approximately 90^{o}C (75^{o}C in Alaska), (2) a maximum depth extent for selected geothermal reservoirs of as much as 6 km, (3) a change in the preferred geothermometers used for estimating reservoir temperatures, (4) a revised method for determining recovery factors, and (5) independent evaluations of reservoir permeability using reservoir models, production histories, and chemical tracer tests.

The adjustment in expected recovery factors 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 an unexploited reservoir in order to reflect the heterogeneous character of fracture permeability.

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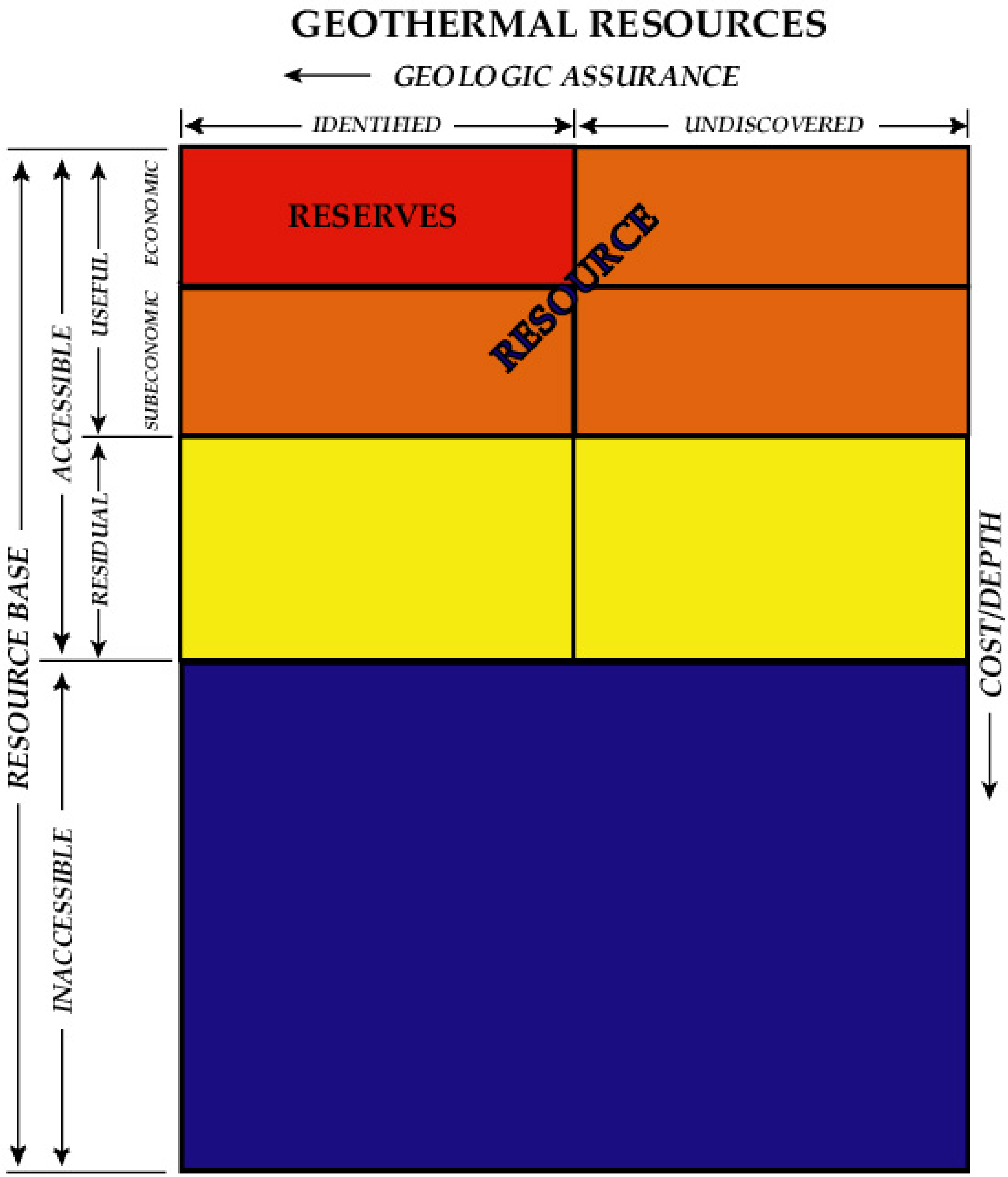

Figure 1. McKelvey diagram representing geothermal resource and reserve terminology in the context of geologic assurance and economic viability.

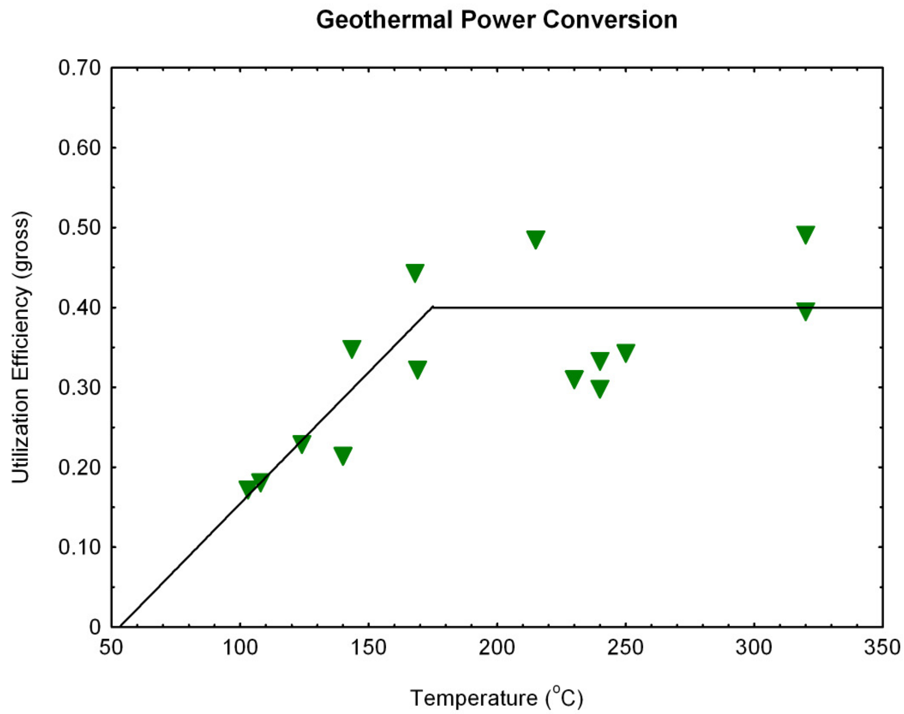

Figure 2. Utilization efficiency as a function of temperature for existing geothermal power plants studied by DiPippo (2005) (green triangles), along with the conversion relationship used in the new assessment (black line).

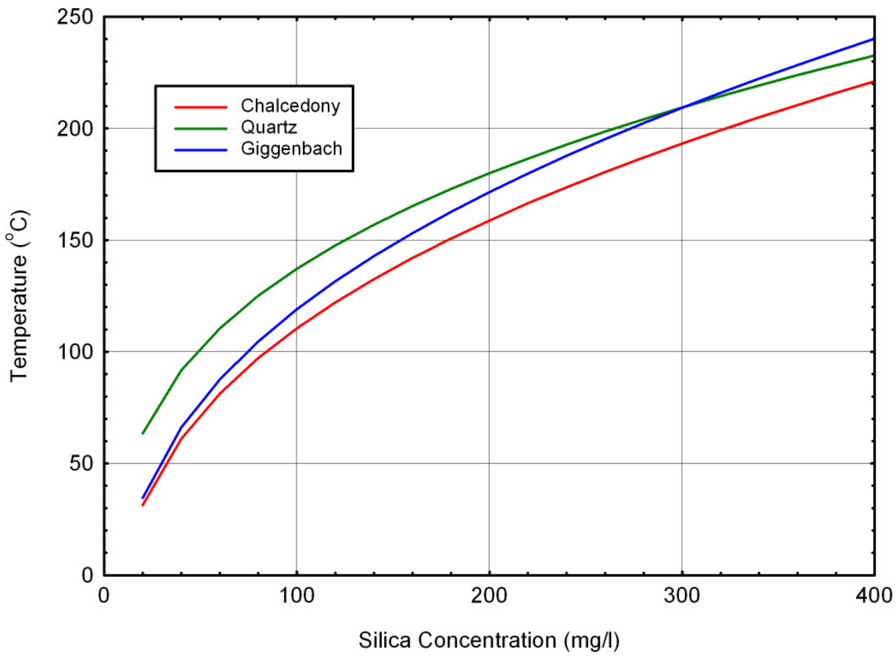

Figure 3. Graph of the solubility curves for quartz (green line) and chalcedony (red line) showing the curve (blue line) of Giggenbach (1992) to approximate the transition from chalcedony to quartz.

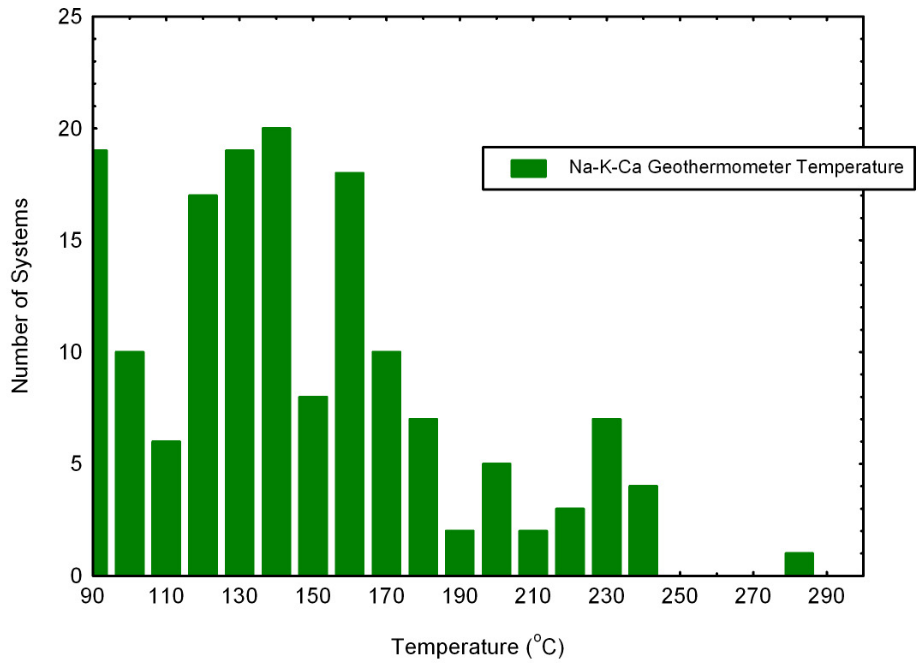

Figure 4. Histogram for 10ºC increments of temperatures calculated with the Na-K-Ca-Mg geothermometer for the geothermal systems identified in USGS Circular 790 (Brook and others, 1979). There are anomalously few systems with calculated temperatures in the range between 100º and 130ºC. This is interpreted as an underreporting of systems between 100º and 130ºC.

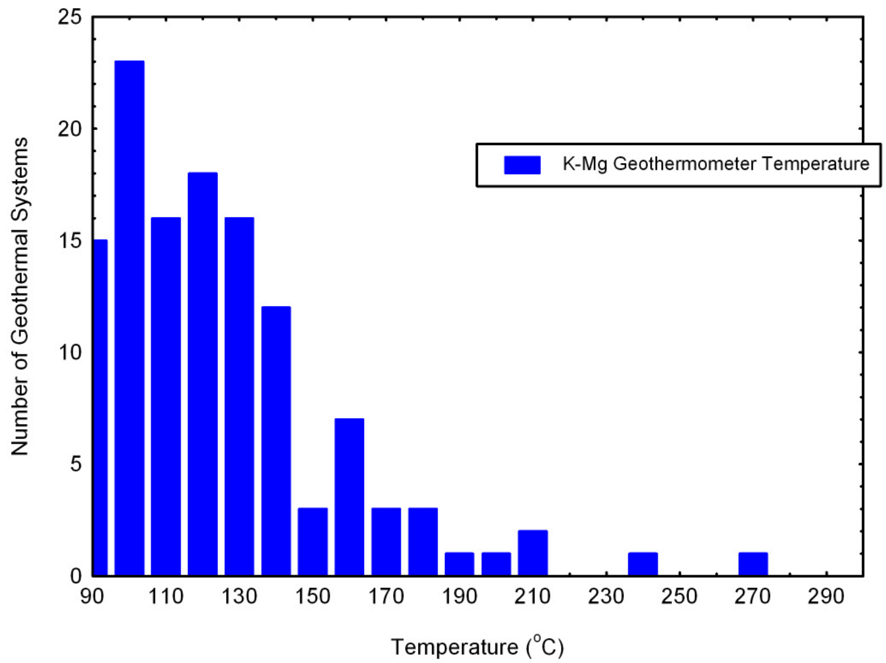

Figure 5. Histogram for 10ºC increments of temperatures calculated with the K-Mg geothermometer for the geothermal systems (with reported Mg concentrations) identified in USGS Circular 790 (Brook and others, 1979). These calculated temperatures exhibit a continuous decrease in the number of geothermal systems as higher temperatures are evaluated, regardless of the type of water chemistry.

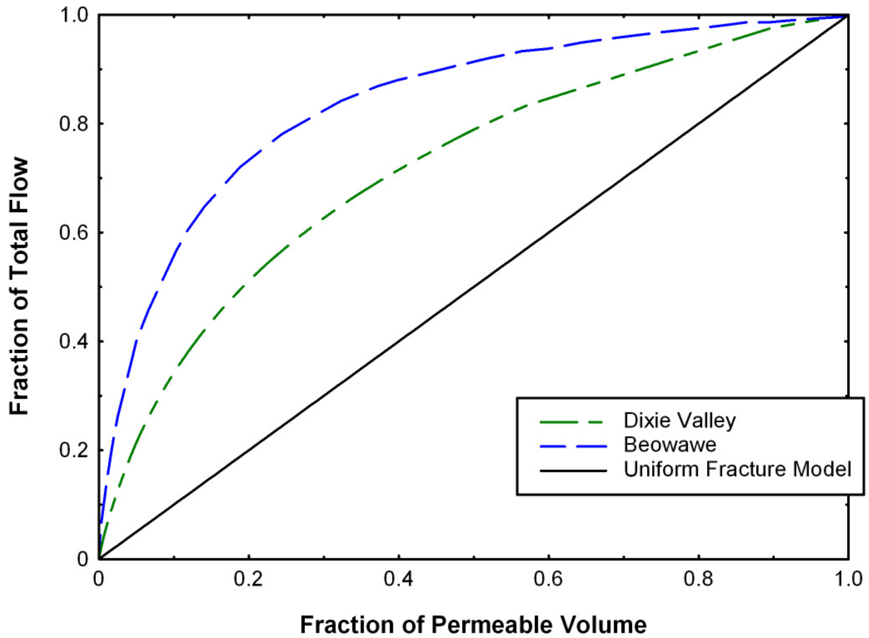

Figure 6. Distribution of flow capacity across the reservoir permeable volume for the fractured reservoir model of Bodvarsson and Tsang (black) and the Beowawe (Shook, 2005) and Dixie Valley (Reed, 2007) geothermal fields.

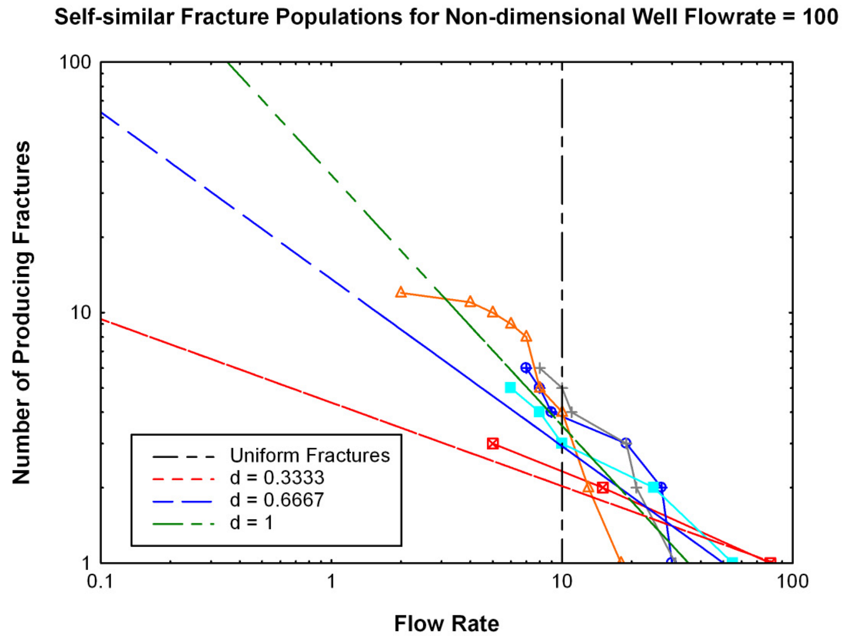

Figure 7. Fracture flow distributions for the uniform fracture model and self-similar models with fractal dimensions of *d*=0.333, 0.667, and 1.0, along with observations derived from pressure-temperature-spinner (PTS) logs in producing geothermal wells reported by Drenick (1986) (orange triangles), Enedy (1988) (blue squares), Garg and others (1997) (red squares and blue circles), and Hardeman and others (2000) (grey crosses).

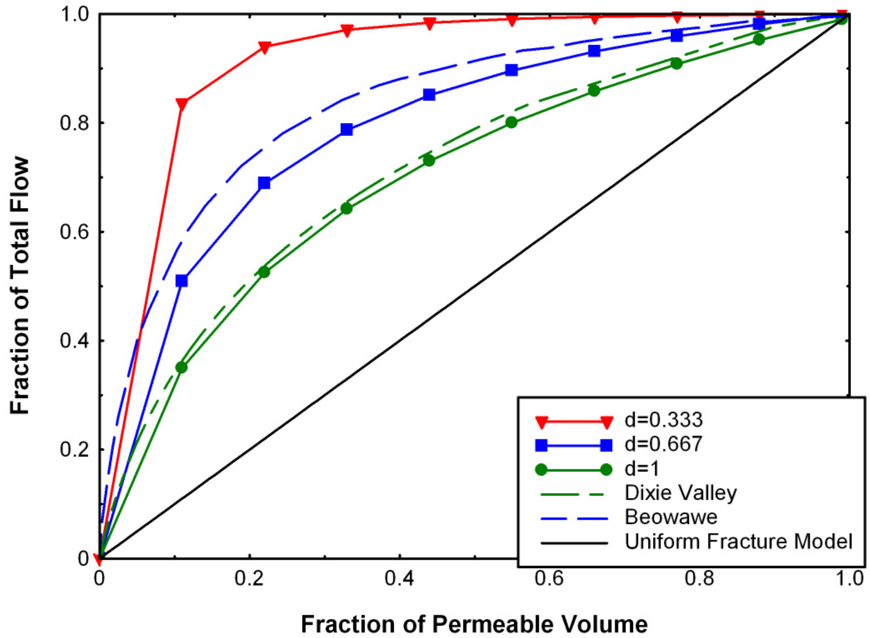

Figure 8. Distribution of flow capacity from figure 6 with the predictions of self-similar models with three different fractal dimensions (after Williams, 2007).

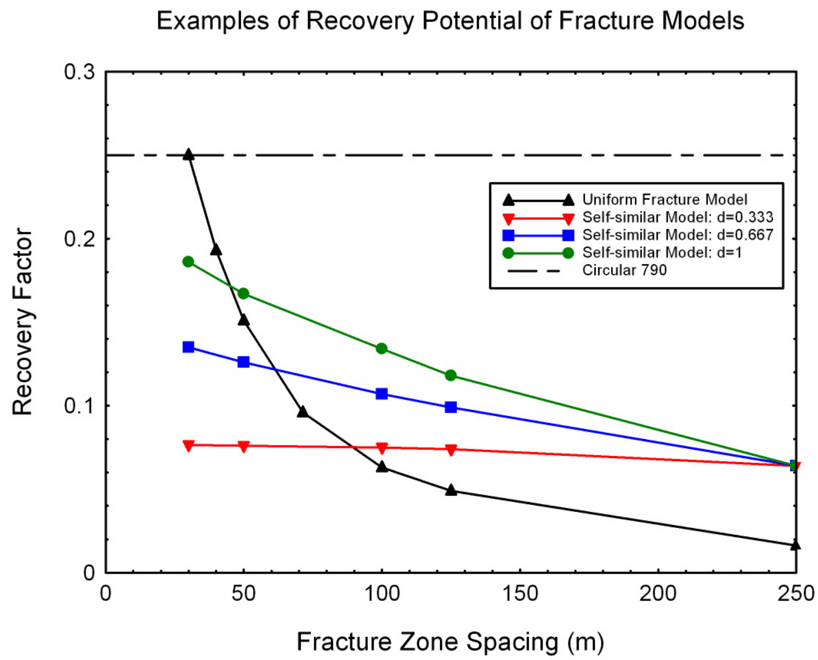

Figure 9. Variations in recovery factor with fracture spacing for example models incorporating planar fractures with uniform flow properties (black) and fractal distributions of flow properties among the producing fractures (green, blue and red).

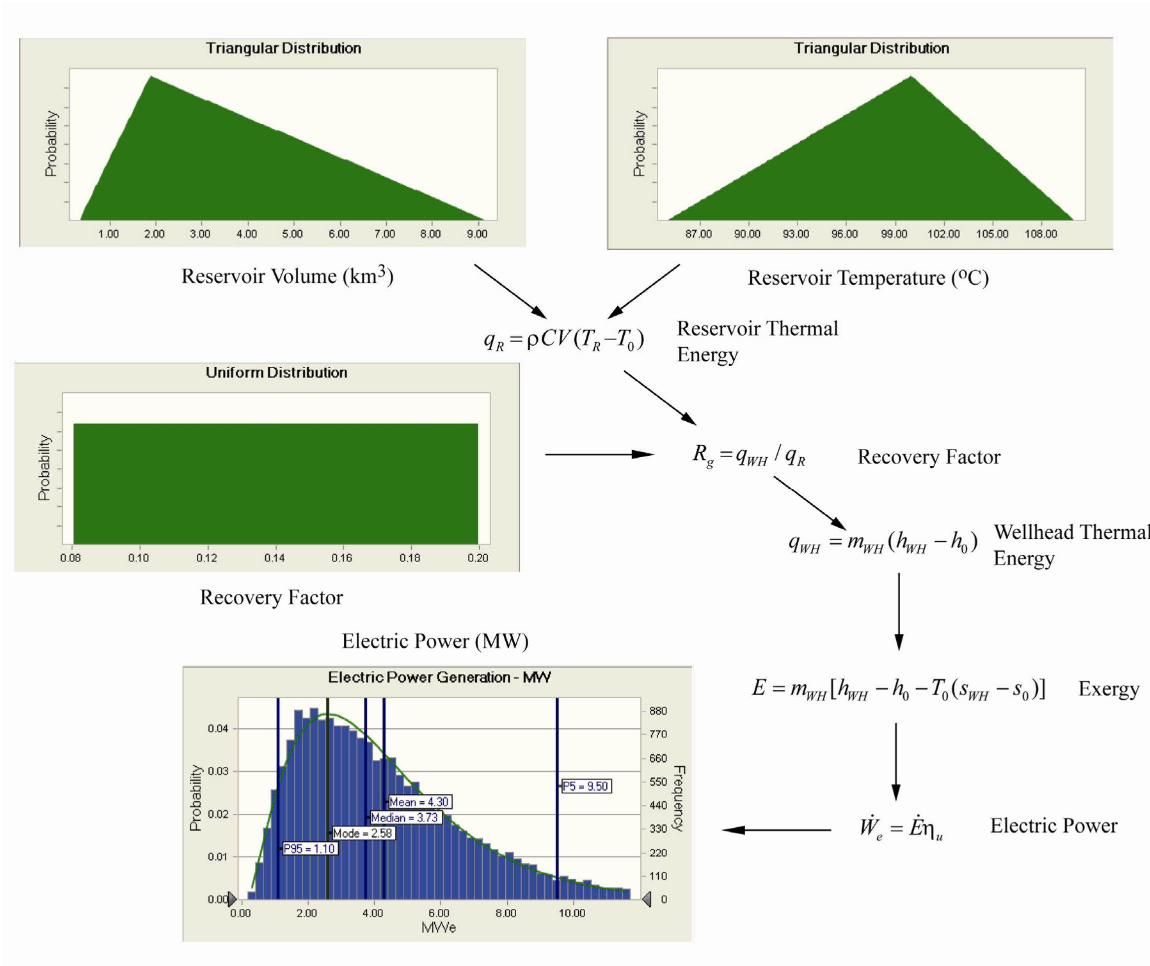

Figure 10. Schematic of the Monte Carlo uncertainty analysis applied in the calculation of reservoir thermal energy, wellhead thermal energy, and electric power generation potential for liquid-dominated geothermal systems in the national resource assessment.