Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Temperature Model and Volumetric Assessment of the Krafla Geothermal Field in N-Iceland

Sæunn Halldórsdóttir, Héðinn Björnsson, Anette Kærgaard Mortensen, Guðni Axelsson, and Ásgrímur Guðmundsson*

Iceland GeoSurvey - Grensásvegi 9 - 108 Reykjavík - Iceland

*Landsvirkjun Power - Háaleitisbraut - 103 Reykjavík - Iceland

saeunn.halldorsdottir@isor.is

Keywords: Reservoir modeling, Krafla geothermal field, temperature model, PETREL, volumetric assessment, Monte Carlo method, recoverable heat, uncertainty distribution

ABSTRACT

In 2008 the conceptual model of the Krafla geothermal field was revisited by a large group of scientists from various disciplines considering a range of new data. The new conceptual model confirms the large scale understanding of the reservoir mechanism but has provided a great increase in knowledge about the detailed structure of the reservoir. In connection with the development of a new conceptual model, geological, geochemical, and geophysical data from the Krafla geothermal field have been compared using the PETREL software. Estimated formation temperature has been used to form a 3-D temperature model for the studied area which forms the basis for a new volumetric assessment of the geothermal system.

The most important factor in the volumetric assessment is an estimation of the volume of the geothermal system. Resistivity data is used to determine the maximum surface area of the system and how the temperature is distributed within the estimated volume of the geothermal area. Other reservoir parameters and their uncertainties are determined on the basis of the recently developed conceptual model and volumetric calculations are carried out using the Monte Carlo method.

The volumetric assessment is calculated with two different temperature estimation schemes. (1) With the traditional method of assuming that the temperature only changes with depth and (2) by constructing a 3-D temperature model of the system. The estimated production capacity of the geothermal field is similar for the two methods. This supports the method and suggests that in general the simpler model gives a fairly good estimate of the production capacity.

1. INTRODUCTION

The Krafla geothermal area is located in northeastern Iceland in the caldera of the Krafla central volcano. The caldera, 8x10 km, and the fissure swarm that is associated with the central volcano are shown in Figure 1. The Námafjall geothermal area is also located on the Krafla fissure swarm south of the caldera but in this paper the focus will be on the Krafla geothermal area.

The first geological research in the area was carried out in the years 1969-1973, and the first experimental drilling in 1974 with two wells reaching to the depth of 1200 m. In 1975 the decision was made to drill production wells for a 60 MWe power plant. The same year the Krafla fires started, lasting until the year 1984. The power plant was completed in 1977, but the available steam only sufficed to produce 7 MWe. This was due to the unexpected nature of the geothermal system that consists of two geothermal zones, one water dominated and another partly boiling (Stefánsson, 1981). Therefore the production characteristics were quite different from water dominated systems that had previously been utilized in Iceland. It was not until 1999 that the production reached the power plant's full capacity of 60MWe. At the time a total of 36 wells had been drilled reviling the complex nature of the geothermal area, which can be divided into different zones on the basis of different chemical composition of the fluid.

Since the year 2006 plans have been on the drawing board to produce more power from the Krafla geothermal field. In 2007 and 2008, six more wells were drilled in order to get more steam for power production. In connection with these plans the conceptual model of the area has been revisited. The original conceptual model of the area was developed in 1977 and is described by Stefánsson 1981. Some years later Bödvarsson and Pruess (1982) developed a more detailed conceptual model for the geothermal field and constructed the first numerical model of the geothermal field. The main structure of this conceptual model is still valid but the new conceptual model includes a more detailed description of the reservoir.

In 2008 a total of 42 deep wells had been drilled in the Krafla geothermal area. All the wells are located within the Krafla caldera. Formation temperature has been estimated for all the wells and is used to construct two different temperature models of the geothermal area, one where the temperature changes with depth and another where the temperature changes in 3-D. The two temperature models are then used to estimate the production capacity of the geothermal area with simple volumetric calculations.

2. VOLUMETRIC METHOD

To calculate the heat contained in the geothermal system we integrate the heat capacity and the temperature over the volume of the geothermal system.

$$Q = \oint_V C\left[T - T_0\right] dV \qquad (1)$$

Where Q is the heat contained in the system, C is the heat capacity per volume T is the reservoir temperature and T_0 is the reference temperature. For example T_0 could be the temperature at the surface (the mean annual temperature). If it is assumed that the heat capacity and temperature are homogeneous in the horizontal directions and that they vary only in the vertical direction, the heat content of the system can be calculated by intergrading the heat capacity per unit-volume $C(z)$ and the difference of the estimated temperature curve $T(z)$ in the system and the cut-off temperature T_0.

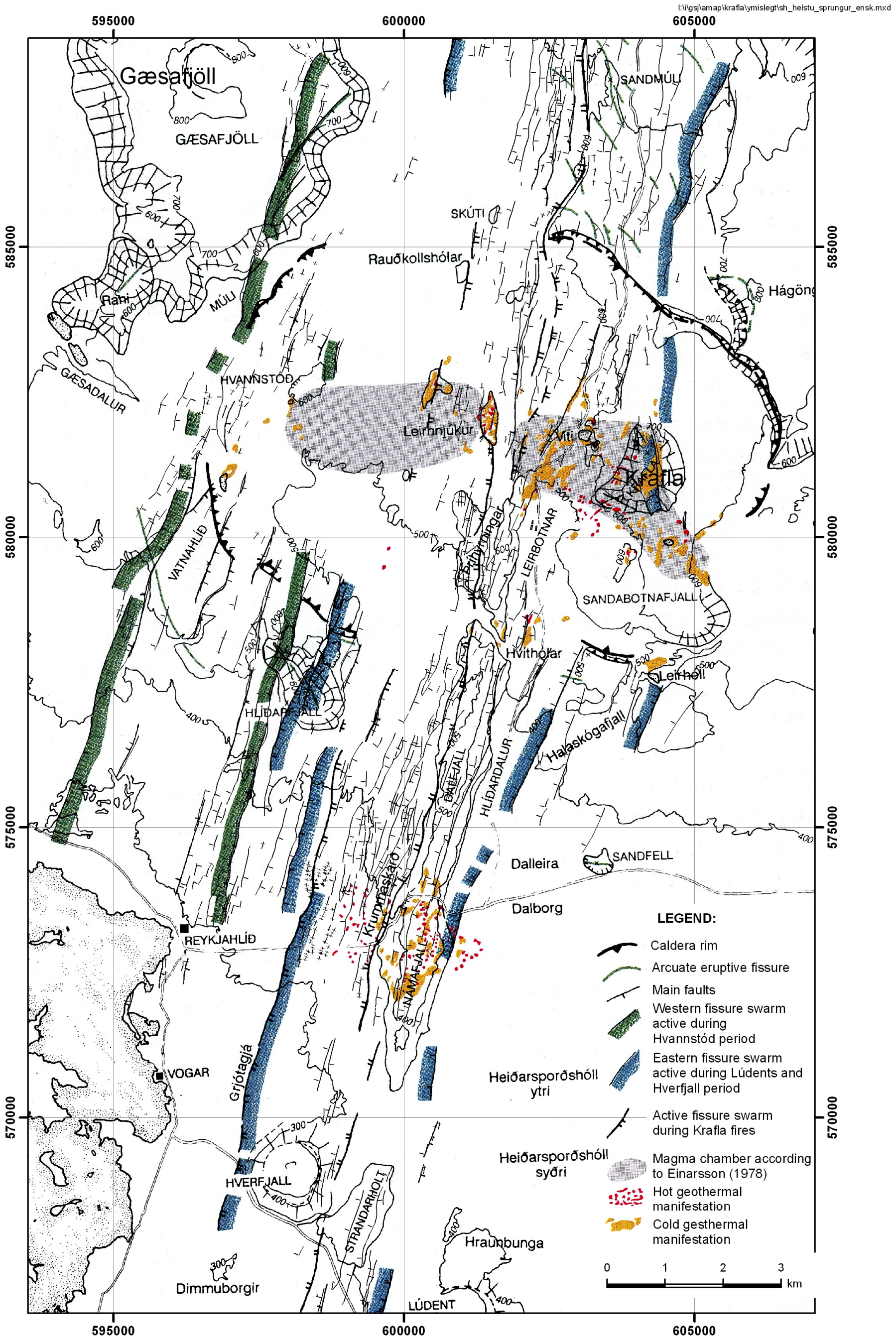

Figure 1: Structural map of the Krafla and Námafjall geothermal areas, showing the Krafla caldera and associated fissure swarm (Sæmundsson, 1991)

$$Q = A\int_{z_0}^{z_1} C(z)\left[T(z) - T_0\right]dz \qquad (2)$$

Where A is the surface area of the geothermal system. For simplicity the geothermal system is often divided into different layers where the heat capacity is constant in each layer and depends only on the specific heat and density of the rock and the water respectively.

$$C = s_w \rho_w \varphi + s_r \rho_r (1 - \varphi) \qquad (3)$$

Where φ is the porosity of the rock, s_r is the specific heat of the rock and ρ_r is the density of the rock, s_w is the specific heat of the water and ρ_w is the density of the water. For many geothermal areas it is convenient to assume that the temperature curve follows a curve shaped like the boiling point curve. Equation 4 describes a temperature curve shaped like the boiling point curve (James, 1970).

$$T(z) = X \cdot 69.56(z - z_{Delta})^{0.2085} \qquad (4)$$

Here X is a ratio factor describing the deviation from the true boiling curve, that runs from zero to one, z_{Delta}, is translation in the z direction in order to meet the upper boundary conditions, Tz_0 at z_0.

Only a small portion of the total heat in the system is recoverable and therefore we define a recovery factor, R, which is the ratio of the heat which can be recovered from the total heat in the system. The recoverable heat is therefore.

$$Q_H = RAC\int_{z_0}^{z_1}[T(z) - T_0]dz \quad (5)$$

From the recoverable heat of the geothermal system only a small portion can be utilized for electric production. We therefore define an electric utilization constant which gives us the electric energy.

$$Q_e = \eta_e Q_H \quad (6)$$

This gives the electric power.

$$P = \frac{Q_e}{t} \quad (7)$$

Where t is the production time of the electric power in seconds.

For a three dimensional model of the temperature it is possible to approach the matter of calculating the heat contained in the geothermal system in a different way. For a grid bock in a grid of the system, where ΔV is the volume of grid block, the heat contained in the block is.

$$\Delta Q = C[T - T_0]\Delta V \quad (8)$$

Where C and T are the heat capacity per volume and the temperature of the volume block, respectively. For a three dimensional model of the pressure additional to the temperature model it is possible to calculate C in the volume block directly from equation 3. Calculating for each block the specific heat and density for the rock and water from the pressure and the temperature. The total heat contained in the system is in therefore.

$$Q = \sum_i^N C_i(\varphi_i, T_i, P_i)[T_i - T_0]\Delta V_i \quad (9)$$

Where C_i depends on the porosity, temperature and the pressure in the volume block.

$$C(\varphi_i, T_i, P_i) = s_w(T_i, P_i)\rho_w(T_i, P_i)\varphi_i$$

$$+ s_r(T_i, P_i)\rho_r(T_i, P_i)(1 - \varphi_i) \quad (10)$$

This reduces the number of variables needed to be estimated in the volumetric calculations and the heat in the system is calculated directly from the properties in the reservoir.

2.1 Monte Carlo Calculations

The variables used in the volumetric method are often shrouded in uncertainty and therefore it is necessary to define a probability distribution for these variables (an example is presented in Figure 2. By choosing one random value for each variable out of their probability distributions one possible outcome of the volumetric method can be calculated. If this process is then repeated several times a discrete probability distribution for the outcome begins to form.

To form the discrete distribution for the outcome we divide the interval of possible outcomes into equally sized subintervals. The probability that the real outcome is in a particular subinterval is the ratio between the possible outcomes that fall in the subinterval and the total number of possible outcomes that have been calculated.

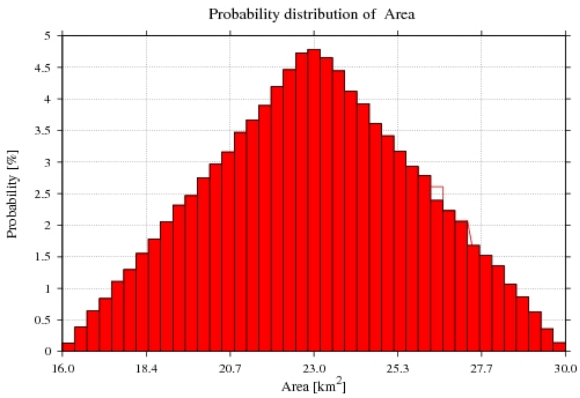

Figure 2: An example of the triangular probability distribution of one parameter (the surface area of the geothermal area)

With the discrete probability distribution it is possible to evaluate the range of probable outcomes of the volumetric method.

3. TEMPERATURE MODEL

A total of 42 wells were drilled in the Krafla geothermal area since the drilling started in 1974 until the year 2008. All the wells are located within the Krafla caldera. The largest number of wells are located within a triangular area reaching from the south flanks of the Krafla volcano to (a) NW over the Hveragil gully towards Leirhnjúkur (in fig. 3) and (b) NNW to the western flanks of Mt. Krafla. Three areas have been explored in the southern rim of the Krafla caldera. There are three wells near Hvíthólar (in fig. 3) about 1.5 km south of the main area, one well KS-01 east of Hvíthólar and one well KV-01 west of Hvíthólar. The location of the 42 wells is shown in Figure 3.

Temperature logs from the wells during warm up periods have been used to estimate the formation temperature. The formation temperature has been collected in the PETREL software and interpolated over an estimated volume of the geothermal system. Four cross sections through the 3-D temperature model are shown in Figure 4.

The Krafla geothermal area is generally divided into five different well fields, mainly on the basis of different chemical composition of the fluid. The oldest well fields, Leirbotnar and Vítismór, are to the west of the Hveragil gully shown in Figure 3. The Sudurhlídar well field is in the south flanks of Mt. Krafla and the Vesturhlídar well field in the western flanks of the mountain. The fifth is the Hvíthólar field which is located to the south of the other four. The characteristic of the formation temperatures is different between the five well fields. A typical formation temperature for each well field is shown in Figure 7.

4. VOLUMETRIC CALCULATIONS

4.1 Volumetric Calculations where the Temperature Changes with Depth

To simplify the volumetric calculations it is often assumed that the temperature changes only vertically and not horizontally. Temperature measurements from wells in the Krafla geothermal field indicated that the formation temperature curve is shaped like the boiling point curve. Equation 4 is an estimation of a temperature curve that is shaped like the boiling point curve.

$$T(z) = X \cdot 69.56(z - z_{Delta})^{0.2085} \qquad (4)$$

Where $0 < X \leq 1$. If X is equal to 1 the temperature is on the boiling point curve and if X is less than 1 the temperature is a ratio of the boiling point curve. Figure 7 shows $T(z)$ for different values of X.

In order to perform the Monte Carlo volumetric calculations the following variables or there probability distribution need to be evaluated: (1) Surface area of the geothermal system, A, (2) thickness of the system, $z_1 - z_0$, (3) porosity of the rock, φ, (4) mean physical characteristics of the rock and water in the system, that is the specific heat and density of the rock and water, s_r, s_w, ρ_r and ρ_w , (5) heat distribution through the reservoir, $T(z)$, (6) recovery factor, R, (7) cut-off temperature, T_0. These variables will give the recoverable heat in the system. To evaluate the electric production capacity of the reservoir the following variables also need to be evaluated: (8) Electric conversion coefficient, η, (9) electric production time, t.

The cut-off temperature is chosen to be 170°C and a proper electric conversion coefficient chosen, 12% (Wilcox, 2006). To estimate possible electric power production we consider three production time scenarios, 30, 50 and 100 years.

4.1.1 Surface Area of the Geothermal System

Surface resistivity surveys of high-temperature geothermal systems in Iceland reveal similar resistivity structure (Árnason et. al., 2000). A low resistivity cap is observed on the outer margins of the reservoirs and underlain by a more resistive core. The size of the reservoir can therefore be estimated from the low resistivity contour circumscribing the high resistivity core at 800-1000 m depth. The alteration of the rock indicates that the temperature of the formation within these contours has reached at least 240°C (Árnason et. al., 2000). Only experimental drilling can confirm if the rock is still at these high temperatures or not. The resistivity at 300 m under sea level (about 800 m depth under the geothermal area) according to TEM measurements is shown in Figure 6. The area within the low resistivity contour is approximately 40 km^2. Some shallow experimental boreholes have been drilled into the south western part of the area (west of Hvíthólar) and the eastern part of the area (north of Mt. Jörundur), revealing low temperatures at these locations. With all of the above taken into account the maximum size of the area is estimated to be 30 km^2.

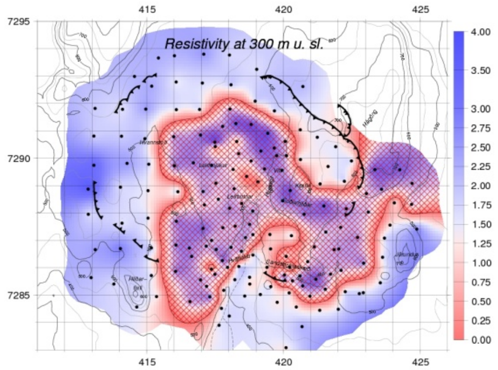

Figure 3: Resistivity at 800 m depth (300 m u.sl.) at Krafla geothermal field (Árnason and Magnússon, 2001)

4.1.2 Thickness of the System

Typical depth of boreholes in geothermal areas in Iceland is in the range 2500-3000 m. With some boreholes in Krafla reaching to the depth of more than 2500 m the thickness of the system is assumed to be 3000 m. Only one layer is assumed reaching from the surface to the depth of 3000 m.

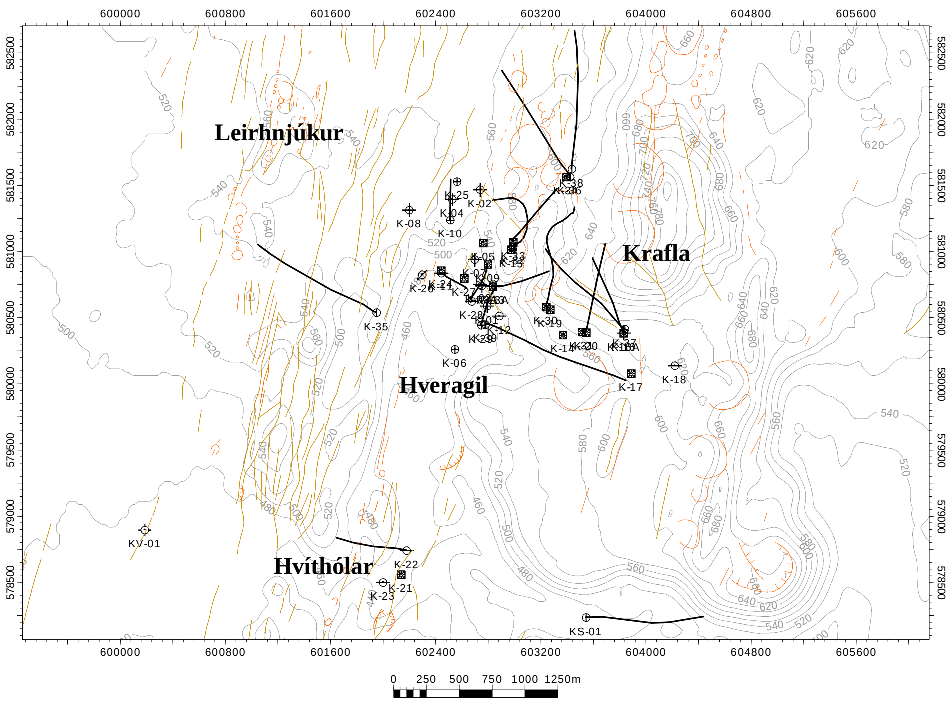

Figure 4: Wells at the Krafla geothermal area

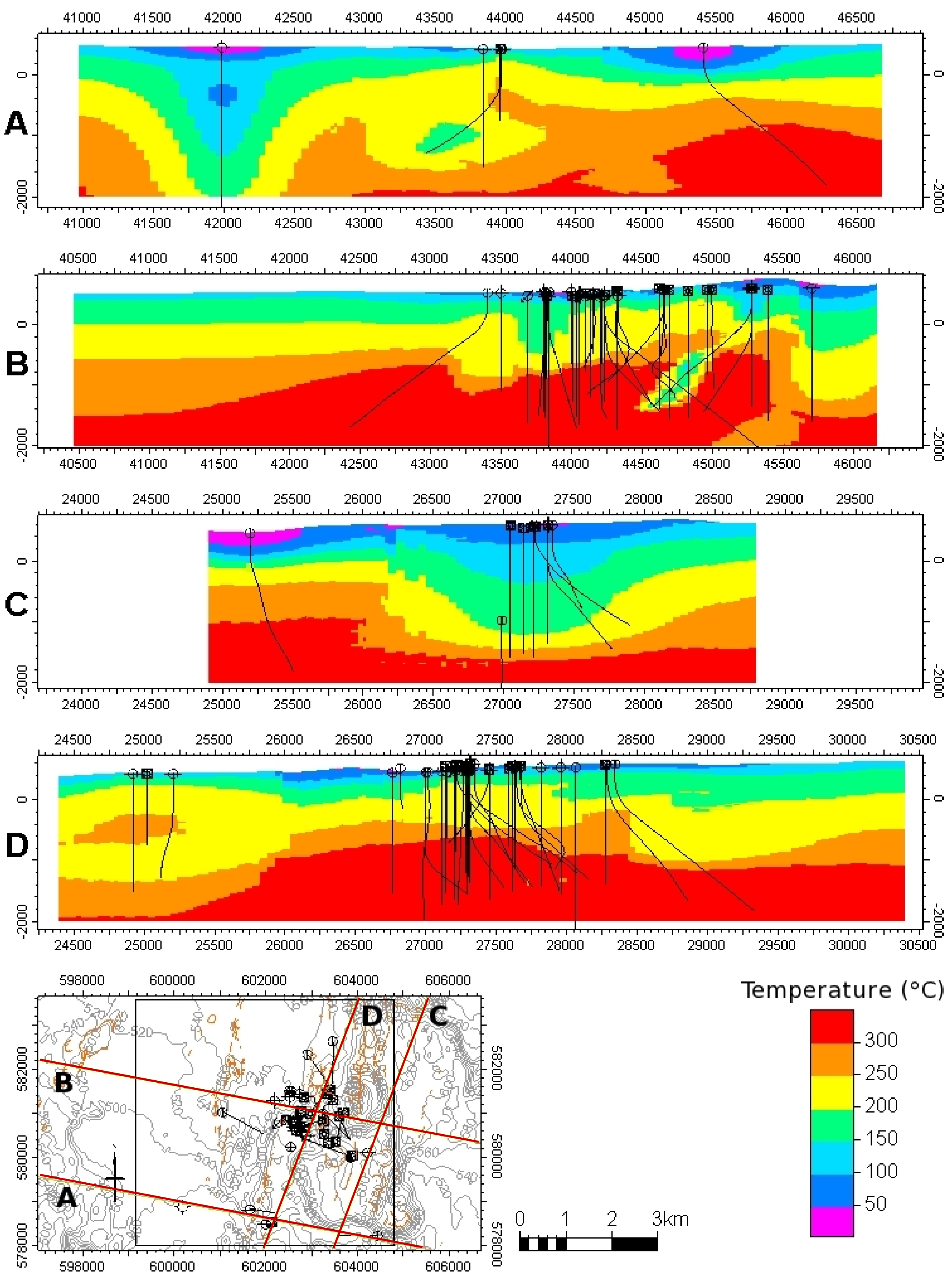

Figure 5: Cross sections of the 3-D temperature model of Krafla. The locations of the sections are shown in the lower left corner

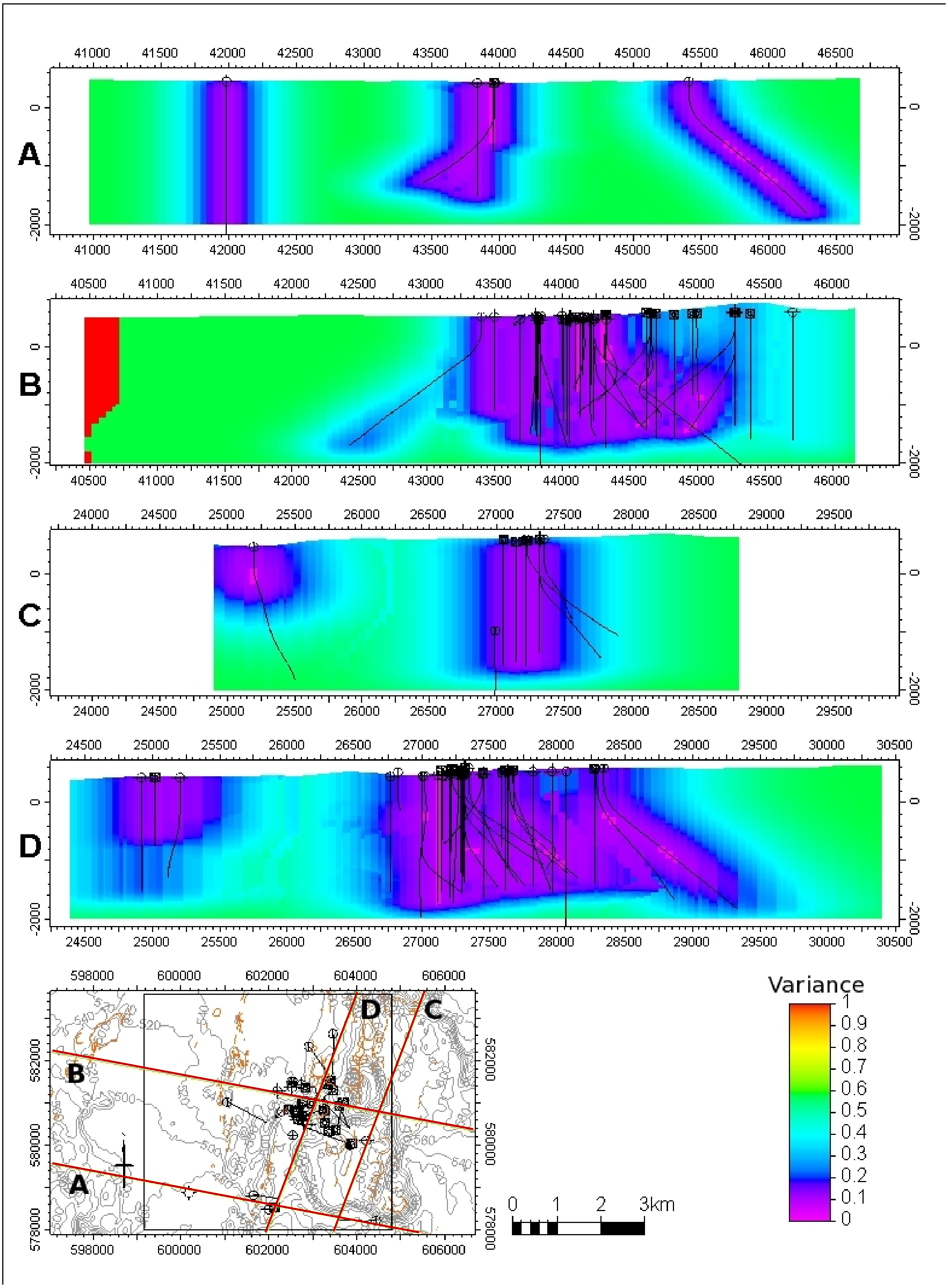

Figure 6: Cross sections showing the variance for the 3-D temperature model of Krafla. The locations of the sections are shown in the lower left corner

4.1.3 Porosity of the Rock in the System

The main geological characteristics of the subsurface rocks have been identified from well cuttings. In general the subsurface rocks can be divided into three lithological units, (1) the hyaloclastic unit, (2) the lava formation and (3) the intrusive formation (Stefánsson, 1981).

It can be assumed that the porosity of the basaltic lavas is in the range of 5-15% (Pálsson et. al., 1984, Sigurdsson and Stefánsson, 1994). The hyaloclastic unit is more diverse in structure and the porosity can be ranging from 15% up to 35% in fresh tuff. Below 900-1200 m depth, intrusions with very low porosity become more common. In the calculations the porosity of the rock is considered to be in the range of 5% to 20% with the most likely value of 10%.

4.1.4 Mean Characteristics of the Rock and Water in the System

The heat capacity is generally calculated from the equation $c = s\rho$, where s is the specific heat and ρ is the density. In the volumetric calculations it is assumed that the recoverable heat is only in the layer of which water can be extracted from. The heat capacity is then calculated from equation 3.

$$C = s_w \rho_w \varphi + s_r \rho_r (1-\varphi) \tag{3}$$

Were s_r and s_w are specific heat of rock and water respectively and ρ_r and ρ_w are the density of rock and water. To simplify the calculations probability distribution is only defined for the porosity and specific heat and density of the rock and water, s_r , s_r , ρ_r and ρ_w , are taken as constants. The specific heat of the rock is chosen to be 880 J/(kg°C) and the density of the rock to be 3000 kg/m^3. The specific heat of the water is chosen to be 5200 J/(kg°C) and the density of the water to be 760 kg/m^3.

4.1.5 Heat Distribution Through the Reservoir

Figure 7 shows the formation temperature from the Krafla geothermal area and *T(z)* according to equation 4 for different values of *X* and Tz_0 equal to 5 °C. The Leirbotnar system is divided into two reservoirs (Stefánsson, 1981). The formation temperature follows a boiling point curve above 200-300 m depth and below 1000-1200 m depth but in between the temperature is rather constant between 180-210 °C. The formation temperature is in the range of *T(z)* where *X* is between 0.7 and 1.0. The Vítismór system is dived into two reservoirs as well as the Leirbotnar system. The reservoir with the constant temperature reaches to more depths than the Leirbotnar reservoir, down to 1500 m, and therefore the temperature are less at Vítismór than at Leirbotnar. The formation temperature is in the range of *T(z)* where *X* is between 0.6 and 1.0. In the Sudurhlídar and Vesturhlídar systems the formation temperature follows a boiling point curve in most wells. The formation temperature at Sudurhlídar is in the range of *T(z)* where *X* is between 0.9 and 1.0. The formation temperature at Vesturhlídar is in the range of *T(z)* where *X* is between 0.9 and 1.0. The formation temperature at the three wells at Hvíthólar are all reversed (see fig. 7). The formation temperature is in the range of *T(z)* where *X* is between 0.6 and 1.0.

Two wells have been drilled away from these five well fields. Well KS-01 is located at Sandabotnaskard and well KV-01 west of the Hvíthólar well field. The formation's temperature at well KS-01 is rather cold at the top but below 1000 m the temperature is close to the boiling point curve (fig. 7). The formation at KV-01 is cold.

In light of all formation temperature data from wells in the Krafla geothermal area it is assumed that *X* is in the range of 0.7 to 1.0 in the volumetric calculations. The most likely value is taken as 0.9 and that is because a part of the area west of Hvíthólar and east of Sudurhlídar has been excluded from the total area shown in Figure 6, therefore higher temperatures can be expected in the remaining part of the area.

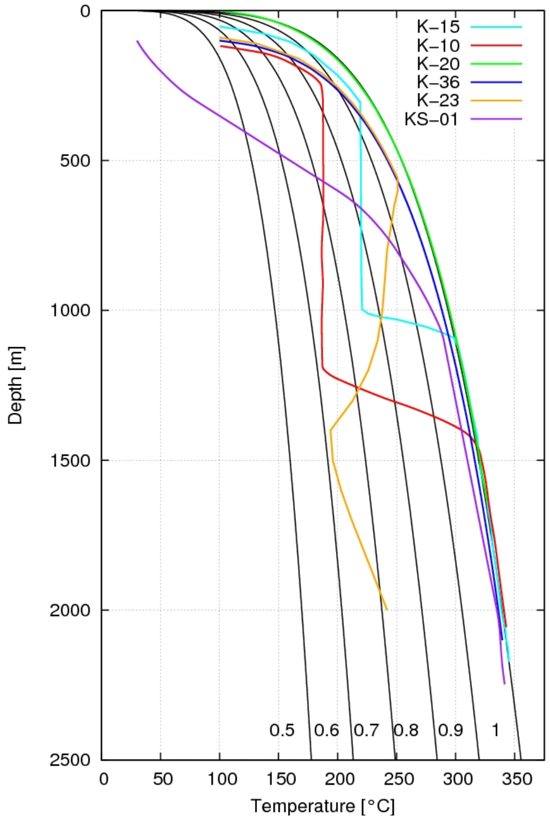

Figure 7: Typical formation temperature from different well fields in the Krafla geothermal area and *T(z)* for different values of *X*. (1) Leirbotnar (well 15), (2) Vítismór (well 10), (3) Sudurhlídar (well 20), (4) Vesturhlídar (well 36) and Hvíthólar (well 23). The formation temperature from well KS-01 east of the Hvíthólar well field is also shown in the figure

4.1.6 Recovery Factor

Recovery factor is defined as the ratio between the heat that can be extracted from the geothermal system and the total heat of the geothermal system. The recovery factor is mostly affected by the porosity and the permeability. The factor is most often given values between 0.1 and 0.25. Muffler (1977; 1979) proposed a linear correlation between the recovery factor and the porosity. According to that correlation, a rock with the mean porosity of 0.10 would have the recovery factor of 0.25. Generally it is assumed that permeability is mostly controlled be faults and fractures, their number, distribution and size, rather than the porosity. It is assumed that this is the case for the Krafla geothermal area. Williams (2007) compared two models for fracture distribution: one where the fractures have a regular distribution and another where the fractures have a self-similar distribution. For fractures separated by 30-250 m the models give recovery factors in the range of 0.02 and 0.25 for the regular distribution model and in the range of 0.08 and 0.20 for the self-similar distribution model. It is unlikely that the distribution of the fractures is perfectly uniform and in the volumetric calculations it is assumed that the recovery factor is ranging from 0.10 to 0.20 with the most likely value of 0.15.

4.1.7 Results of the Volumetric Calculations

An estimate for the electric power that could be produced from the recoverable heat with cut-off temperature of 170°C from the Krafla geothermal area has been calculated according to Equation 7. This was done for three production time scenarios. The results are presented as a discrete probability distribution, seen in Figure 8, and as a discrete cumulative probability distribution, seen in Figure 9. Each figure consists of 100,000 random outcomes. From these random outcomes, various statistical parameters can be calculated. These include the likeliest outcome, 90% confidence interval, mean and median of the outcomes, standard deviation and where the 90% limit for the cumulative probability lies. These statistics are presented in Table 1 for each of the three production periods.

According to the probability distribution in Figure 8, it is most probable (with 7% probability) that the electrical power production capacity lies between 275 MWe and 290 MWe if the recoverable heat is used for 30 years, between 165 MWe and 175 MWe if it is used for 50 years and between 85 MWe and 90 MWe if it is used for 100 years. Also from the statistics of the distribution in Figure 8, it can be seen that the volumetric model predicts with 90 % confidence that power production capacity lies between 170-460 MWe for 30 years, between 100-270 MWe for 50 years and between 50-140 MWe for 100 years.

From the statistics of the cumulative probability in Figure 9 it can be seen that the volumetric model predicts with 90% probability that at least 190 MWe can be produced for a production period of 30 years, at least 110 MWe for 50 years and at least 55 MWe for 100 years.

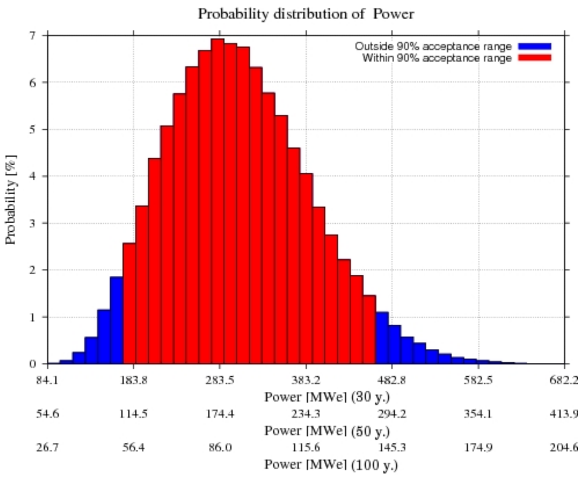

Figure 8: Probability distribution for electric power generation. Each pillar is about 15 MWe wide for 30 years, about 10 MWe for 50 years and about 5 MWe for 100 years. Statistical information for the distribution can be seen in table 1

Table 1. Statistical parameters for the probability distribution for electric power production for the Krafla field estimated by the Monte Carlo method.

Statistical sizes	Values [MWe] (30 y.)	Values [MWe] (50 y.)	Values [MWe] (100 y.)
Most probable value (with 7% probability)	275-290	165-175	85-90
90% confidence interval	170-460	100-270	50-140
Mean	300	180	90
Median	300	180	90
Standard deviation	80	50	20
90% limit	190-205	110-120	55-60

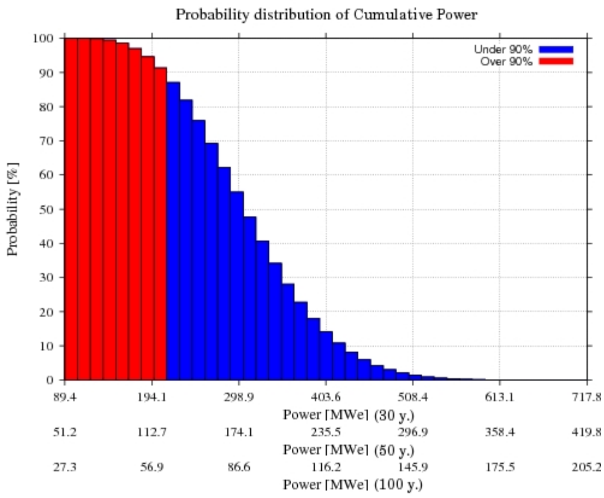

Figure 9: Cumulative probability distribution for electric power generation. Each pillar has the same width as given for fig. 8. The height of each pillar represents the probability that the result is in or above the interval of that pillar. In table 1 the upper limit of the last pillar that is larger than 90% is presented

4.2 Volumetric Calculations with a 3-D Temperature Model

With the 3-D temperature model of the area both temperature and volume are linked. The grid is regular so that the volume of each element is constant. The temperature in each element is found by interpolating the formation temperature. The heat is calculated from Equation 9.

$$Q = \sum_{i}^{N} C_i(\varphi_i, T_i, P_i)[T_i - T_0]\Delta V_i \qquad (9)$$

Where T_i is the temperature and ΔV_i is the volume of a grid block. The heat capacity can be calculated from Equation 10 but for simplicity Equation 3 is used, as in the case of the volumetric calculation for temperature changing only with depth.

A probability distribution is defined for the porosity and the recovery factor of the geothermal system. In the calculations the porosity of the rock is considered to be in the range 5% to 20% with the most likely value of 10% and the recovery factor in the range 10% to 20% with the most likely value of 15%. The specific heat of the rock is chosen to be 880 J/(kg°C) and the density of the rock to be 3000 kg/m^3. The specific heat of the water is chosen to be 5200 J/(kg°C) and the density of the water to be 760 kg/m^3. The cut-off temperature is chosen to be 170°C and a proper electric conversion coefficient chosen 12% (Wilcox, 2006). To estimate possible electric power production we consider three production time scenarios, 30, 50 and 100 years.

4.2.1 Results of the Volumetric Calculations

An estimate for the electric power that could be produced from the recoverable heat with cut-off temperature of 170°C from the Krafla geothermal area has been calculated according to Equation 9. This was done for three production time scenarios. The results are presented as a discrete probability distribution, seen in Figure 10, and as a discrete cumulative probability distribution, seen in Figure 11. Each figure consists of 100,000 random parameters. From these random outcomes various statistical information can be calculated. These include the likeliest outcome, 90% confidence interval, mean and median of the outcomes, standard deviation and where the 90% limit for the cumulative probability lies. These statistics are presented in Table 2 for each of the three production periods.

According to the statistics of the probability distribution in Figure 10 it is most probable (with 5% probability) that the electrical power production capacity lies between 285 MWe and 290 MWe if the recoverable heat is used for 30 years, between 170 MWe and 175 MWe if it is used for 50 years and between 85 MWe and 90 MWe if it is used for 100 years. Also from the statistics of the distribution in Figure 10 it can be seen that the volumetric model predicts with 90 % confidence that power production lies between 220-360 MWe for 30 years, between 130-210 MWe for 50 years and between 70-110 MWe for 100 years.

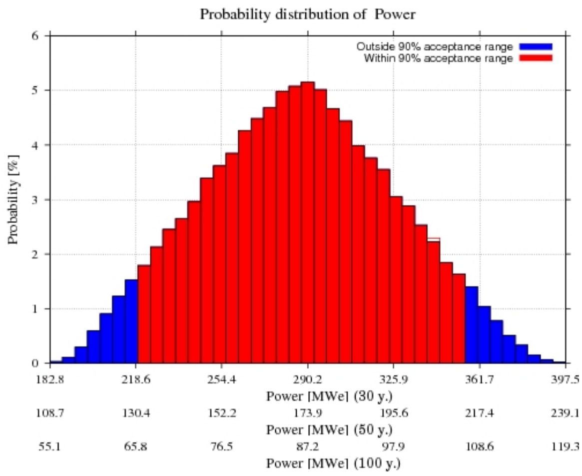

Figure 10: Probability distribution for electric power generation. Each pillar is about 5 MWe wide for 30 years, about 3 MWe for 50 years and about 2 MWe for 100 years. Statistical information for the distribution can be seen in table 2

From the statistics of the cumulative probability in Figure 11 it can be seen that the volumetric model predicts with 90% probability that at least 230 MWe can be produced for a production period of 30 years, at least 135 MWe for 50 years and at least 65 MWe for 100 years

Table 2. Statistical parameters for the probability distribution for electric power production for the Krafla field estimated by the Monte Carlo method.

Statistical sizes	**Values [MWe] (30 y.)**	**Values [MWe] (50 y.)**	**Values [MWe] (100 y.)**
Most probable value (with 5% probability)	285-290	170-175	85-90
90% confidence interval	220-360	130-210	70-110
Mean	290	170	90
Median	290	170	90
Standard deviation	40	20	10
90% limit	230-235	135-140	65-70

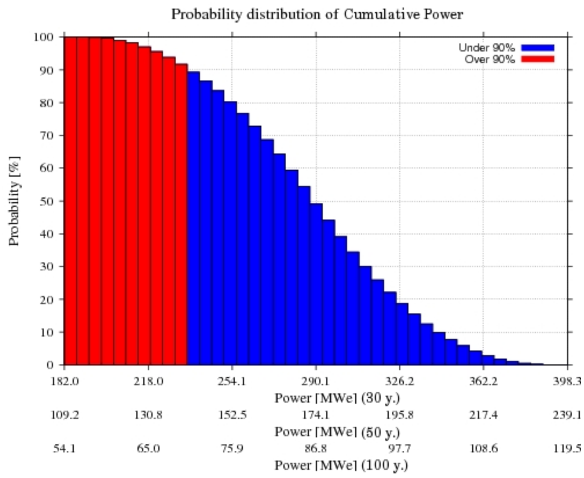

Figure 11: Cumulative probability distribution for electric power generation. Each pillar has the same width as given for fig. 10. The height of each pillar represents the probability that the result is in or above the interval of that pillar. In table 2 the upper limit of the last pillar that is larger than 90% is presented

CONCLUSION

Volumetric calculations using the Monte Carlo method have been carried out for the Krafla geothermal area. The volumetric assessment was calculated with two different temperature estimation schemes. (1) The traditional method of assuming that the temperature only changes with depth and (2) by constructing a 3-D temperature model of the system.

For the first method the volumetric model predicts with 90% confidence that power production lies between 170-460 MWe for 30 years, between 100-270 MWe for 50 years and between 50-140 MWe for 100 years.

For the second method the volumetric model predicts with 90% confidence that power production lies between 220-360 MWe for 30 years, between 130-210 MWe for 50 years and between 70-110 MWe for 100 years.

It should be emphasized that the temperature in each volume block has been included in the calculations without considering its uncertainty distribution. Defining an uncertainty distribution for the temperature in each block would increase the uncertainty.

The estimated production capacity of the geothermal field coincides for the two methods. This supports the method of using the traditional volumetric calculations with the simple temperature model. This suggests that in general the simpler model gives a fairly good estimate of the production capacity.

ACKNOWLEDGEMENTS

The authors would like to thank Landsvirkjun (The National Power Company) for financing the work presented in this paper and for allowing its publication. Iceland GeoSurvey is likewise thankfully acknowledged for providing time and financial support for this publication.

REFERENCES

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flovenz, O.G. and Gudlaugsson, S. Th.: The resistivity structure of high-temperature geothermal systems in Iceland, *Proceedings,* WGC Congress in Japan (2000).

Árnason, K. and Magnússon, I.Th.: *Results of resistivity measurements from the Krafla geothermal area,* Orkustofnun report OS-2001/062 143p. (2001) (in Icelandic)

Bödvarsson, G.S. and Pruess, K.: The Krafla geothermal field - Final report on modeling studies, *Proceedings*, 8th Workshop of Geothermal Reservoir Engeneering, (1982).

Einarsson, P.: S-wave shadows in the Krafla caldera in NE-Iceland, evidence for a magma chamber in the crust. *Bull. Volcanol*. 41, (1978), 1-9.

James, R.: Factors controlling borehole performance. *Geothermics*, 2, (1970) 1502-1515.

Muffler, L.P.J.: 1978 USGS geothermal resource assessment, *Proceedings,* Stanford Geothermal Workshop. Stanford University, Stanford, CA, (1977).

Muffler, L.P.J. (Editor): Assessment of geothermal resources of the United States -1978, U.S. *Geological survey circular* 790 (1979).

Pálsson, S., Haraldsson, G.I. and Vigfússon, G.H.: *Density and porosity of rock*, Orkustofnun report OS-84048/VOD18 35p. (1984) (in Icelandic).

Sigurðsson, Ó. and Stefánsson, V.: *Reservoir parameters – Measurements from rock core*, Orkustofnun report OS-94049/JHD-28 35p. (1994) (in Icelandic).

Stefánson, V.: The Krafla geothermal field, northeast Iceland, in *Geothermal systems*, edited by L. Ryback and L.J.P. Muffler, pp. 273-294, John Wiley, New York, (1981).

Sæmundsson, K.: The geology of the Krafla geothermal system, *Náttúra Mývatns* publ. by the Icelandic Society of Natural Sciences, (1991) 25-95. (in Icelandic)

Wilcox, G. (Editor): *The future of geothermal energy, impact of enhanced geothermal systems [EGS] on the United Sates in the 21. Century*, Massachusetts Institute of Technology (2006).

Williams, C.F.: Updated methods for estimating recovery factors for geothermal resources. *Proceedings,* Thirty-Second Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, CA, (2007).