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GEOTHERMAL ASSESSMENT OF THE GLERARDALUR AND SVARTSENGI FIELDS

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ABSTRACT

The methods for assessment of geothermal resources are reviewed. Assessment are made for the resources of two geothermal fields by the volumetric and the modelling methods.

One of the fields is the Glerardalur low-temperature geothermal field in N-Iceland. The resource base is estimated to be 1.51×10^{15} kJ by the volumetric assessment. The extractable quantities are 3.85×10^{12} kJ for the closed system and 1.7×10^{14} kJ for the recharged system, respectively, under the specified exploitation methods. In the lumped parameter model, calibration and verification were conducted with data accumulated over 10 years observation of the reservoir response to production. The obtained parameters were used for predicting the reservoir response to different constant production rates over the next 15 years. The present trend of stabilized drawdown can be maintained only for an annual average production rate not larger than 15 l/s.

The other field is the Svartsengi high-temperature geothermal field in SW-Iceland. The reservoir was divided into upper and deeper parts for the volumetric assessment which estimated the resource base as 9.87×10^{15} kJ. The extractable quantities are 2.53×10^{15} kJ for the closed system and 3.76×10^{15} kJ for the recharged system, respectively, under the specified exploitation methods. In the lumped model, the calibration and verification were conducted with data accumulated over 14 years observation of reservoir response to production and on the results of geological and geophysical surveys. The model obtained was used to predict reservoir response to different constant production rates over the next 15 years. The optimum production rate is estimated to be slightly less than 200 kg/s.

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1. INTRODUCTION

As a part of the course for the fellows of the UNU Geothermal Training Programme, a project was conducted from August to October 1992. The programme was divided into four stages, 5 weeks of introductory lectures, 4 weeks of specialized training, 2 weeks of field excursion and seminars, and finally three months for project work. This report presents the result of the project undertaken during the last stage.

The report discusses generally the methods for geothermal resource assessments. The resources of two geothermal fields, the Glerardalur field and the Svartsengi field in Iceland, are assessed by the volumetric method and lumped parameter modelling. The program LUMPFIT, which was used for the modelling study, was developed by Dr. Gudni Axelsson and Dr. Pordur Arason at Orkustofnun.

2. GEOTHERMAL RESOURCE ASSESSMENT REVIEW

Assessment of a geothermal resource refers to the proceeding by which quantitative estimates for the resource can be obtained. The geothermal reserve of that resource or the useable amount of energy that can be extracted without environmental problems will depend on the technology and economics in the foreseeable future. In general, the methodology for geothermal resource assessment may be divided into two categories, the volumetric method (the static method) and the modelling method (the dynamic method). These methods are discussed in the following chapters.

2.1 The volumetric method

The volumetric method, as the name implies, is used to estimate "volumetric heat" or "stored heat". The first step in applying the method is the estimation of the accessible resource base:

$$H_i = V_i \phi_i \rho_{iw} (H_{iw} - H_{ow}) + V_i (1-\phi_i) C_{ir} (T_i - T_o) \rho_{ir} \tag{1}$$

$$H_i = V_i \rho_{iw} C_{iw} \phi_i (T_i - T_o) + V_i \rho_{ir} C_{ir} (1-\phi_i)(T_i - T_o) \tag{2}$$

$$H_i = C_{vi} V_i (T_i - T_o) \tag{3}$$

$$H = \sum_{1}^{n} H_i \tag{4}$$

where

H	= stored heat (kJ);
V	= volume (m^3);
ϕ	= porosity of the geothermal reservoir;
ρ	= density (kg/m^3);
C	= specific heat ($kJ/m^{3\circ}K$);
C_v	= mean volumetric specific heat of rock and water ($kJ/m^{3\circ}K$);
T	= temperature (°C);

and the subscript

i	refers to the specific block or layer under consideration;
w	refers to to the water part of the rocks;
r	refers to the rock matrix;
o	refers to the status at the reference temperature T_o;

Equation 1 can be applied to liquid-dominated reservoirs; the first part of the right hand side of the equation is heat stored in the water contained in volume V_i of rock, and the second part is the heat stored in the rock matrix. Equation 2 is the same as Equation 1, but with the heat in the water expressed differently. Equation 3 calculates the total heat contained in the rock and the fluid. Based on an estimated volumetric specific heat C_v Equation 4 is the sum of the heat in all blocks or layers within the geothermal field under consideration.

For the exploitation of a geothermal field the quantity of extractable heat is most important but it is usually only a small fraction of the accessible resource base. To describe the useful accessible resource base, a recovery factor, *Rg*, is introduced that allows one to express recoverable heat as a percentage of the heat stored in a given subsurface volume:

$$H_R = \sum_{1}^{n} H_i R_{gi} \tag{5}$$

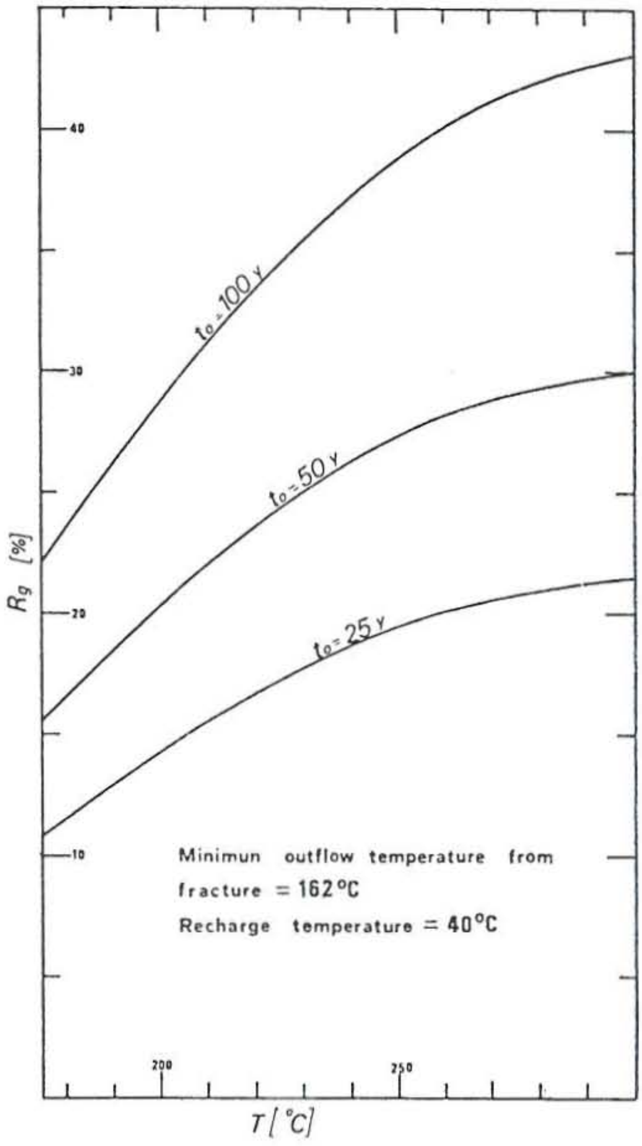

FIGURE 1: Theoretical geothermal recovery factors (heat recoverable divided by heat originally in rock) in % relative to 40°C as a function of original rock temperature and time, for the planar fracture model of Bodvarsson (1974)

The geothermal recovery factor under natural conditions of porosity and permeability ranges up to perhaps 25% in some hydrothermal convection systems, but in most natural systems it is substantially lower, approaching zero in unfractured, impermeable rock. The geothermal recovery factor in most cases is poorly known, and can usually only be estimated subjectively. It depends on many factors, the most important of which seem to be the type of geothermal system under investigation, porosity, the nature of fluid in the pores, reservoir temperature, and extraction technology (Muffler and Cataldi, 1977).

Many authors have estimated the recovery factor by dealing with various idealized reservoirs (Bodvasson, 1974; Nathenson, 1975, Nathenson and Muffler, 1975; Banwell, 1963). The following diagrams (Figures 1, 2, 3 and 4) are from Muffler and Cataldi (1977).

Figure 1 is based on the planar fracture model of Bodvarsson (1974), which is a volume of impermeable rock penetrated by a planar horizontal fracture along which water flows to a well. Assuming a distance of 338 m between adjacent fractures means that the interaction between parallel horizontal fractures is negligible; recovery factors were calculated by Nathenson (1975, 17-18) for different operation life and temperature of the geothermal field. Figure 2 is for an ideal intergranular vaporization of a reservoir initially filled with water. It is based on Figures 11 and 12 of Bodvarsson (1974), the recovery factor was calculated as a function of porosity and temperature. Similarly, Figure 3 was presented by Nathenson (1975), taking 2.5 bar as abandonment pressure of the reservoir for an intergranular flow model (hot-water reservoir). Figure 4 relates the recovery factor to effective porosity. It assumes that the geothermal recovery factor is independent of reservoir temperature (Bodvarsson, 1974; Nathenson, 1975) and a direct linear function of effective porosity.

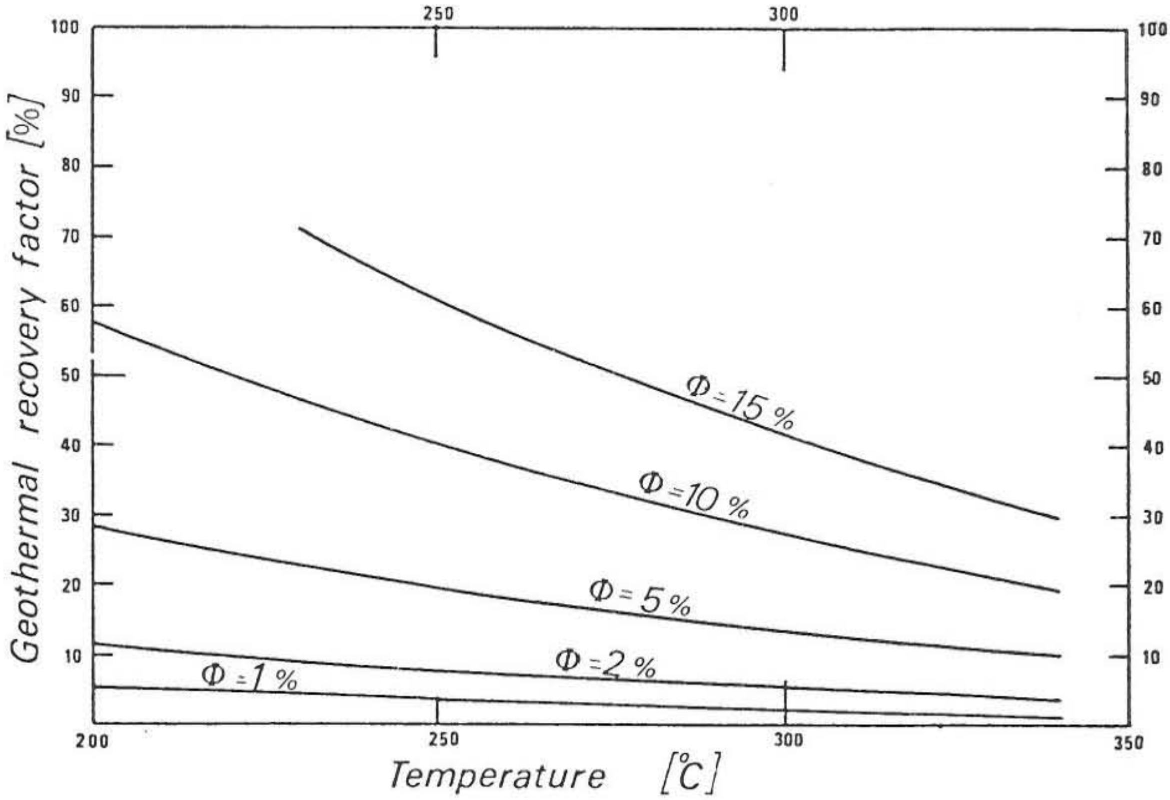

FIGURE 2: Theoretical geothermal recovery factors (heat recovered divided by heat originally in reservoir) in % relative to 40°C as a function of reservoir temperature and porosity

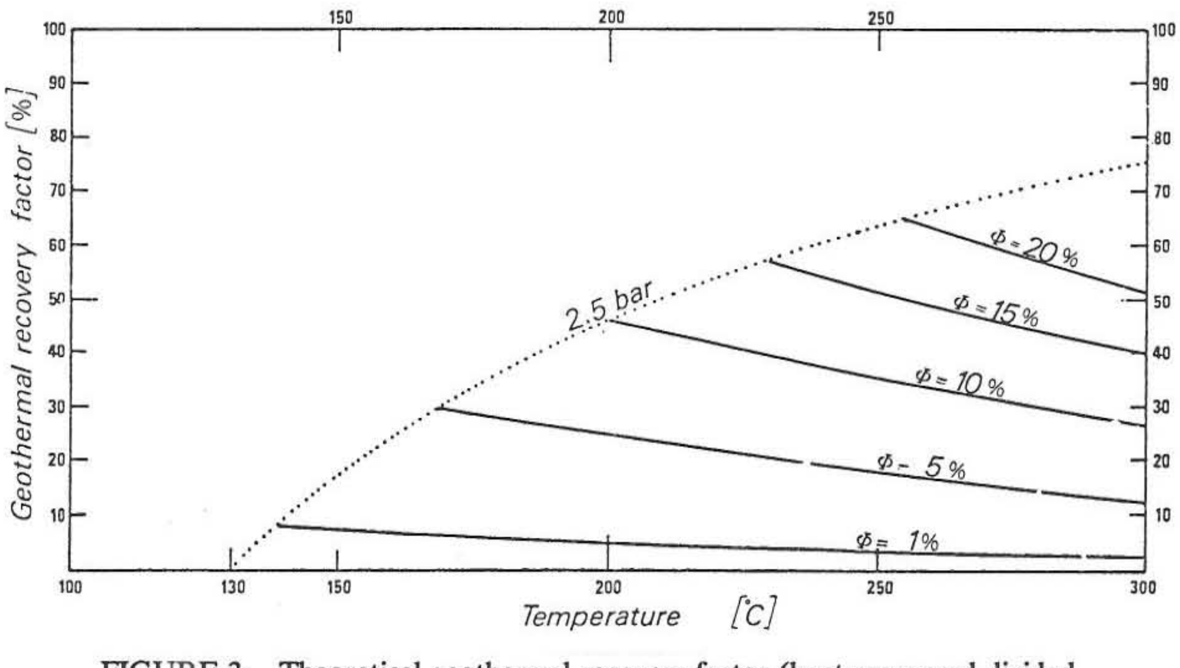

FIGURE 3: Theoretical geothermal recovery factor (heat recovered divided by heat originally in reservoir) in % relative to 15°C as a function of reservoir temperature and porosity

The volumetric method is borrowed from the mining industry where it is used for the estimation of solid ore and petroleum reserves. The method considers the geothermal reservoir as a static, fixed volume without recharges of heat and water, and even if recharges are taken into account, it is still quite subjective. Its advantage is simplicity as minimum data is required. In the virgin geothermal field with only surface data available, the volumetric method is suggested to be preferable in the preliminary stage of the project, and its results can affect the basis for the next steps in the development. The method is rough, and estimates only the quantity of the geological resources and to a limited extent its industrial reserves. It does not give information on production design needed for developing the resource, such as siding of wells, well depth or expected production rate.

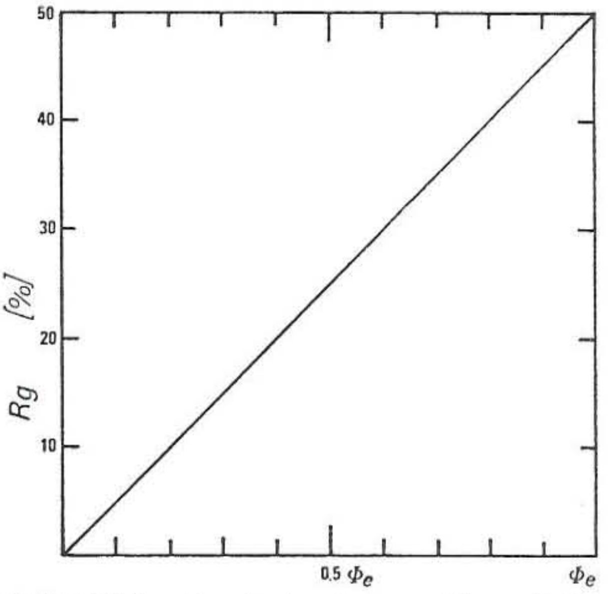

FIGURE 4: Graph showing possible variation of geothermal recovery factor in % as a function of effective porosity for reservoirs producing by a mechanism of intergranular flow.

2.2 The modelling method

Modelling of geothermal systems, as a tool for resource assessment, has grown considerably during the last decades. Modelling, in a broad sense, is the construction of a model, which is designed to represent a simplified version of reality, in essence, the behaviour of the constructed model (system) is made identical with the object simulated in some functions but not all. Then the model can be used to predict the response of the system simulated in time and space. Lastly, the model is used to test proposed management schemes, the optimum extractable quantity of the resource and optimum production schemes. The models can be divided into two broad categories: analog models and mathematical models. The latter will be discussed in more detail here.

The mathematical model is established by investigating the properties of the object system, and parameters of the model are obtained by various fitting technology and from actual measurements. The calibrated model shows similarity in some functions but differs in inner structure from the object system, so prediction by the model can possibly have inherent large errors. Matching with existing data can usually be obtained, but it is difficult to ensure reliable prediction in some cases. In order to ensure the validity of the model for prediction, the model and object system must be as alike in structure as possible. The verification of the model, therefore, becomes important. The general process of calibration and verification is that: the parameters of the model are obtained by fitting part of the available data, such as data on well tests and data on monitoring of the production history, then the validity of the model is checked by comparing the prediction of the model with the other part of the data. If the prediction is reasonable, the model is acceptable, else refinements of the model are needed until the model is feasible. A flow diagram for geothermal resource assessment by the modelling method is shown in Figure 5.

Not all assessments must meet each stage in the diagram due to various reasons. The work indicated by the dashed lines is long-term, dynamic and routine throughout the lifetime of the project on geothermal field exploitation. In practice, the prediction cannot exceed 1.5 times the time span of the data used to calibrated the model.

The modelling method can be subdivided into two methods in terms of the parameter characteristics of the model, the lumped parameter model and the distributed parameter model.

2.2.1 Lumped parameter model

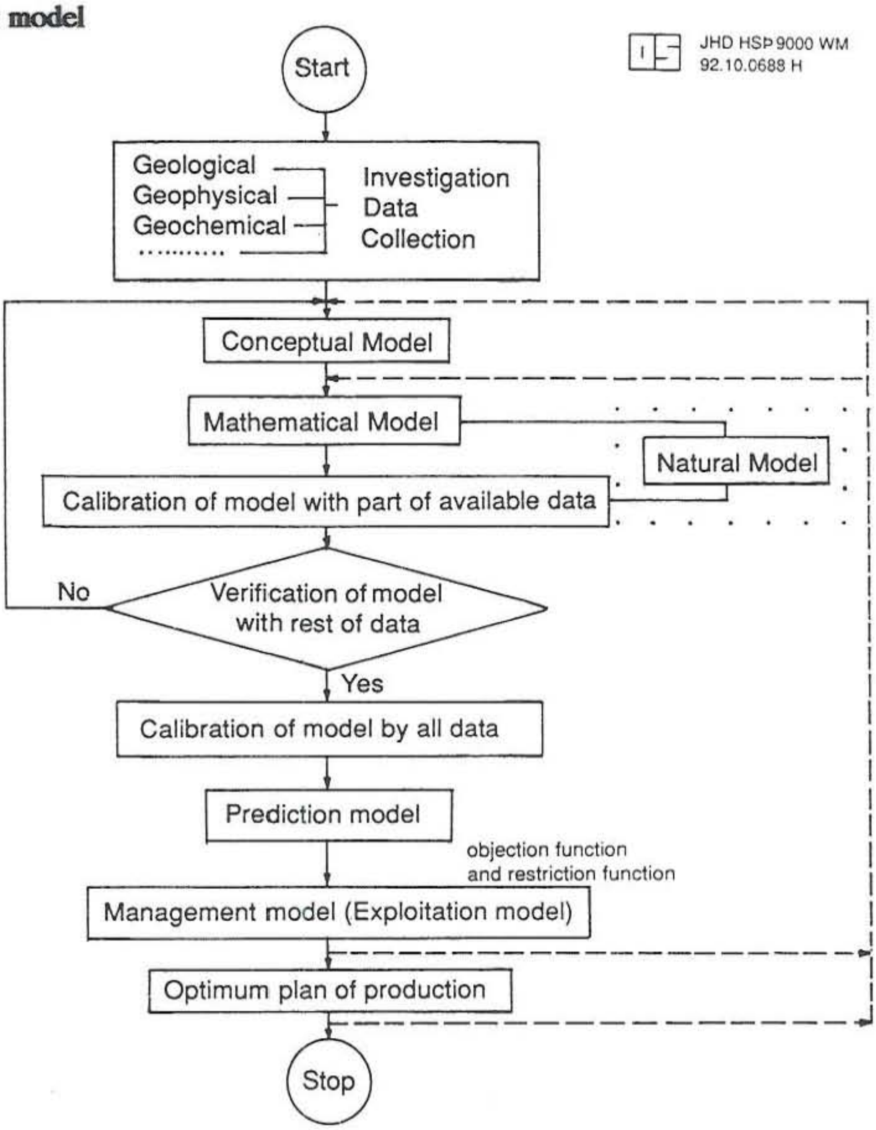

FIGURE 5: Flow diagram of geothermal assessment by the modelling method

The lumped parameter model considers a system as a mathematical point (black box). In other words, properties are the same all over the system, and changes occur simultaneously everywhere within the system. Its basic concerns are the quantitative relationship between input and output of the system regardless of the actual physical properties of the system. Lumped parameter models with two or three blocks are simple distributed parameter models with a coarse spatial discretization in a rigorous sense. There, one of the blocks is used to represent the main reservoir and the other blocks for recharge through a fixed resistance. The governing equation for such a model can often be reduced to ordinary differential equations that can be solved analytically or semi-analytically. The main advantages of lumped parameter models are their simplicity and the fact that they require relatively little time and are not too costly. The lumped parameter model, however, can not describe the distributed characteristics of the various parameters of the geothermal field, such as pressure, temperature, chemical composition and so on. Furthermore, it cannot give information for planning the siding of wells, appropriate well spacing and injection well locations. The lumped model is suitable where or when a limited number of wells have been drilled, some pressure-transient data is available, and when more complex numerical simulation cannot be performed due to finances.

The *P/Z* method or decline curve analysis is a simple lumped parameter model. The *P/Z* method considers the relationship between cumulative produced yield and *P/Z*, in which *P* is the average reservoir pressure and *Z* the gas deviation factor, as a straight line for closed vapour dominated reservoirs. Decline curve analysis only considers the dynamic tendency of the yield with time.

The lumped parameter model used in this report is the programme LUMPFIT version 3.1

developed by Dr. Gudni Axelsson and Dr. Pordur Arason in 1992. The programme simulates pressure response data from liquid-dominated geothermal reservoirs, and is based on an automatic non-linear least-squares iterative inverse technique. The theoretical background of this method were given by Axelsson and Bodvarsson (1987) and Axelsson (1985; 1989).

2.2.2 Distributed parameter model

The distributed parameter model is closer to a realistic system as it considers the change in parameters as a function of time and space. It can be used to simulate in as much detail as desired the characteristics of the various parameters (P, T, Q, etc.) of the geothermal field. It is, therefore, the model that can best evaluate all important reservoir management questions that need to be considered. Its disadvantages are the need for detailed data on the properties of the reservoir; they usually take a great deal of computer time so they can be costly, and they require a minicomputer and experience.

3. ASSESSMENT OF THE GLERARDALUR GEOTHERMAL FIELD

3.1 Geological and geophysical outline

The Glerardalur geothermal field is located in N-Iceland on the western outskirts of the town Akureyri. It is one of the low-temperature fields supplying water to the Akureyri District Heating System. It is sided in a typical Icelandic lava pile of tertiary age, close to 6 m.y. old. West of Akureyri the strike of the lava pile is east-west and its dip is to the south in the range of 3-5°. The basaltic lava at the surface is in the middle of the mesolite/scolesite alteration zone with increasing alteration with depth. Therefore, the basaltic pile is quite dense and of rather low permeability except in a relatively few macroscopic fractures (Flovenz et al., 1984).

The crust in Eyjafjordur is cut by numerous near-vertical dykes and normal faults which are not active any more. The strike of the dykes and the faults is north-south (Figure 6). The geological structure of the Glerardalur field was recognized by surface geological mapping as well as by geophysical surveys. Head-on resistivity profiling was mainly used. The methods indicated anisotropy of the strata (Figure 7).

3.2 Field development and utilization

Before any drilling took place in Glerardalur, the presence of the geothermal reservoir was manifested by several warm springs. By collecting the water from the springs, a discharge of 2.5 l/s was measured. The hydrothermal system itself is not well recognized. The recharge area to the system is probably in the mountains to the southwest of the field and the water migrates along vertical fissures. The hot springs disappeared after production from the wells started.

Most of the wells drilled into the reservoir are shallow exploration wells (100-300 m); only one of them, GY-7, reached the depth of 790 m. Production from the field started in 1982 and currently one well, GY-7, is used for production. The main feed zone in the well is at a depth of 450 m and the temperature of the water is 60°C. Since 1986 production has been stopped for 2-3 months during the summer to reduce the strain on the field and to allow the water level to recover. The water from well GY-7 is pumped directly to the central pumping station in Akureyri.

3.3 Volumetric method

Regional resistivity is higher than 175-200 Ωm. The 100 Ωm line was selected to mark the boundary of the geothermal field for the volumetric assessment, enclosing an area of about 6.5 km^2 (Figure 7).

Input parameters used for the volumetric assessment are shown in Table 1.

TABLE 1: The Glerardalur geothermal field, parameters for volumetric assessment

Lateral area, A	6.5 km^2
Estimated thickness, h	2000 m
Porosity, ϕ	0.06
Mean temperature, T	60°C

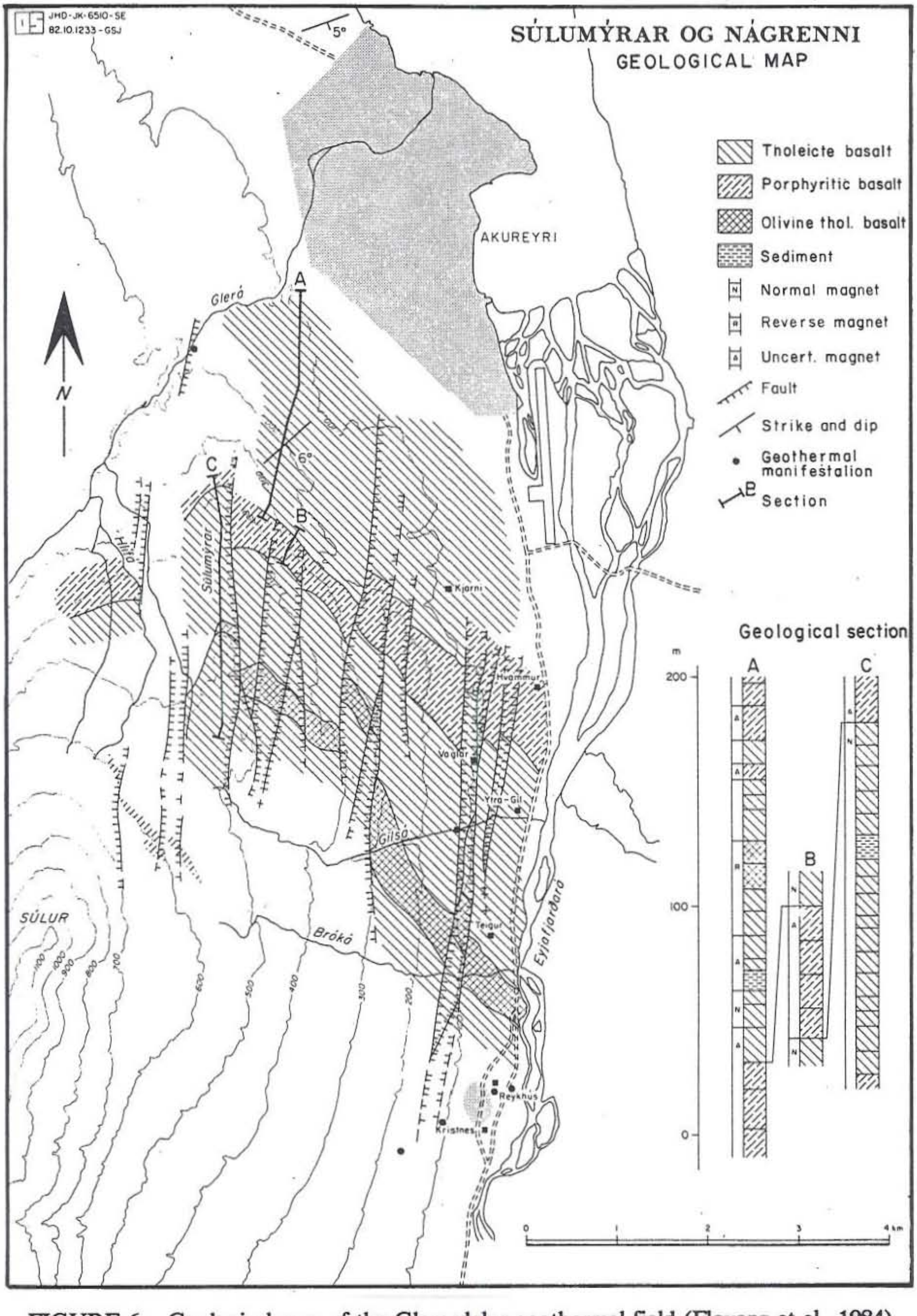

FIGURE 6: Geological map of the Glerardalur geothermal field (Flovenz et al., 1984)

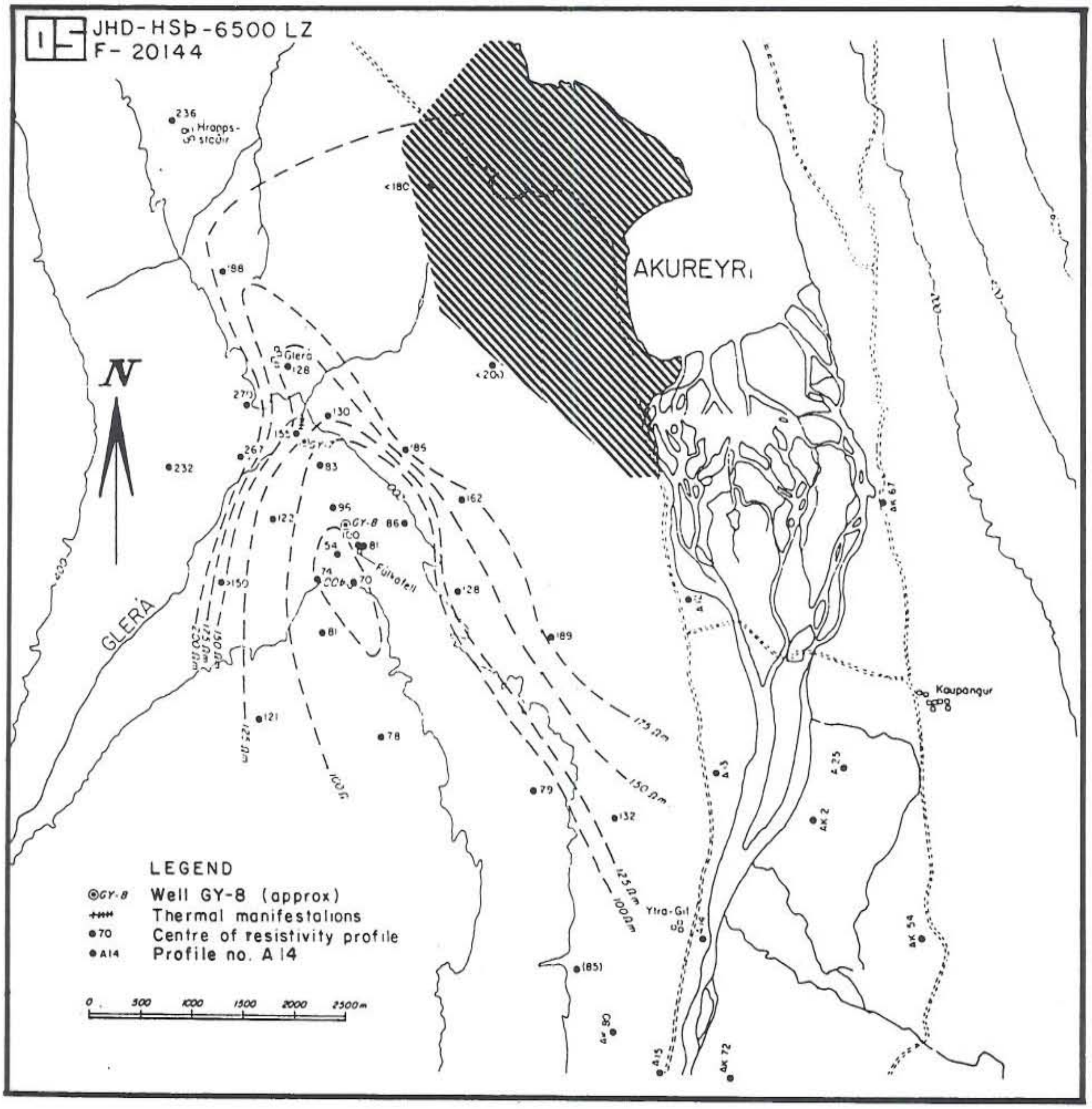

FIGURE 7: Resistivity map of the Glerardalur geothermal field at a depth of 400 m (Flovenz et al., 1984)

The geothermal resource base is calculated by Equation 1. Substituting the values in Table 1 and taking rock density as 2,800 kg/m^3, specific heat of rock as 0.89 kJ/kg°C and assuming reference temperature to be 15° one obtains

$$\begin{aligned} H &= 6.5\times10^{6} \times 2000 \times 0.06 \times 983.12 \times (251.09 - 62.94) \\ &\quad + 6.5\times10^{6} \times 2000 \times 0.94 \times 0.89 \times (60\text{-}15) \times 2800 \\ &= 1.51\times10^{15}\ \text{kJ} \end{aligned}$$

Taking effective porosity as 0.012 (Gladyz, 1991), a recovery factor, *Rg*, of 10% is obtained by using Figure 4. In an actual geothermal field, the value of the recovery factor is lower than for an ideal reservoir, therefore, *Rg* was taken to be 5%. The quantity of heat extractable from the geothermal field was then calculated by Equation 5 as

$$H_R = 1.51\times10^{15} \times 0.05 = 7.55\times10^{13} \text{ kJ}$$

If 15 l/s of the 60°C geothermal water are extracted from the geothermal field, the lifetime of the geothermal field is 646 years.

For low-temperature geothermal fields such as the Glerardalur field, the key factors that control the extractable quantity of the resource are porosity, recharge and the technology of exploitation. For the Glerardalur field, effective porosity is known. Furthermore, for downhole pumping, 200 m can be taken as the extractable depth, as it is reasonable with regard to economics and technology. The quantity of extractable geothermal water depends then on the condition of the system. Here the cases of a closed system and a fully recharged system are discussed as follows.

I. Closed system

Taking 200 m as the depth that can be economically exploited and effective porosity as 0.012 (Gladysz, 1991), the extracted volume of 60°C geothermal water from the field is calculated to be:

$$V_R = 6.5\times10^6 \times 200 \times 0.012 = 1.56\times10^7 \text{ m}^3$$

The corresponding extracted heat is

$$H_R = 1.56\times10^7 \times 983.12 \times 251.09 = 3.85\times10^{12} \text{ kJ}$$

For this case the recovery factor is obtained by the formula

$$Rg = H_R/H = 3.85\times10^{12} / 1.51\times10^{15} = 0.0025 \quad \text{or } 0.25\%$$

The recovery factor for this case is quite small compared to the result for the ideal reservoir. If 15 l/s of 60°C geothermal water are extracted from the geothermal field, its lifetime would be about 33 years. This can be seen later to be close to the lumped modelling result.

II. Recharged system

Assuming that it is not economical to use the hot water for space heating after its temperature has dropped to 55°C, recharge water to the system is at reference temperature. Furthermore, assume that geothermal water is in full contact with the rock and heat exchanges are complete, so that water and rock are at heat equilibrium at all time. When the reservoir temperature has dropped to 55°C the stored heat is calculated by Equation 1 to be:

$$H_{55} = 6.5\times10^6 \times 2000 \times (0.06 \times (230.17\text{-}62.94) \times 985.71 + 0.94 \times 0.89 \times 2800 \times (55\text{-}15)) = 1.34\times10^{15} \text{ kJ}$$

Then the extracted heat is

$$H_R = H - H_{55} = (1.51 - 1.34)\times10^{15} = 1.7\times10^{14} \text{ kJ}$$

In this case the recovery factor is

$$Rg = H_R / H = 1.7\times10^{14} / 1.51\times10^{15} = 0.112 \quad \text{or } 11.2\%$$

If 15 l/s of 60°C geothermal water are extracted the lifetime of the geothermal field would be 1580 years.

The results from these three approaches are very different, therefore, it is clear that it must be associated with specific conditions to determine the extractable quantity of geothermal resources in the volumetric assessment.

3.4 Lumped parameter model

The field is relatively small, its main feed zone is at 450 m depth and the water temperature is 60°C. Most of the wells drilled into the reservoir are shallow exploration wells. At present, only well GY-7 is used for production. Therefore, because of the limited field data, a lumped parameter model is appropriate for the simulation of the Glerardalur field. Production from well GY-7 started in 1982, so a production history of over a decade is available for calibrating the model.

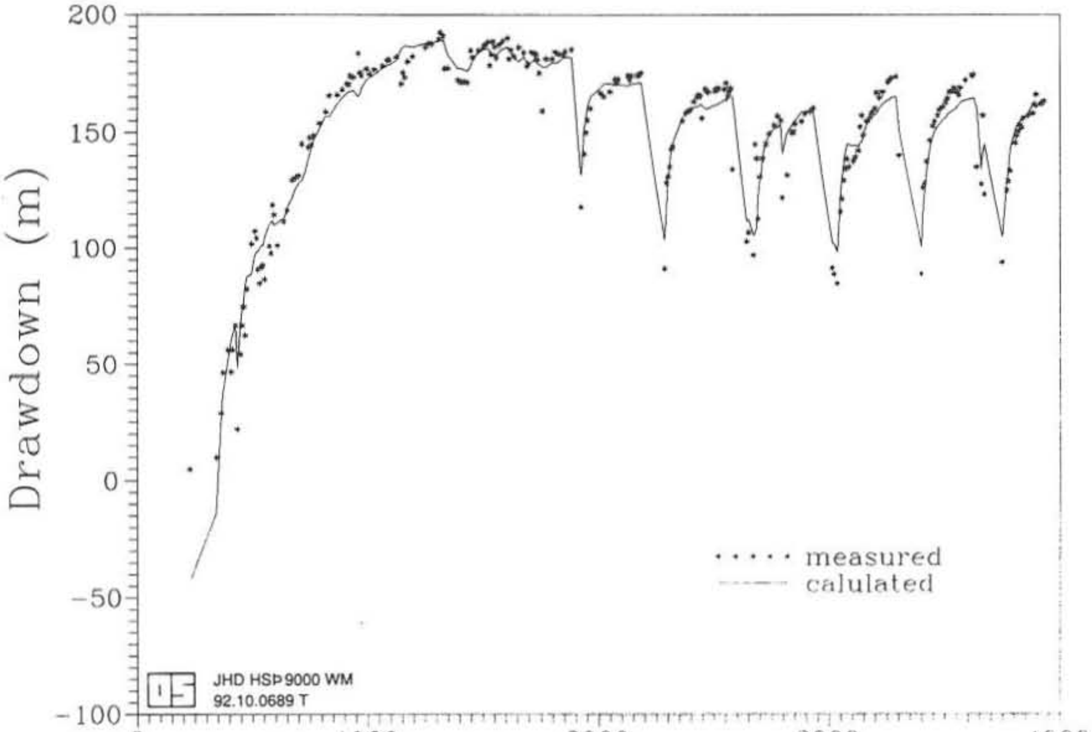

FIGURE 8: The Glerardalur field, the open three tanks model for calibration

Matching was carried out by lumped parameter models with varying complexity until a good fit to the observed data was obtained. Both the model with open three tanks and closed three tanks match quite successfully the production history data from GY-7 (Figures 8 and 9). It was then the task for verification to determine which model more closely fitted the properties of the reservoir. Fitting was conducted with the data for the first five years of the production history,

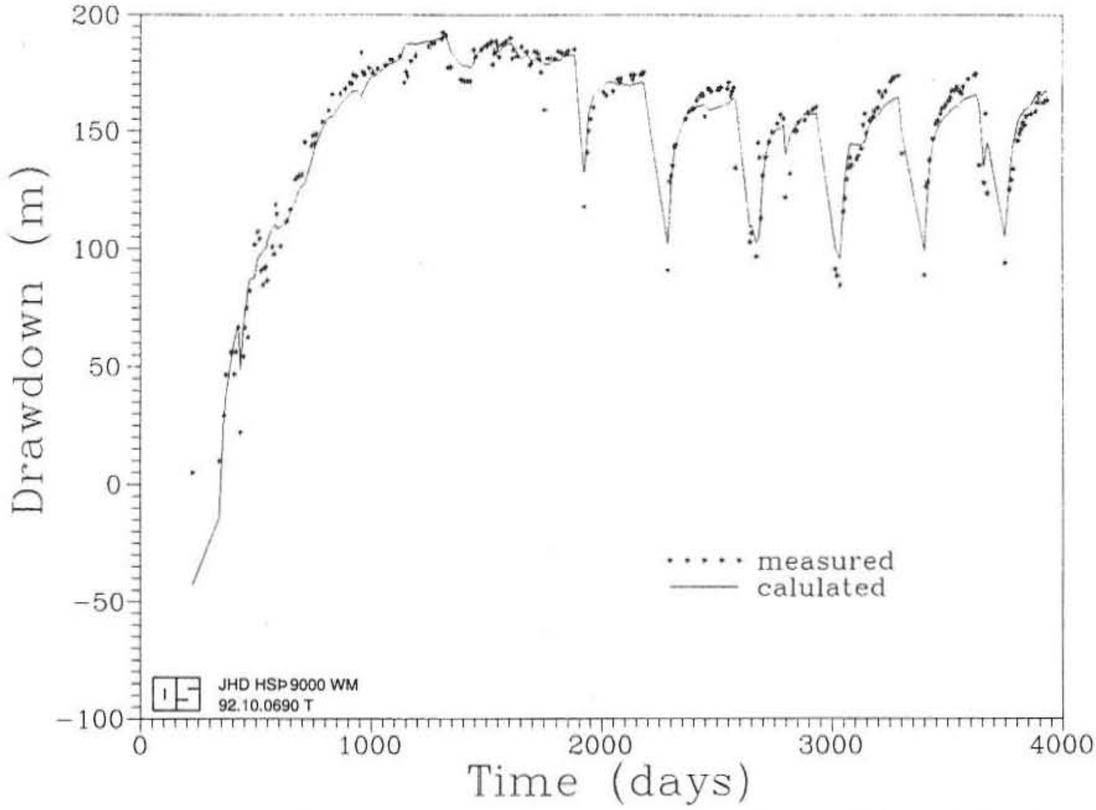

FIGURE 9: The Glerardalur field, the closed three tanks model for calibration

and then the response of the reservoir for the next five years was predicted by the model. The model which best matched the whole data set in that way was then selected. The results are shown in Figures 10 and 11. Left of the dash line is the fitting result, and right of it the result of the prediction. The verification indicates that the closed three tanks model gives a better match than the open three tanks model. Furthermore, it can be seen that the predictions deviate more from the observed data in the tenth year, or in other words, the reliability of the prediction reduces sharply when the time span of prediction exceeds the time span of the data used to calibrated the model. It can be mentioned that the open three tanks model gives a better match than the closed three tanks model if the result of calibration alone is considered. It is, thus, clear how important verification of the model is in order to ensure model reliability.

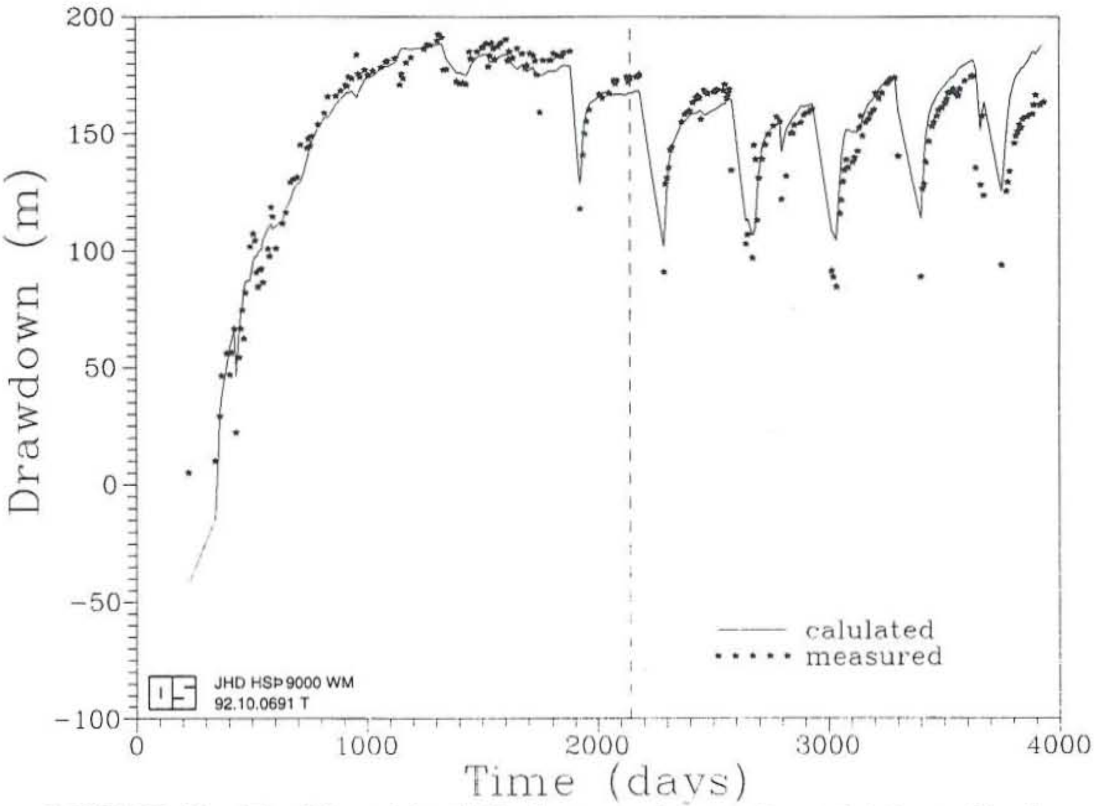

FIGURE 10: The Glerardalur field, the open three tanks model for verification

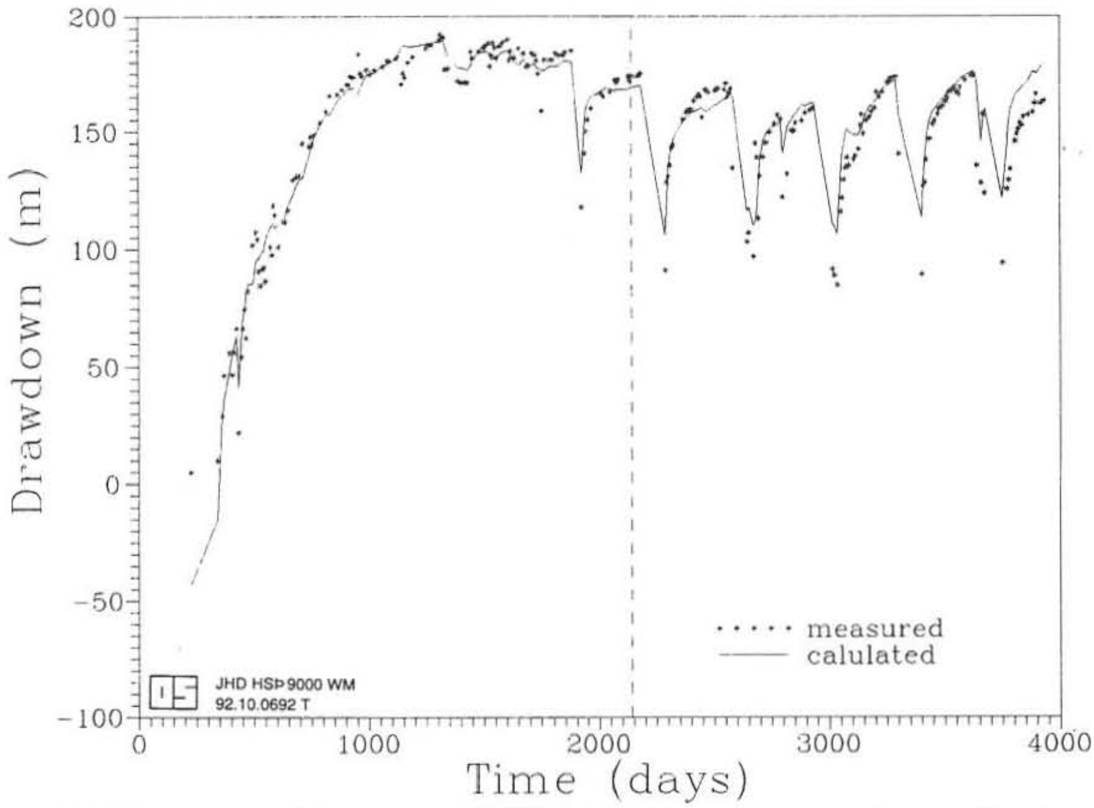

FIGURE 11: The Glerardalur field, the closed three tanks model for verification

4. ASSESSMENT OF THE SVARTSENGI GEOTHERMAL FIELD

4.1 Geological and geophysical outline

The Svartsengi geothermal field, which is classified as high-temperature and liquid-dominated, is among six geothermal fields associated with an active rift zone which is the landward extension of the Mid-Atlantic ridge on the Reykjanes peninsula, SW-Iceland (Figure 12). Above 700 m depth, lava flows which erupted during interglacial periods and hyaloclastites formed during glacial periods are found. Below 800 m depth the proportion of intrusions increases quite sharply to 20-40 %. The formation of cap rock is evident between 300-500 m depth and is attributed to the filling of pore spaces by alteration minerals and the absence of intrusives. The high permeability within the reservoir is thought to result from near-vertical intrusions and fractures. Hydrothermal surface manifestations are evident in an area of about 4 km^2.

The results of resistivity surveys from the outer Reykjanes Peninsula, including the Svartsengi field, indicate that rocks penetrated by geothermal brine show resistivity of 2-5 Ωm, compared to 6-15 Ωm in the cold brine outside the fields. Using the 5 Ωm resistivity line to define the geothermal field, an area of about 10 km^2 was delineated (Georgsson, 1984). The surveys show that the Svartsengi resistivity anomaly extends in a westerly direction toward the Eldvorp field (Figure 13).

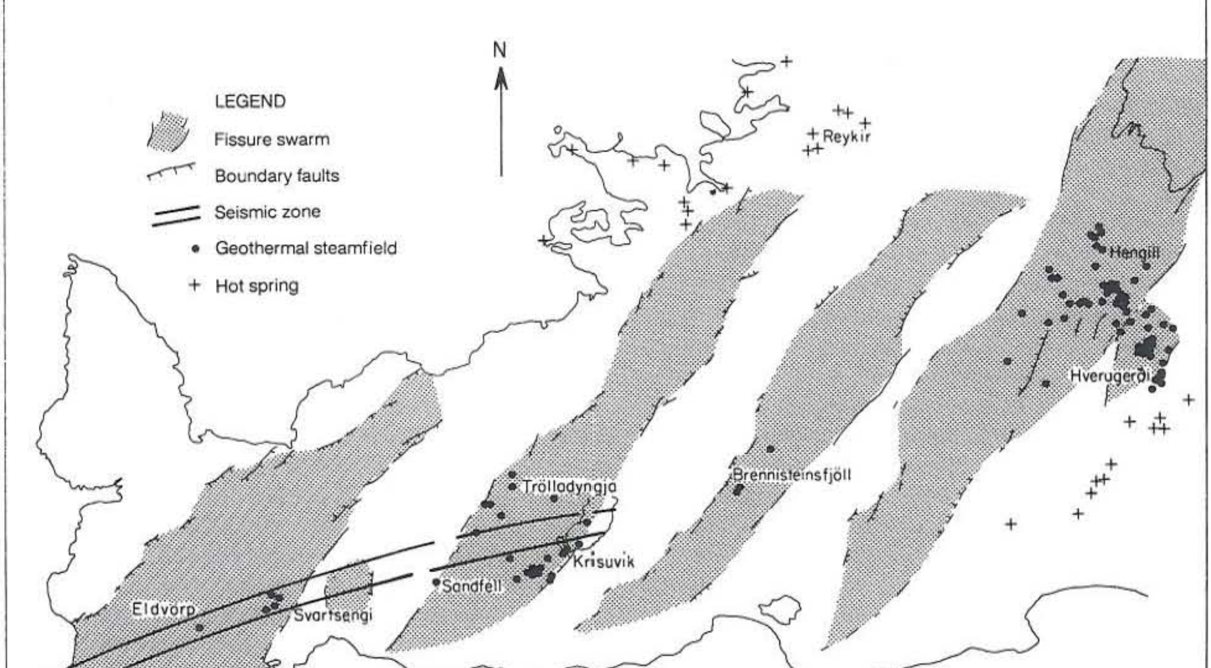

FIGURE 12: The high-temperature fields on the Reykjanes Peninsula and their geological features

4.2 Field development and utilization

The Svartsengi field has been developed by the Sudurnes Regional Heating Company, which provides district heating services to the local communities. The power plant has been operating since 1976. The two-phase mixture produced by the wells is piped to the power plant and used in a heat exchange process to produce hot water. This is done by heating and degassing fresh cold water. At present, the capacity of the plant is 125 MW_t and 11.6 MW_e. The total mass produced from the reservoir amounts to more than 80 million metric tons and the average rate of production is presently around 230 kg/s. In order to maintain the pressure in the reservoir, injection needs to be carried out.

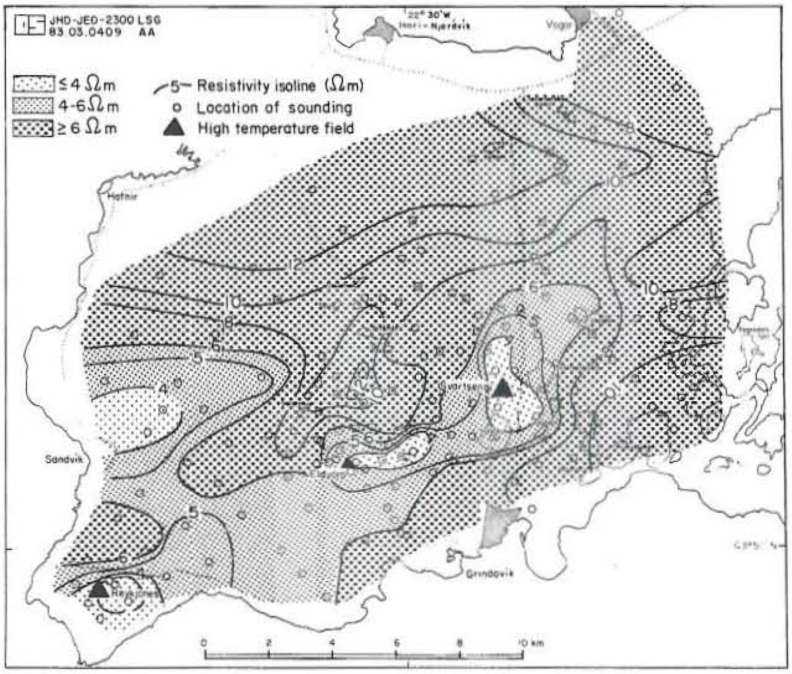

FIGURE 13: The resistivity of the Outer Reykjanes Peninsula at 400 m depth below sea level (Georgsson, 1984)

4.3 Volumetric method

According to earlier work and a conceptual model (Gudmundsson and Thorhallsson, 1986), the Svartsengi field has high permeability and connectivity. An almost uniform 230-240°C temperature reservoir exists below 600 m depth down to 2000 m. Using the 5 Ωm resistivity contour to define the field (Georgsson, 1984), the area of the reservoir is about 10 km^2. The reservoir can be divided into two parts, the part below 600 m depth, which is a liquid-dominated uniform 235°C reservoir, and the part above 600 m to the surface, in which there is lower porosity and permeability, and the heat transport in natural state is conductivity-dominated. The parameters used for the volumetric assessment are shown in Table 2.

TABLE 2: The Svartsengi geothermal field, parameters for volumetric assessment

	Upper part	Deeper part
Lateral area, A	10 km^2	10 km^2
Thickness, h	600 m	1400 m
Porosity, ϕ	0.001	0.1
Mean temperature, T	140°C	235°C

Looking at Figures 2 and 3, the theoretical recovery factors for the upper and deeper parts are 6% and 45%, respectively. Considering realistic geothermal field conditions, the recovery factors of the upper and deeper parts are taken to be 3% and 20%, respectively. The total heat stored and extracted heat from the geothermal field are calculated by Equations 1, 4 and 5, respectively:

$$H_{upper} = 10\times10^6 \times 600 \times [0.001 \times (589.1 - 62.94) \times 925.8 + 0.999 \times 0.89 \times (140 - 15) \times 2800] = 1.87\times10^{15} \text{ kJ}$$

$$H_{deeper} = 10\times10^6 \times 1400 \times [0.1 \times (1013.8 - 62.49) \times 820.5 + 0.9 \times 0.89 \times (235-15) \times 2800] = 8.0\times10^{15} \text{ kJ}$$

$$H_{total} = H_{upper} + H_{deeper} = 9.87\times10^{15} \text{ kJ}$$

$$H_R = H_u \times Rg_u + H_d \times Rg_d = (1.87 \times 0.03 + 8.0 \times 0.2) \times 10^{15} = 1.43\times10^{15} \text{ kJ}$$

The limiting factors which control the recovery factor are porosity, the nature of the fluid, extraction technology and possible recharge to the Svartsengi field. Similarly, as before, the recoverable quantity for the cases of a closed system and a fully recharged system are calculated. In those cases only the reservoir between 600 m and 2000 m was considered, but not the caprock.

I. Closed system

Assume that wells will not flow when reservoir pressure has dropped down to 11 bara in the reservoir (corresponding to saturation temperature of 185°C). In the natural state the reservoir is overpressured, so first mass can be taken out of the reservoir by reducing the pressure from 78 bar (natural state) to 30.6 bar (saturation state for average reservoir temperature of 235°C). The mass withdrawal is calculated by the following formula, taking the compressibilities of water, c_w, and rock, c_r, as 5×10^{-10} Pa^{-1} and 1.5×10^{-11} Pa^{-1}:

$$M = Ah\rho_w(\phi c_w + (1-\phi)c_r)(P_1 - P_2) \tag{6}$$

or

$$M = 10\times10^6 \times 1400 \times 820.5 \times (0.1 \times 5\times10^{-10} + (1 - 0.1) \times 1.5\times10^{-11}) \times (78 - 30.6) \times 10^5 = 3.46\times10^9 \text{ kg}$$

The corresponding heat withdrawn is

$$H_{op} = MH_w = 3.46\times10^9 \times 1013.8 = 3.51\times10^{12} \text{ kJ}$$

Secondly, heat is withdrawn as steam when the reservoir changes from a 235°C saturated liquid-dominated condition to a 185°C vapour-dominated condition. Considering the balances of mass and energy in an unit volume, the following formulas were obtained:

$$M_s = \phi(\rho_{w1} - (S\rho_{s2} + (1-S)\rho_{w2})) \tag{7}$$

$$(1-\phi)C_r\rho_r(T_1 - T_2) + \phi\rho_{w1}H_{w1} - \phi\rho_m H_m = M_s H_{s2} \tag{8}$$

where

$$\rho_m = S\rho_{s2} + (1-S)\rho_{w2} \tag{9}$$

$$H_m = (S\rho_{s2}H_{s2} + (1-S)\rho_{w2}H_{w2}/\rho_m \tag{10}$$

The subcripts "1" and "2" refer to the initial and terminal states of the system, respectively. Solving for volumetric steam fraction, S, gives

$$S = 1 - [(1-\phi)C_r\rho_r(T_1 - T_2) + \phi\rho_{w1}(H_{w1} - H_{s2})]/[\phi\rho_{w2}(H_{w2} - H_{s2})] \tag{11}$$

Substituting for known parameters and fluid properties from steam tables, S was obtained as

$$S = 0.183$$

So, mass recovered as steam, M_g, during the boiling process is then calculated in the following way:

$$M_s\, V = 10{\times}10^6 \times 1400 \times 0.1 \times \{(820.5 - (0.813 \times 5.75 + (1 - 0.813) \times 881.52)\}$$
$$= 9.11{\times}10^{11}\ \text{kg}$$

The corresponding heat withdrawn is

$$H_{Bo} = M_s\, V\, H_{s2} = 9.11{\times}10^{11} \times 2780.4 = 2.53{\times}10^{15}\ \text{kJ}$$

Lastly, the total recoverable heat from the closed system under the specified conditions equals the sum of the above two parts:

$$H_R = H_{op} + H_{Bo} = 2.533{\times}10^{15}\ \text{kJ}$$

The heat due to elastic releasing of mass is so small in comparison with the mass recovered in the boiling process that it can be ignored. The recovery factor in this case is

$$Rg = H_R\, /\, H = 25.6\%$$

II. Recharged system

As the reservoir brine is used with heat exchangers to produce hot water for space heating it is assumed that the reservoir can be used down to 130°C. Assuming recharge temperature to be at reference temperature, and no pressure decline, the reservoir will be liquid-dominated. Similarly, the extractable heat can be calculated in the following manner:

$$H_{130} = 10{\times}10^6 \times 1400 \times (0.1 \times (546.31 - 62.94) \times 934.58 + 0.9 \times 0.89 \times (130\text{-}15) \times 2800) = 4.24{\times}10^{15}\ \text{kJ}$$

and

$$H_R = H_{235} - H_{130} = 3.76{\times}10^{15}\ \text{kJ}$$

This gives the recovery factor as

$$Rg = 38\%$$

4.4 Lumped parameter model

All of the 11 wells drilled in the Svartsengi field have been productive. Fluid extraction and reservoir drawdown have been monitored since the start of production in 1976, and up to the present. Therefore, production history data over a fifteen year period is available for calibrating the model. The total production rates of the 11 wells are taken for the production from the reservoir, and the pressure at 900 m depth is taken to represent the reservoir pressure response.

Two models, one with closed two tanks and one with open two tanks, give good matches (Figures 14 and 15). The models were calibrated using the data for the first 7.5 years. Predictions for the reservoir response were also given for the next 7.5 years. The results are shown in Figures 16 and 17. There is very little difference between the two models. It is difficult, therefore, to determine

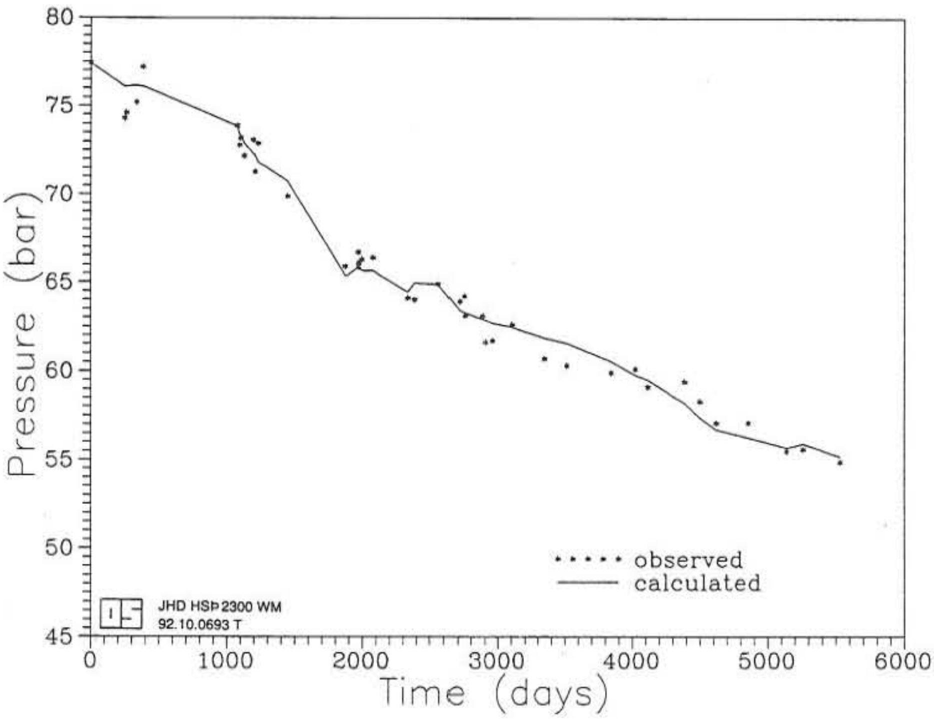

FIGURE 14: The Svartsengi field, the closed two tanks model for calibration

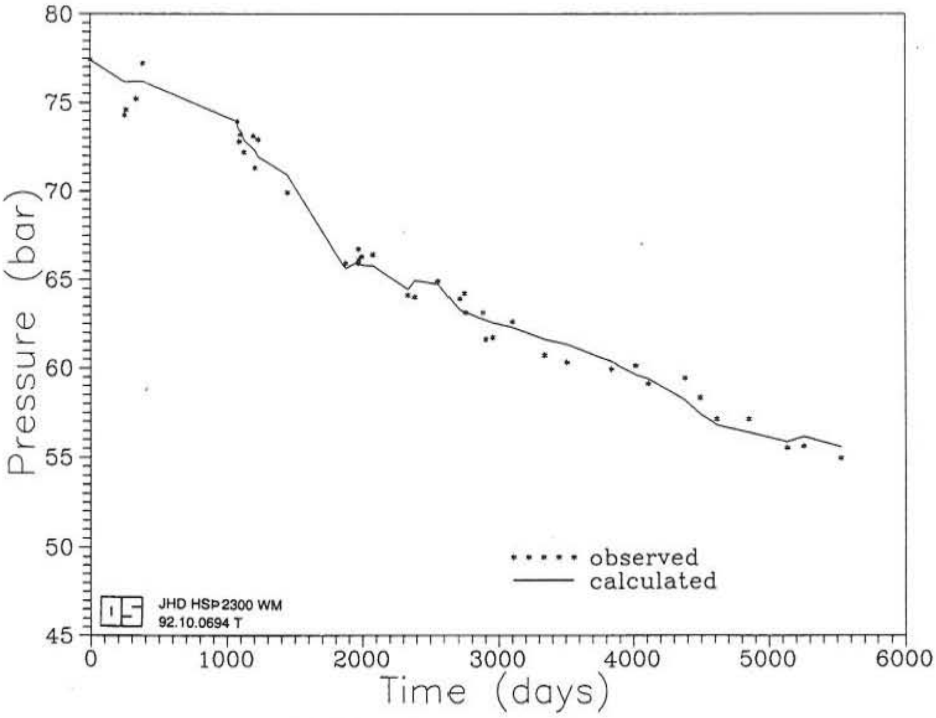

FIGURE 15: The Svartsengi field, the open two tanks model for calibration

which model is more appropriate for modelling the reservoir considering only the matching results. In this case, the results of geological and geophysical surveys should be used for choosing between the models. As mentioned earlier, the Svartsengi field is located in an active rift zone and cut by fissure swarms and large faults; the reservoir has high permeability and connectivity. Furthermore, it is possible that the Svartsengi field is linked up with the Eldvorp field about 5 km south from the Svartsengi field. Resistivity surveys could confirm that. The analysis of the produced fluids, composed of two-thirds seawater and one-third rainwater, indicates that the reservoir is open to the sea. As a result, the open two tanks model was selected for the simulation of the reservoir.

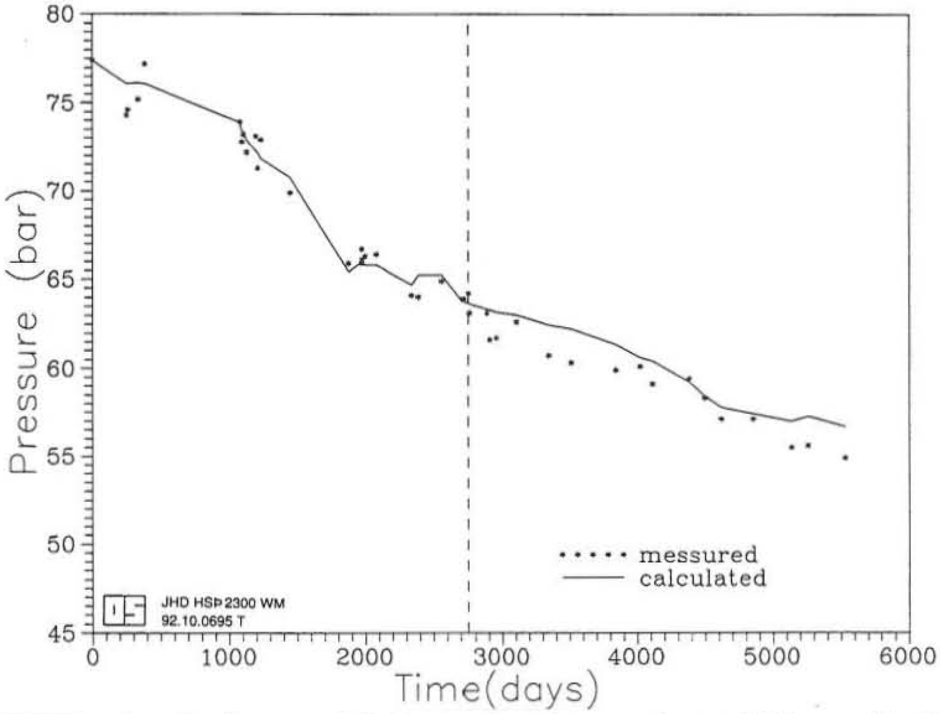

FIGURE 16: The Svartsengi field, the closed two tanks model for verification

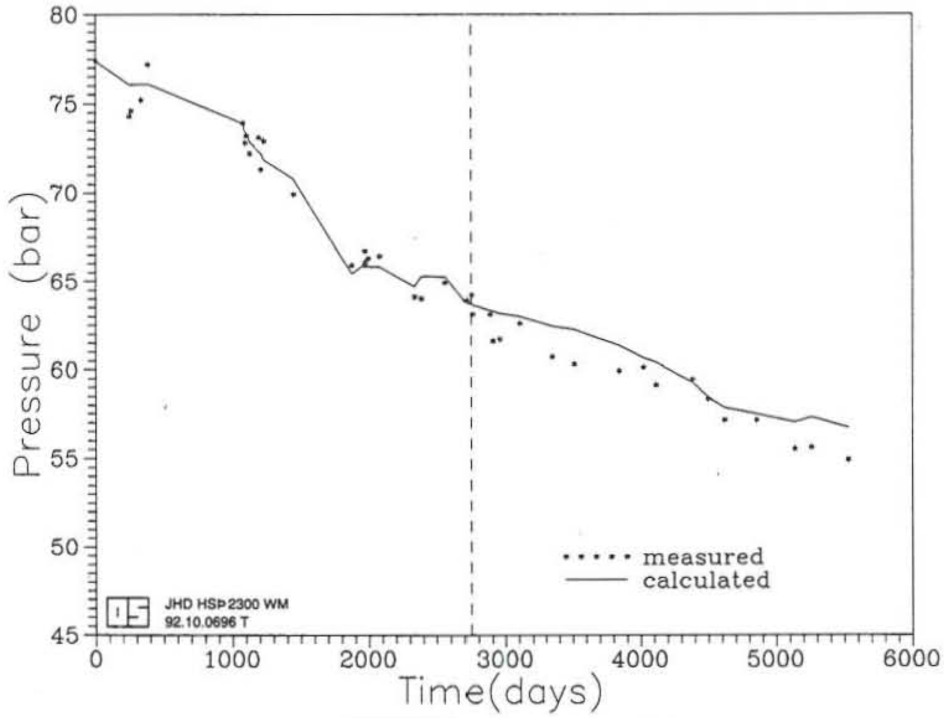

FIGURE 17: The Svartsengi field, the open two tanks model for verification

5. DISCUSSION AND CONCLUSIONS

5.1 Discussion on the properties of the reservoirs

For the Glerardalur field three recovery factors, 10% (was discounted to 5%), 0.25% and 11.2%, were obtained for an intergranular flow model, closed system and recharged system. It is clear from the span of the recovery factor that it can differ much depending on the production technology and nature of the system. Comparing the result to the lumped modelling result, the factor 0.25% for the closed system gives comparable results. For the Svartsengi field three recovery factors, 45% (was discounted to 20% in the practical calculation), 25.6% and 38%, were obtained for ideal intergranular vaporization of a reservoir initially filled with water, closed system and recharged system. Due to high effective porosity, high temperature and the different nature of the system, the recovery factors are all larger than for the Glerardalur field. Considering the geological condition of the Svartsengi field, the reservoir can be assumed to behave closely to ideal case of intergranular vaporization of a reservoir initially filled with water. Therefore, the recovery factor for the recharged system, 38%, can be assumed to give an estimate for the recoverable energy from that system.

Considering the fitting results in Figures 9 and 15, one sees that the match between observed and calculated values is quite satisfactory. The parameters of the models in Table 3 reflect clearly the very different productivity of the two fields. The model for the more productive field has a higher total capacity (storage) as well as higher conductivity (permeability) values.

TABLE 3: Parameters of the best fitting lumped models

	κ_1 (ms^2)	κ_2 (ms^2)	κ_3 (ms^2)	σ_{12} (10^{-5} ms)	σ_{23} (10^{-5} ms)
Glerardalur field	83.4	588	6913	3.63	1.43
Svartsengi field	876	58893		27.8	8.59

The Svartsengi field, which is very productive, has the high capacity. The total capacity as well as the conductivity values, are an order of magnitude greater for the Svartsengi field than for the Glerardalur field.

Capacity in a liquid-dominated geothermal system can result from two types of capacity effects, storage or releasing mechanism. In the first case, the capacity may be controlled by liquid/formation compressibility, the capacity of a capacitor in a lumped model is then given by

$$\kappa = V \rho c_t \tag{12}$$

In the other case, the capacity may be controlled by the mobility of a free liquid surface. Then

$$\kappa = A \phi / g \tag{13}$$

Analysis based on the above two equations indicates that the Glerardalur field and the Svartsengi field are likely to have connected free liquid surface mobility, since their area is expected to be less than 10 km^2. Otherwise, based on their capacity, their area would be more than 1000 km^2, which is too large to accept.

The effective porosity can be estimated from Equation 13 and parameters in Tables 1 to 3. The estimated effective porosities are 0.012 for the Glerardalur field and 0.06 for the Svartsengi field, respectively. Those porosities are close to the values that were selected in the volumetric assessment.

5.2 Future prediction of the reservoirs' responses

The main objective of modelling a geothermal system is to assess its potential. After calibration and verification the models were used to predict the pressure change (waterlevel drawdown) in the reservoirs for different cases of future production. so that optimum production rates can be selected. The results of the predictions are shown in Figure 18 for well GY-7 at Glerardalur and Figure 19 for the Svartsengi field, respectively. It is possible to ensure normal operation of the geothermal fields for the next fifteen years, that is, keep their pressure drawdown close to present limits if the average production rates do not exceed 15 l/s for the Glerardalur field and 200 kg/s for the Svartsengi field, respectively.

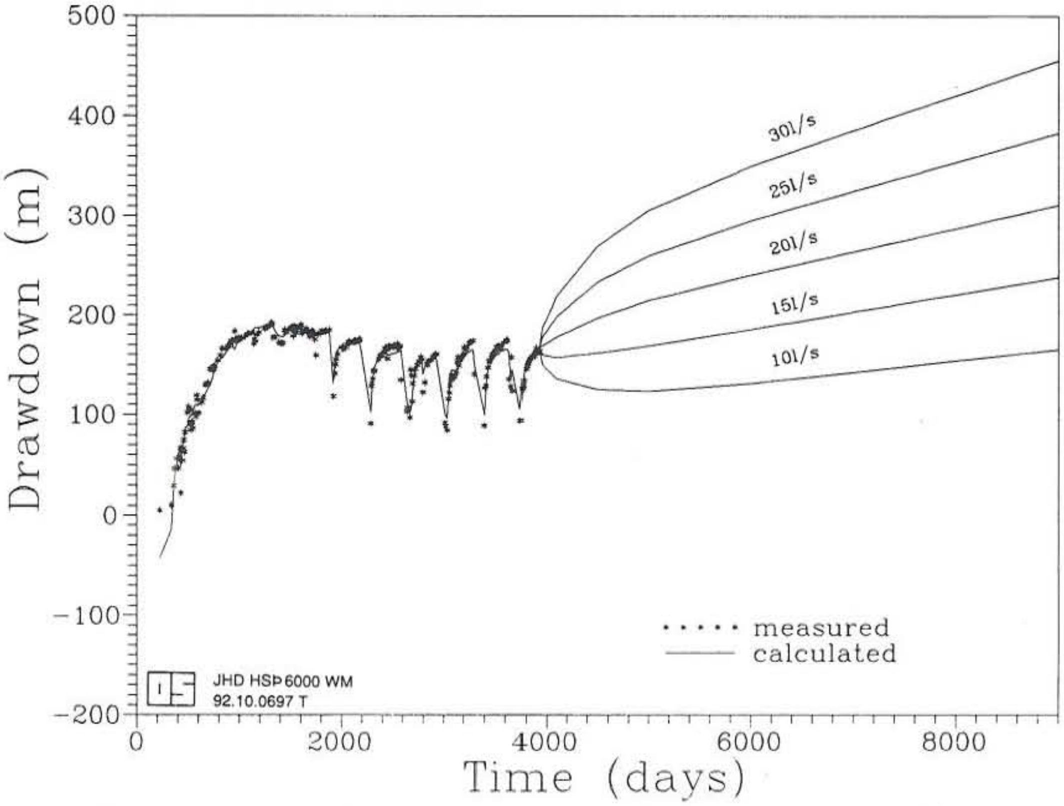

FIGURE 18: Drawdown predicted for the Glerardalur geothermal field

5.3 Conclusions

1. The volumetric method is useful in the first stage of a project for geothermal assessment because of scarcity of data, but it should be supplemented with modelling studies as data on the geothermal field is accumulated.

2. The quantity of the resource that is extractable relies on the production technology available. It is, therefore, associated with specified.conditions when determining the

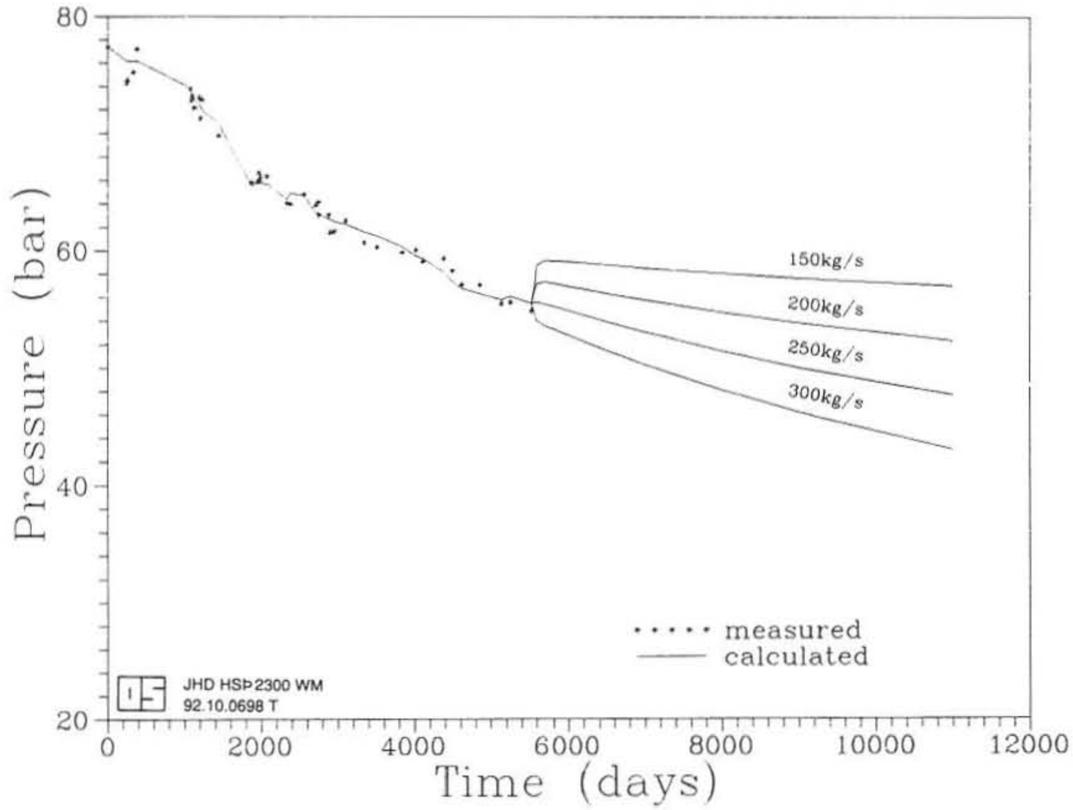

FIGURE 19: Pressure predicted for the Svartsengi geothermal field

extractable quantity of a geothermal resource in the volumetric assessment.

3. For the Glerardalur field the resource base is estimated as 1.51×10^{15} kJ by the volumetric assessment. The extractable quantity is 3.85×10^{12} kJ for the closed system and 1.7×10^{14} kJ for the recharged system under the specified exploitation methods.

4. For the Svartsengi field the reservoir was divided into upper and deeper parts for the volumetric assessment. The resource base is estimated as 9.87×10^{15} kJ. The extractable quantity is 2.533×10^{15} kJ for the closed system and 3.76×10^{15} kJ for the recharged system under the specified exploitation methods.

5. Verification of a numerical model is very important for ensuring its prediction reliability in a modelling study.

6. For lumped parameter modelling the closed three tanks model was selected for the Glerardalur field and the open two tanks model for the Svartsengi field after verification of the models.

7. It is possible to ensure normal operation for the next fifteen years if the average production rates do not exceed 15 l/s for the Glerardalur field and 200 kg/s for the Svartsengi field, respectively.

8. The storage mechanisms of both geothermal fields considered here are probably due to free liquid surface mobility.

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NOMENCLATURE

A - surface area of geothermal reservoir (m^2)
C_{ir} - mass specific heat of i element rock ($kJ/m^{3\circ}K$)
C_{vi} - mean volumetric specific heat of i element rock and water ($kJ/m^{3\circ}K$)
C_{iw} - mass specific heat of i element water ($kJ/m^{3\circ}K$)
c_t - total compressibility of formation (Pa^{-1})
g - acceleration due to gravity (m/s^2)
h - thickness of reservoir (m)
H - total heat in geothermal reservoir (kJ)
H_i - heat stored in i element (kJ)
H_m - enthalpy of water and steam mixture
H_{iw} - enthalpy of water contained in i element (kJ/kg)
H_{ow} - enthalpy of water at reference temperature (kJ/kg)
H_R - heat extractable from geothermal reservoir (kJ)
Rg_i - recovery factor of i element (%)
S - volumetric fraction of steam
T_i - temperature of i element (°C)
T_o - reference temperature (°C)
V_i - volume of i element (m^3)

ρ_m - density of water and steam mixture
ρ_w - density of water (kg/m^3)
ρ_r - density of rock (kg/m^3)
ϕ - porosity of geothermal reservoir
κ_i - capacity of i block (ms^2)
σ_{ik} - conductor between blocks i and k (ms)

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