PROCEEDINGS, TOUGH Symposium 2003
Lawrence Berkeley National Laboratory, Berkeley, California, May 12–14, 2003

# DEVELOPMENT OF A 3-D GEOTHERMAL RESERVOIR MODEL FOR THE GREATER HENGILL VOLCANO IN SW-ICELAND

Grimur Bjornsson*, Arnar Hjartarson*, Gudmundur S. Bodvarsson+ and Benedikt Steingrimsson*

*Orkustofnun, GeoSciences, Grensasvegur 9, IS-108 Reykjavik, Iceland
+Lawrence Berkeley National Lab, 1 Cyclotron Road, Mail Stop 90R1116, Berkeley, CA 94720, California, USA

e-mail: grb@os.is, arh@os.is, GSBodvarsson@lbl.gov, bs@os.is

## ABSTRACT

In the year 2001 Reykjavik Energy decided to expand an existing high-temperature geothermal reservoir model to fully cover the ~110 km$^2$ low-resistivity and high-temperature anomaly, associated with the Hengill volcanic system in SW-Iceland. Thereby, virtually all available surface and subsurface data in the region have been integrated into one and the same numerical model. The model development is a major task and is supported by inverse modeling (iTOUGH2) and parallel computing on a multi-node Linux cluster. The first phase of the modeling effort was completed in June 2002. The existing Nesjavellir model properties were integrated into the new model and natural state and production data matched. Consequently, several future production scenarios were studied in order to address the feasibility of expanding the Nesjavellir unit. At present we are focusing on the Hellisheidi area, where the aim is to develop the numerical model in parallel with drilling activities. This effort may, optimally, speed up the decision process on additional power plant development in the region.

## INTRODUCTION

The vast geothermal system of the Hengill volcano in SW-Iceland is currently considered a potential resource for future electrical and heating needs for the city of Reykjavik and surroundings. Reykjavik Energy is currently operating a 90 MW electric and 200 MW thermal unit in the Nesjavellir field. Recently, 7 deep production wells have been drilled to the south of the Hengill volcano to explore the Hellisheidi area. Numerical reservoir modeling has been considered an integral part of the field development and management strategy. The Nesjavellir field was initially modeled in 1986 and the model has, furthermore, been recalibrated several times as more production and drilling data became available. This effort is considered a success, as the model has repeatable been able to forecast accurately the field response to production.

Figure 1 shows the study area to be presented in this paper. The Hengill volcanic system lies on the plate boundary between the North America and the European crustal plates. These plates are diverging at a relative motion of 2 cm/year. The rifting of the two plates has opened a NNE trending system of normal faults and frequent magma intrusions. This rift zone is also highly permeable and numerous fumaroles and hot springs are found on surface. The Hengill volcanic system is currently active while its predecessor, the Hveragerdi system, is now extinct in terms of volcanic activity but still very active seismically and hosts lively geothermal reservoirs. Three wellfields have been developed within the greater Hengill area: 1) Nesjavellir where the 90 MW power plant is currently in operation, 2) Hellisheidi where a resource assessment is underway and 3) Hveragerdi where the geothermal resource is utilized by the local community.

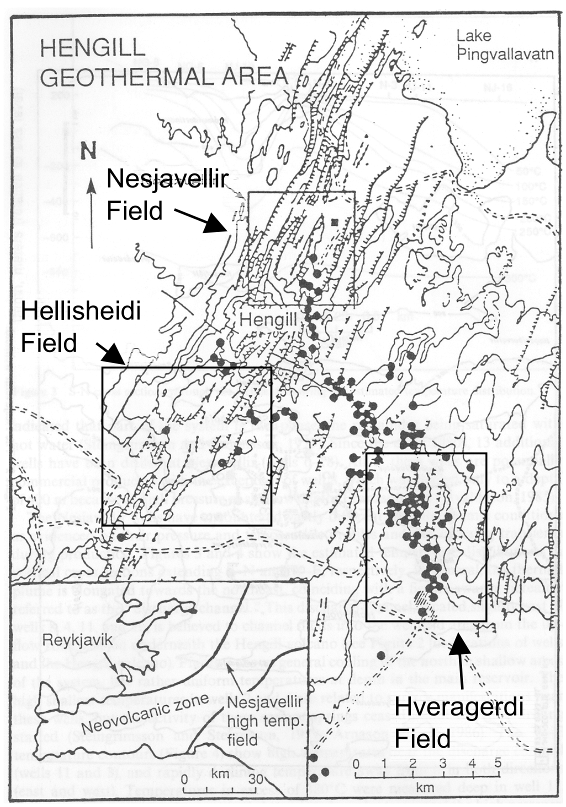


*Figure 1. Location of the Hengill volcano and the Nesjavellir, Hellisheidi and Hveragerdi subfields. Hot springs and fumaroles are shown by bullets (•) and major faults by tagged lines (from Bodvarsson et al., 1990).*

Due to an increased demand for thermal and electrical power in the Reykjavik area, Reykjavik Energy plans to commission new power units in the Hengill area around 2006-2010. As a part of this strategy, many geoscientific surveys have already been carried out and a few exploration wells drilled. Based on these data, the Geosciences Division of Orkustofnun (the Icelandic National Energy Authority) has been contracted to develop a full size geothermal reservoir model of the large-scale Hengill volcano. This modeling effort is at present well into the calibration phase, and has already provided some valuable conclusions. In this paper we give a brief summary of the previous geothermal exploration, the field development and reservoir modeling in the Hengill area. We present a revised conceptual reservoir model, describe the new numerical model that simulates the conceptual model, address some lessons learned during its calibration process on a multi-processor Linux cluster and, finally, show some predictions made for the Nesjavellir field.

## FIELD DEVELOPMENT AND DATA SOURCES

The geothermal fields around the Hengill volcano have been studied extensively from as early as 1947. Initial work focused on geological, geophysical and geochemical sampling, which led to the drilling of a few shallow exploratory wells. Based on these, a 30 MW electrical unit was proposed in the Hveragerdi region while pumping of hot water to Reykjavik was considered uneconomical at that time (Bodvarsson, 1951). Neither came to reality. More wells have, however, been drilled in Hveragerdi as a spin-off from the initial exploration phase.

The Reykjavik Municipal District Heating (later Reykjavik Energy) purchased land rights in the Nesjavellir field in the early sixties and drilled 5 exploratory wells between 1965 and 1972. The drilling proved the existence of a high-temperature geothermal reservoir. Another 13 production wells were drilled between 1980 and 1986 that yielded sufficient flow of steam and separate to commission a 100 MW thermal power plant in September 1990 (Gunnarsson et al., 1992). Optimal production characteristics of the Nesjavellir reservoir led to the purchase and installation of 3 additional 30 MW electrical units in 1996-1999 and another 100 MW thermal. The construction of the fourth 30 MW electrical unit is underway and 4 new production wells have been drilled in order to better define the southern margin of the current wellfield.

The favorable conditions observed in Nesjavellir awoke interest for the Hellisheidi field, to the south of the Hengill volcano. Reykjavik Energy recently expanded its land rights in the area and drilled 7 deep exploration wells in Hellisheidi between 1994 and 2002. All these wells are productive and currently being thoroughly tested in order to characterize the Hellisheidi resource. Special emphasis is put on recording pressure transients, which are induced by temporary production out of new wells. These data are considered highly valuable by providing permeability constraints for the numerical reservoir model that is currently under calibration.

Figure 2 shows location of wells presently drilled into the three sub fields of the greater Hengill volcano. These wells reach depths of 1000-2300 m. Initially most wells were drilled vertically but lately more emphasis has been put on directional drilling. Well outputs range between 3-9 MW electrical and 30-60 MW thermal. Discharged fluids are low in total dissolved solids (<1000 ppm) and noncondensable gas in the steam is also quite low (<0.5 %).

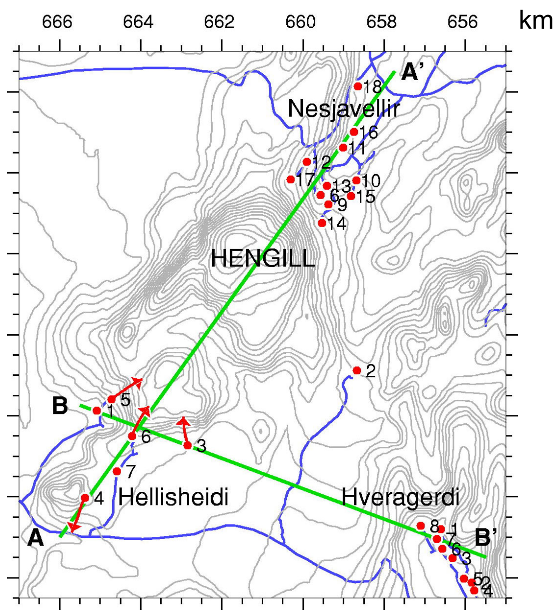


*Figure 2. Well locations in Nesjavellir, Hellisheidi and Hveragerdi. Also shown are locations of pressure and temperature cross sections.*

Extensive geological, geophysical and geochemical surveys have been carried out in the greater Hengill area in conjunction with the Nesjavellir and Hellisheidi drilling activities. As an example, the pioneering work of Saemundsson (1967) became the foundation of the present full size ArcInfo map database, including all major geological units, location of hot springs and fumaroles, fault lines and thermally altered grounds. Aeromagnetic, gravity and DC-resistivity surveys were carried out between 1975 and 1986. These delineated a 110 $km^2$ low-resistivity area at 200 m b.s.l. and, furthermore, showed a negative and transverse magnetic anomaly coherent with the most thermally active grounds (Bjornsson et al., 1986). The resistivity map was revised between 1986 and 2000, by applying the central loop transient electromagnetic sounding method (TEM) at 186 sites

(Figure 3). These data imply that despite being widespread, the resistivity anomaly is complex and affected by processes such as faulting, shearing and spreading (Arnason and Magnusson, 2001).

A tectonic event, consisting of approximately 100 thousand micro-earthquakes, vibrated the Hengill area between 1994 and 2000. Most quakes were located at 5 ± 3 km depth, reflecting the locally very thin and hot crust. The quakes group on lines striking either E-W or N-S, but surprisingly not to the NNE as seen in the surface geology (Arnason and Magnusson, 2001). Another surprise occurred when a velocity model was developed on basis of the seismic data. Namely that anomalously low P-wave velocity is needed at 3-9 km depth inside the rift zone. This implies that fluid is present down to these great depths, possibly a consequence of supercritical fluid convection (Tryggvason et al., 2001). Precise GPS measurements, geodetic surveys and ground radar interferometry have finally led to the hypothesis that subsurface movement of magma has accompanied the recent quake activity (Sigmundsson et al., 1997; Feigl et al., 2000).

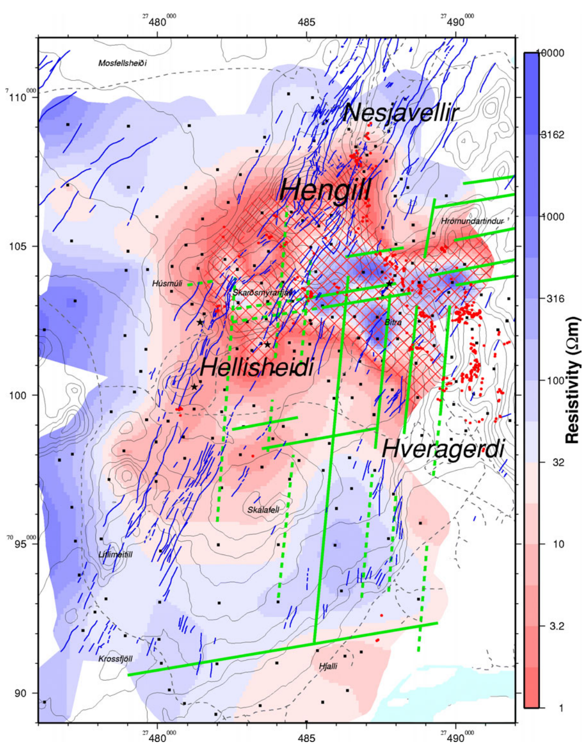


*Figure 3. Resistivity at 100 m.b.s.l. according to a recent TEM survey. Also shown in blue are visible fault lines and in green faults as defined by earthquake locations (from Arnason and Magnusson, 2001).*

## PREVIOUS MODELING STUDIES

Reservoir models have been an integral part of reservoir assessment and management in the Hengill area since 1986. Initially the modeling effort focused on the Nesjavellir site. The first model was developed during 1984 to 1986, it was 3 dimensional, consisted of 4 layers (12 by 12 km) and ~250 elements. Calibration was done against the estimated initial pressure and temperature distribution and a limited production history. This preliminary model study resulted in a generating capacity estimate of 300 MW thermal for 30 years without re-injection, and that 400 MW thermal could only be sustained by injection (Bodvarsson et al., 1990). Based on this study, the Reykjavik Municipal District Heating decided to build the first unit of the Nesjavellir power plant. Furthermore, an intense field-monitoring program was set up in order to gather data for future maintenance and recalibration of the numerical model.

By 1992 it became evident that the 1986 model overestimated pressure drawdown rates and, hence, underestimated discharge of some production wells. Otherwise the model had predicted the field status remarkably well, considering the very short production history available for calibration in 1986. A recalibration was therefore carried out in 1992. Only a few minor adjustments were needed to make the model match the production history collected between 1986 and 1992. Of these adjustments, possibly the most important one was to extend the model base layer from 12x12 km to 100x100 km, increase the model outer permeabilities and adjust the mesh near new wells. The boundary pressure support, provided by the increased outer model permeabilities, raised the estimated generating capacity of the Nesjavellir field from 300 to 400 MW thermal (Bodvarsson, 1993).

The second update of the Nesjavellir model was carried out in 1998. Again it was observed that the 1992 model matched very well the new 1992-1998 field data. Some minor modifications were however needed, mostly in conjunction with the wellfield permeability and porosity distribution. Based on this modeling effort it was concluded that the Nesjavellir reservoir could sustain the proposed power plant expansion to 60 MW electric and 200 MW thermal for another 30 years, provided that 4 make-up wells were to be drilled. However, predicted enthalpy declines will make some of the peripheral wells less productive with time (Bodvarsson, 1998).

In the year 2000 it was decided to recalibrate the numerical model once more, in order to study the feasibility of adding another 30 MW electrical and 100 MW thermal unit to the existing power plant. Two new wells had been drilled in 1999 that raised expectations for the field generating capacity. Again the 1998 model was only slightly modified to include the new wells and production data. Based on the study, the field should continue to sustain massive generation. Some enthalpy decline is, however, to be expected. This will eventually reduce electrical generation in Nesjavellir while the thermal part of the power plant still receives enough steam and brine in 30 years time (Bjornsson et al., 2000).

All the abovementioned reservoir models were developed using the MULKOM or the TOUGH2 numerical simulators (Pruess, 1992; Pruess et al., 1999). A break-through occurred in the year 2000 when inversion techniques were applied for the first time. The iTOUGH2 code (Finsterle, 1999) ran successfully on HP workstations, but due to the size of the forward problem, only a single processor did the automated matching.

## A CONCEPTUAL RESERVOIR MODEL

The ~30 deep wells already drilled in the Hengill area, together with another 30-40 wells in Hveragerdi and vicinity, comprise a vast database of subsurface pressure, temperature, lithology, thermal alteration and fluid chemistry. As an example, a total of 1100 temperature measurements and 450 pressure measurements are available in high-temperature wells drilled by Reykjavik Energy, amounting to 1800 km of logging. The logs span 38 years in time and serve both as a basis for defining initial reservoir status as well as transients due to production. All these data are presently stored in an Oracle relational database. An effort was recently made to define initial pressures and temperatures of the new wells in the Hellisheidi area and correlate with existing information in Hveragerdi and Nesjavellir. Figures 4 and 5 show the temperature and pressure distribution in two cross sections (see Figure 2 for locations). These types of graphics, combined with other geoscientific studies, make up the basis for the conceptual reservoir model of the greater Hengill volcano.

Figure 4 shows initial pressures and temperatures in a cross-section connecting the "old" Nesjavellir and the "new" Hellisheidi wellfields. A few items are of interest here like 1) that wells in the Hellisheidi field are characterized by reversed temperatures at depths exceeding 1000 m b.s.l., 2) that the Nesjavellir temperatures increase towards the south where the proposed upflow zone of the reservoir resides, 3) that pressure is also generally increasing to the south in Nesjavellir, and 4) that the deep Nesjavellir temperature is high and gradually increasing with depth. Also of interest is a local pressure low, deep in the Nesjavellir field.

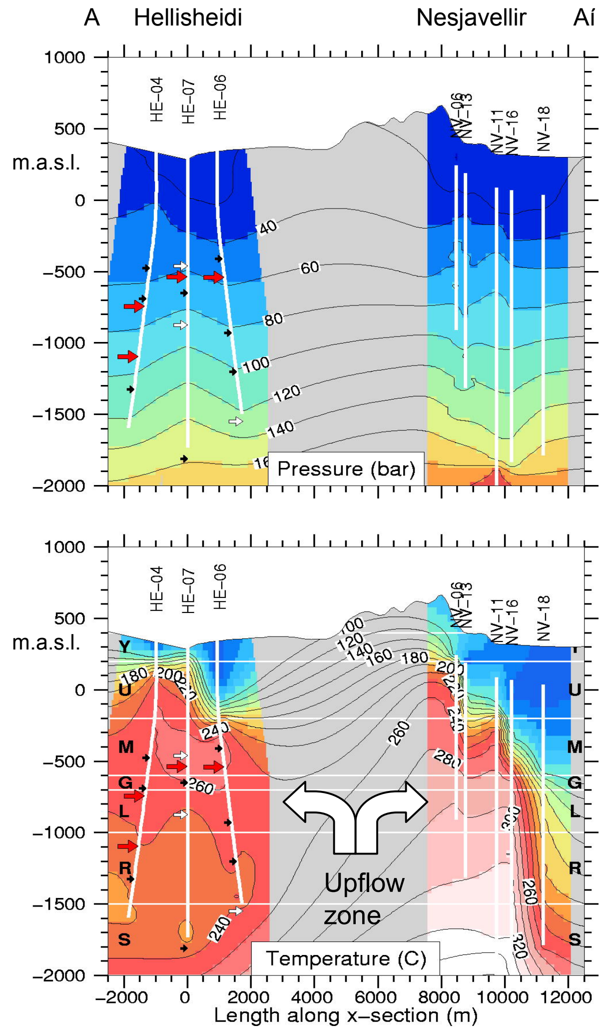


*Figure 4. S-N temperature and pressure cross-section between Hellisheidi and Nesjavellir. Wells are shown as thick white lines, feed-zones by arrows and layering of numerical model by thin horizontal lines.*

A somewhat different story is seen on Figure 5, which presents in a cross section the temperature and pressures between Hellisheidi and Hveragerdi. Firstly, that the Hellisheidi temperatures are reversed in the east but not in the west, at the margin of the rift zone. Another most interesting feature is a lateral pressure decline towards the center part of the cross-section. This pressure behavior is taken as an indicator of a fluid sink, probably due to lateral discharge towards the south. The outflow zone hypothesis is supported by the microseismic data collected between 1994 and 2000 (Figure 3). Finally, the Hveragerdi deep temperature is also reversed with depth as on Hellisheidi, which may infer that this field is recharged by fluid coming from the north.

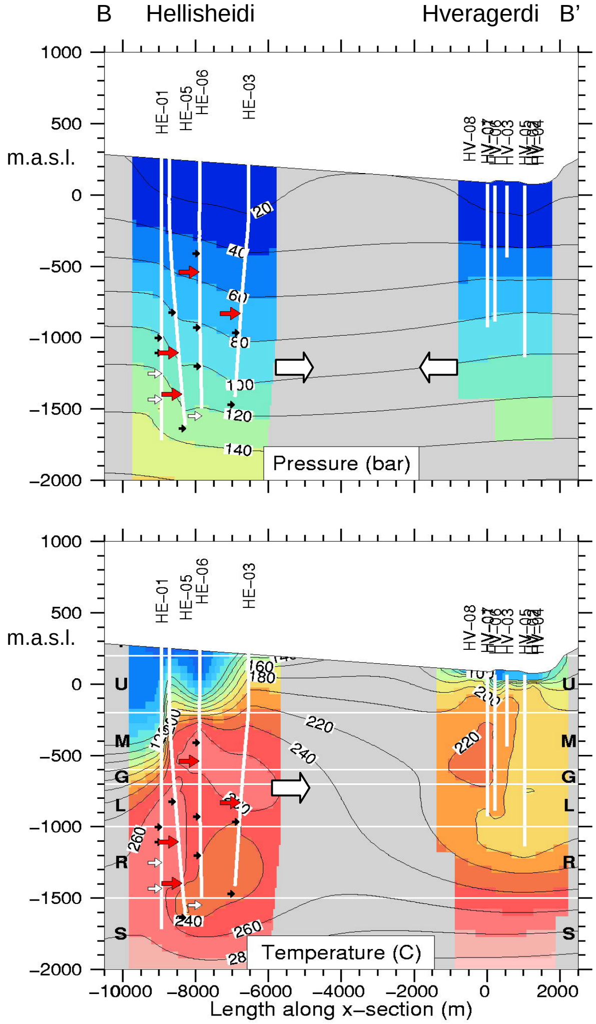


*Figure 5. W-E temperature and pressure cross-section between Hellisheidi and Hveragerdi. Wells are shown as thick white lines, feed-zones by arrows and layering of numerical model by thin horizontal lines.*

Figure 6 shows the estimated initial pressure distribution in the Hengill area at 650 m depth below sea level. Of interest here is the pressure low in the center south portion of the figure. The pressure low coincides with a line of active seismicity (Figure 3). It is regarded here as an important feature in the conceptual reservoir model, which should be accounted for in the current numerical modeling work. Figure 7 shows finally the estimated temperature distribution of the Hengill area, also at 650 m b.s.l. Of importance here is that the high temperature anomaly can be regarded as continuous between Hellisheidi and Nesjavellir, and that this anomaly is parallel with the rift zone and tectonic lines seen on surface. This may imply that both fields are being recharged by the same upflow zone, located mid way between the two. Figures 6 and 7 also indicate that there is only minor or even no connection between Hveragerdi and the Hengill fields, which is important when it comes to estimating the environmental impact of mass production out of these two areas.

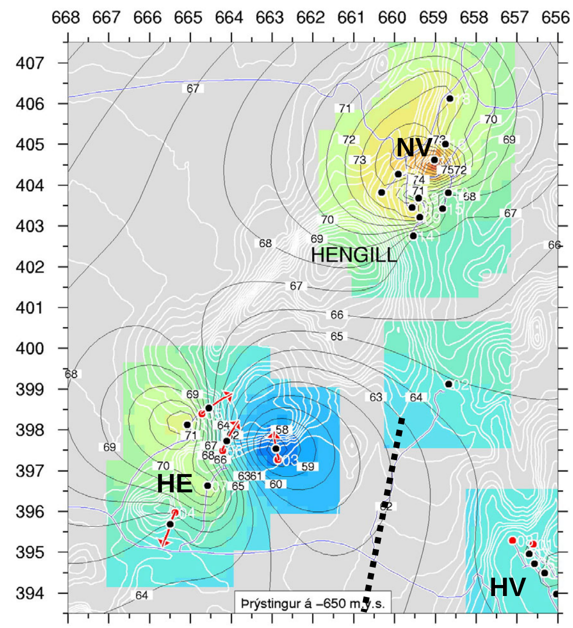


*Figure 6. Pressure distribution (bars) at 650 m.b.s.l. in the Hengill area. NV stands for Nesjavellir, HE for Hellisheidi and HV for Hveragerdi. Dotted line shows the fault line that is presumed to drain fluid out of the area towards south.*

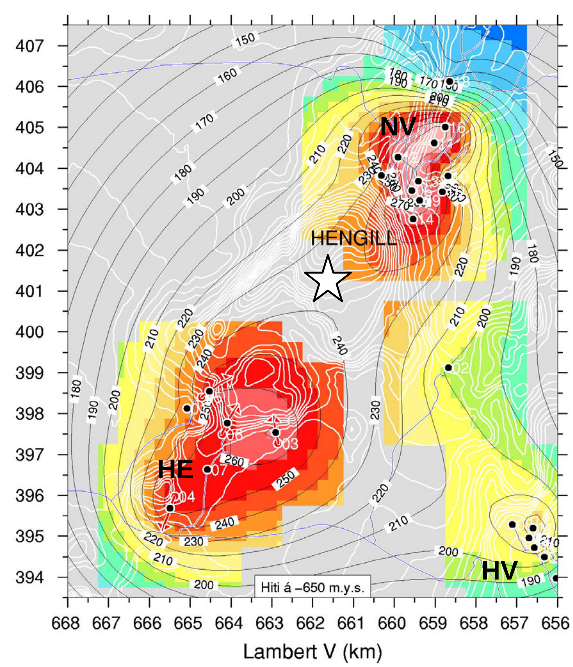


*Figure 7. Temperature distribution (°C) at 650 m.b.s.l. in the Hengill area. Same legend as in Figure 6. A common upflow zone for Hellisheidi and Nesjavellir may be located near the star.*

**THE NEW NUMERICAL MODEL**

Although the old Nesjavellir numerical model can be regarded as highly successful during its 14 years of existence, it became evident in year 2000 that the model mesh was unable to account properly for the new Nesjavellir wells. Considering that exploration of the Hellisheidi area had also intensified, it was decided to develop a completely new model of the greater Hengill area. This model is supposed to simulate nearly all data available in the subsurface, can be used to investigate possible pressure interference between wellfields and, finally, should run under the iTOUGH2 structure and use parallel processing to estimate many model parameters simultaneously. The model is developed at the request and expense of Reykjavik Energy, and the decision on its development was made in late 2001.

A primary reason for this bold modeling decision was that the Orkustofnun geosciences group had become a partial owner of a Linux Networx cluster, made up of 26 nodes. The cluster had shown excellent performance in calibrating reservoir models from Africa and Central America. We therefore felt that computer power was not the same limiting factor as earlier, and that the manpower was better spent on checking the model calibration results than performing the often-frustrating forward modeling. In principle this means that most of the work time is spent on setting up the grid, preparing observation files to be matched by iTOUGH2, write Unix shell scripts and tools which graphically present model match to the field data and, most importantly, have the luxury to focus on parameter sensitivity and behavior as shown by iTOUGH2.

As a first step in the new model development, a 2-day meeting was set up in August 2001, attended by many of the geoscientists involved in the Hengill area resource assessment. A primary goal of the meeting was to come up with a conceptual reservoir model, agreed upon by the participants. Some of the main conclusions derived were:

1. The existing Nesjavellir model parameters should be included as an initial guess.
2. Two NNE striking volcanic fissures, which intersected the Hengill volcano ~2000 and ~5500 year ago, act as primary conduits for subsurface fluid flow in the region.
3. A single upflow zone, situated underneath the Hengill volcano, is feeding hot fluid to both Nesjavellir and Hellisheidi.
4. The Hveragerdi field may also receive fluid from that same upflow zone. Therefore the model mesh should allow for a transverse flow structure already suggested by geophysical and geological studies.
5. Due to practically no production data and limited number of wells in the Hellisheidi field, the first phase of the model development should presume that the Nesjavellir rock properties can be mirrored across the Hengill volcano.

The Amesh code generated the new model mesh (Haukwa, 1998). We like its flexibility when the mesh has to be refined, for example when new wells are drilled. The three dimensional mesh is made of 8 identical and horizontal layers. Its area extent is 100x100 km. Figure 7 shows the full mesh, projected on a geographical map of Iceland. Figure 8 zooms on the inner mesh and the 3 fields of Nesjavellir, Hellisheidi and Hveragerdi. The mesh axes are oriented in parallel with the strike of the western volcanic zone and the two volcanic fissures that may dominate fluid flow in the region.

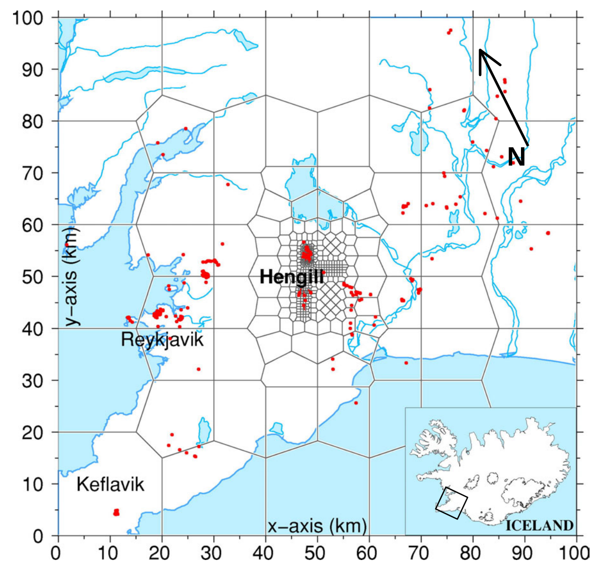


*Figure 7. Layout of the new Hengill mesh, in model coordinates. Red dots present wells. The inlet shows the mesh location in SW-Iceland.*

Vertical layering of the model was kept similar to that of the older Nesjavellir model. The layering is shown on the temperature cross-sections in Figures 4 and 5 and in Table 1. The mesh consists currently of 4,358 elements whereof 3,218 are active. The number of connections exceeds 15,000. An important aspect in the mesh management is to use the element names to merge files with location of element centers, element rock properties and the endpoints of the line segments that surround each element (output file of Amesh). Homemade Unix shell scripts manipulate these files and the open source Generic Mapping Tool software (GMT) is used for making illustrations (Wessel and Smith, 1995). Two Fortran codes were also developed. One is used to subgrid elements, which are defined as feedzones in geothermal wells. The other code projects well information on cross sections that serve as a base for defining the conceptual reservoir model. These graphics also show in which layers productive feedzones are encountered.

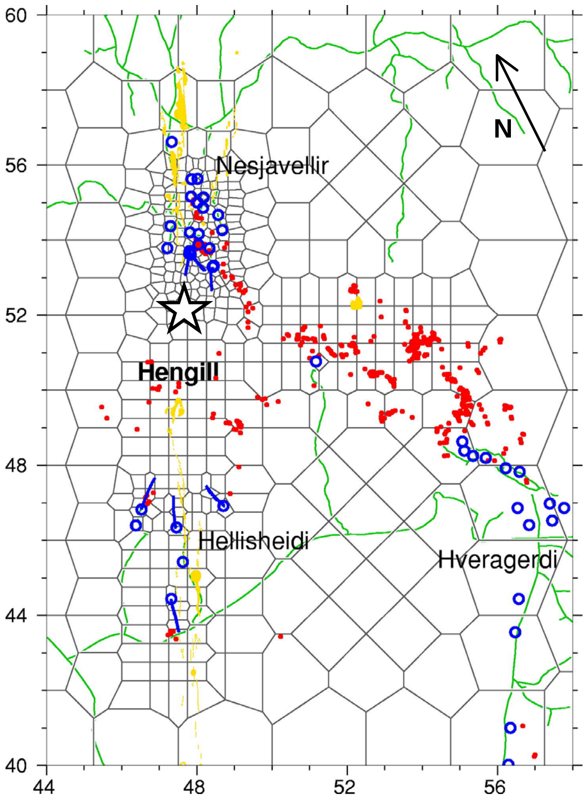


*Figure 8. Inner part of the Hengill mesh. Fumaroles and hot springs are shown in red, wells by blue circles and main roads by green lines. A star shows the model upflow zone. The finest mesh coincides with the volcanic rift zone and a possible transverse structure towards the ESE. Young volcanic fractures are shown in yellow and roads in green.*

*Table 1. Layering of the Hengill model.*

| Layer name | Thickness (m) | Center (m.a.s.l) | Property |
|---|---|---|---|
| Y | 200 | 300 | Inactive, atmosphere |
| U | 400 | 0 | Partially active |
| M | 400 | -400 | Fully active |
| G | 100 | -650 | Fully active |
| L | 300 | -850 | Fully active |
| R | 500 | -1250 | Fully active |
| S | 500 | -1750 | Fully active |
| B | 400 | -2200 | Inactive, impermeable |

## MODEL CALIBRATION

The inverse modeling technique of iTOUGH2 and the parallel capability of the Linux cluster resulted in a relatively fast model calibration process. Lately we have been inverting for 116 parameters, most are permeabilities and productivity indices for wells on deliverability. Strength and enthalpy of the upflow zone is also estimated, as well as conductive heat flow into the base of the model. We have defined 319 sets of observations at 360 calibration times that are to be matched by the inversion process. These are histories of well enthalpies, flowrates and pressure drawdown. Initial temperatures and pressures of wells are also accounted for. Still to be included are initial temperatures which can be defined indirectly from the resistivity model. Figure 9 shows, as an example, the permeability distribution in layer L.

The iTOUGH2 source code only needed a few changes to suite the project. Of these most time was spent on defining time intervals when wells discharge. We used the annotation feature in the observation section of iTOUGH2 to mark and select appropriate lines out of the large output files generated. These lines were then used to plot measured and simulated observations with time or depth. In order to make this work, the iTOUGH2 source code was modified to include the annotation in every line of the Tecplot outfile. Finally, a handy date2sec Fortran module, developed in Iceland, was embedded in the iTOUGH2 source, which allowed for using dates instead of a linear time in the inverse file.

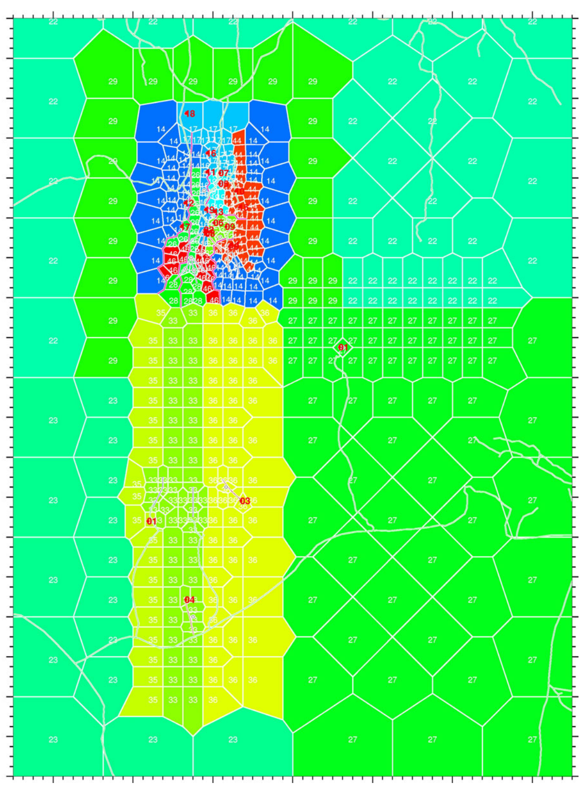

*Figure 9. Permeability distribution in layer L. The color ramp is from blue (low) to red (high).*

The *steady-state-save* option of iTOUGH2 proved to be essential in the calibration phase. If time steps exceed ~5000 years, we assume that steady state conditions have been achieved. This feature assures that one and the same parameter set matches both initial and transient observations and should therefore improve the model confidence if correctly applied.

Inverse problems like the one of Hengill include numerous observations collected at different times and locations. Great care has, therefore, to be put into time stepping and time window definitions for the field observations. This work consumed substantial fraction of the man time spent on the model calibration. For example, producing a new well required one time definition in the TOUGH2 source code and recompilation, one or two times in the TOUGH2 forward file to make sure that the code would jumpstart the well at the right time and, finally, an observation time and a time window in the inverse file. This time manipulation had importance in the Hengill model as pressure recoveries have often been measured when production wells are shut-in. We have included these data as observations, but still need to polish the procedure.

The 26 nodes Linux cluster spent 6-8 hours to perform 4-5 iterations where all the 116 parameters were estimated. Overall we are pleased with its performance although a few problems arose from an old version of the Redhat operating system installed. The parallel virtual memory feature of iTOUGH2 (PVM) dramatically speeded up the execution time in this project, as in other ones completed earlier. The cluster has recently been expanded to 50 nodes, which probably triples the computer power available for the inverse problem. A new operating system is also believed to have solved some of the file transfer problems that were encountered in the 26 nodes version.

## FUTURE FIELD PERFORMANCE

A simulation project like the one presented above generates numerous graphics presenting computed and measured field data. For practical reasons we have chosen not the show any of these graphics in the paper. Instead we show how the model is able to match the total Nesjavellir field production and enthalpy history and predict its future performance. Predictions have also been made for the Hellisheidi wellfield, but are not presented here due to new field data that have drastically changed the conceptual reservoir model. These changes must be accounted for in the numerical model and have to do with very different geological conditions than observed in Nesjavellir. The figures below are taken from an intermediate report submitted in June 2002 (Bjornsson et al., 2002)

Although the June 2002 version of the Hengill reservoir model was not fully calibrated at that time, we generated upon request of the Reykjavik Energy some preliminary performance studies. The goal of the study was to address the feasibility of adding the fourth 30 MW electrical unit to the Nesjavellir power plant. Two sets of model parameters were considered for the predictions, one that has been defined as the *dry model* and overestimates the mean enthalpy history of the field while the *wet model* is under-estimating the mean enthalpy. These parameter sets may define two extremes in the future field response to production and, thereby, assist in the power plant decision-making. Figures 10 and 11 present how the wet and the dry models match the actual production history of the Nesjavellir field between 1975 and 2002. In general the inversion process is able to match the total flowrates fairly well while enthalpy matching is more troublesome.

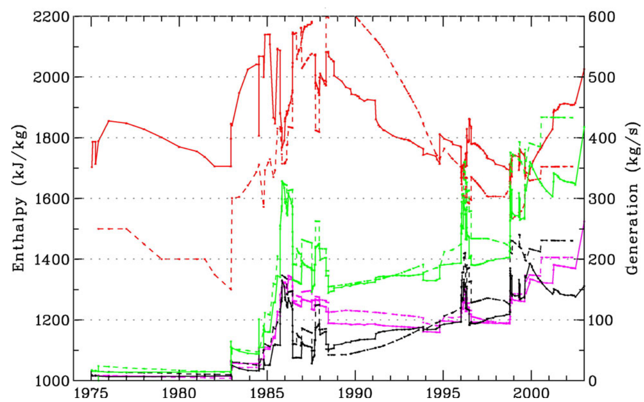


*Figure 10. Simulated (solid lines) and measured (dashed) total generation rates and mean enthalpies for the **dry** parameter set of the Hengill model. Red is enthalpy, green total generation, purple high-pressure steam flow and black is the separated brine flow.*

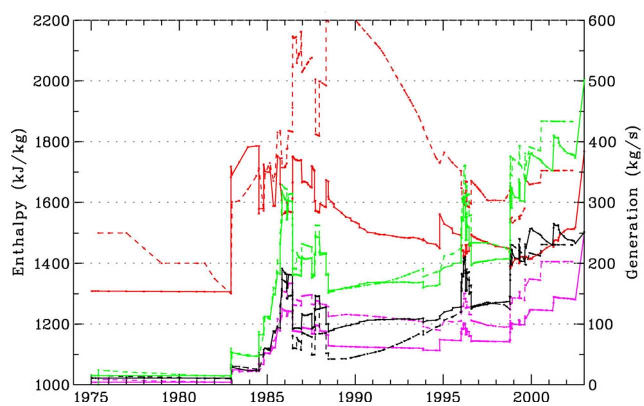


*Figure 11. Simulated (solid lines) and measured (dashed) total generation rates and mean enthalpies for the **wet** parameter set of the Hengill model. Same legend as in Figure 10.*

With these two parameter sets at hand, a few production scenarios were studied (Table 2). Firstly we predict the Nesjavellir performance if the current 90 MW generation continues for another 30 years. Secondly we withdraw sufficient mass to generate 120 MW electric and site make-up wells only in the deep reservoir layers R and S. Thirdly we ran the 120 MW case tapping the intermediate layers L and R only by new make-up wells. Finally the 120 MW case is studied for make-up wells tapping the shallow layers G and L. This results in 8 future production scenarios. All wells produce on deliverability and new make-up wells are assumed to come on line every 5 years. Their productivity indices were adjusted such that each drilling project yielded the right amount of high-pressure steam to sustain the 90 or 120 MW generation rates. Steam is separated at 10 bars and it is assumed that 2 kg/s of high-pressure steam flow generate 1 MW electric.

*Table 2. Production scenarios for the Hengill model*

| Case number | Generation (MWe) | Parameter set | Make-up wells in layers |
|---|---|---|---|
| 1 | 90 | Dry | G,L,R,S |
| 2 | 90 | Wet | G,L,R,S |
| 3 | 120 | Dry | R,S |
| 4 | 120 | Wet | R,S |
| 5 | 120 | Dry | L,R |
| 6 | 120 | Wet | L,R |
| 7 | 120 | Dry | G,L |
| 8 | 120 | Wet | G,L |

Figure 12 shows predicted total generation rates in the 8 production scenarios. In general the wet model is producing ~20 % more total mass than the dry one. Also a gentle increase in the total mass generation is seen for all the model cases. This behavior is the consequence of a predicted decline in the mean field enthalpy. The power plant is, on the other hand, consuming the same flow rate of high-pressure steam, which only is possible by increasing the total generation.

Figure 13 shows predicted flow of high-pressure steam for the 8 production cases. This time we adjust timing and productivity indices of make-up wells such that the total steam flow is either ~180 or ~240 kg/s, equivalent to 90 or 120 MW electrical in a condensing turbine.

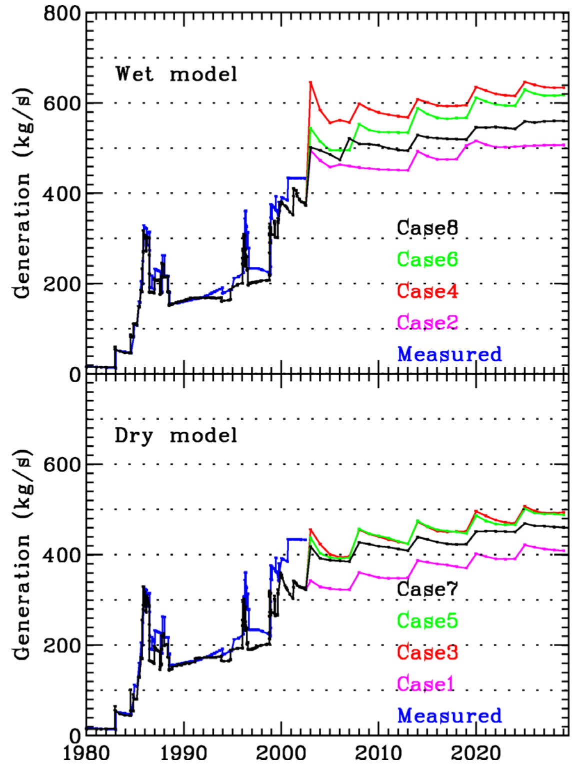


*Figure 12. Predicted total generation rates for the Nesjavellir field. Jumps in the flowrate curves coincide with times when make-up wells start discharge.*

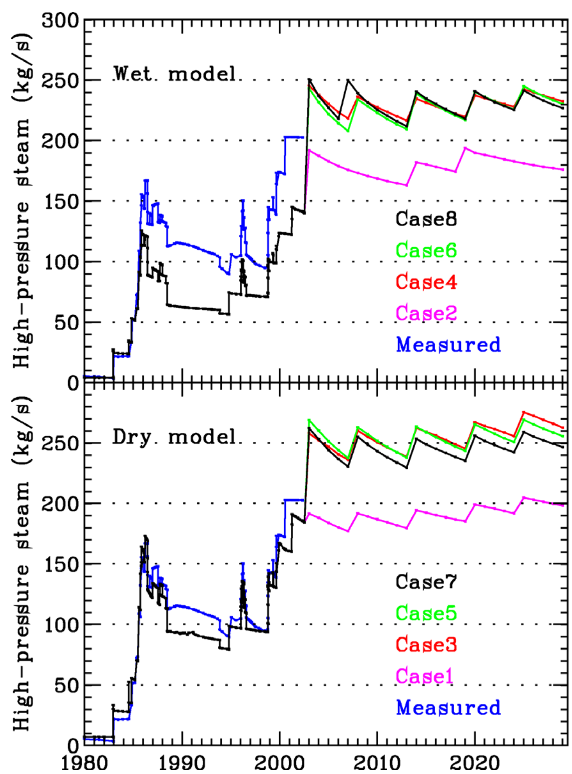


*Figure 13. Predicted total flowrates of high-pressure steam for the Nesjavellir field.*

We estimate that in order to operate the Nesjavellir power plant at full load (120 MW electric) for the next 30 years somewhere between 5 and 15 make-up wells may be required. Also we observe that if the new make-up wells encounter very deep feedzones, a much lower productivity index will provide similar mass flow rates compared to wells that tap the shallow layers. The mean enthalpy of the Nesjavellir wells is at present around 1700 kJ/kg but is predicted to decline down to around 1500 kJ/kg during the 30 years prediction period. The enthalpy decline is a combined effect of cooler boundary recharge and less intensive boiling inside the current wellfield.

## CONCLUSIONS

Some of the major conclusions of past and present reservoir modeling studies in the Hengill area are as follows:

- The ~300 element reservoir model developed for Nesjavellir in 1986, has been recalibrated in 1992, 1998 and 2000. At times of recalibration work, we have observed that the former model version in general predicts the field performance quite well.
- Overall, the estimated generating capacity of Nesjavellir field has increased gradually as more field data became available for the model calibration.
- Continuous maintenance and recalibration of geothermal reservoir models appears, therefore, feasible as a reservoir management tool.
- Drilling of new wells in the Hellisheidi field, together with surface exploration activities, indicate that the Nesjavellir and the Hellisheidi fields can be regarded as the same system, joined by a common upflow zone midway between the two.
- A seismically active fault zone, located between Hveragerdi and the Hengill complex, is suspected to drain fluid out of the area. This fault zone may also indicate that the two fields are either vaguely, or not at all, hydrologically connected.
- Due to the large area extent of the geothermal systems in Hengill, it was decided to develop a new, large-scale reservoir model for the area, instead of working more on the older Nesjavellir version. The new model is presently made of 4400 elements in 8 horizontal layers, covering an area of 100x100 km.
- Inverse techniques and parallel computing have been applied successfully in the model calibration. Presently we invert for 116 parameters on a 26 nodes Linux Networx computer cluster. Around 320 sets of observations and 360 calibration times have been defined in the inversion process and more is to be included.
- The new model development, initiated in late 2001, resulted in a preliminary generating capacity estimate for the Nesjavellir field in June 2002. Due to uncertainties, two sets of model parameters were studied and four depth strategies for make-up wells, in total 8 production scenarios.
- No drastic changes are predicted in the field performance between the 90 and 120 MW electrical power plants studied. As a best case the field operation may require only 5 make-up wells during 30 years of operation and as a worst case around 15 wells.
- A presumed geological similarity between the Nesjavellir and the Hellisheidi fields has proven wrong with more field data becoming available. The conceptual reservoir model has been adjusted to this new information and the new numerical model will be recalibrated accordingly in the next few weeks.

The experience gained in applying inverse techniques in geothermal reservoir model calibrations has been very positive and stimulating for the authors of this paper. The text file environment of iTOUGH2 works fine in Unix systems and sophisticated graphics are being generated using homemade Unix shell scripts and open source graphic tools. The concept of computer clusters and parallel computing is also very important and allows for very complex and lengthy simulation runs. In the continuation of this work, we plan to break up the inversion modeling runs and try to reduce the number of parameters being estimated. For example, should one month pressure recovery data accompany 25 year history of reservoir drawdown in an observation well? And should calibration of the new Hellisheidi data be somehow disconnected from the Nesjavellir model parameters. These questions and many more are being addressed in our current work and will hopefully be published in due time.

## ACKNOWLEDGMENT

We thank Reykjavik Energy for permission to publish their data. Also we thank Dr Gudni Axelsson for reviewing the paper and for making some valuable suggestions.

**REFERENCES**


Arnason K. and I.Þ. Magnusson: *Geothermal activity in the Hengill area. Results from resistivity mapping*. Orkustofnun report, in Icelandic with English abstract, OS-2001/091, 250 p., 2001.

Bjornsson A., Hersir G.P. and G. Bjornsson: The Hengill High-Temperature Area in SW-Iceland. Regional Geophysical Survey. *Geothermal Resources Council Transactions,* Vol. 10, pp. 205-210, 1986.

Bjornsson, G., Sigurdsson O., Bodvarsson G.S. and B. Steingrimsson: *Nesjavellir. Recalibration of a numerical reservoir model and estimated generating capacity.* Orkustofnun report, in Icelandic, OS-2000/019, 40 p., 2000.

Bjornsson, G., Hjartarson A. and B. Steingrimsson: *Three-dimensional reservoir model for the Hengill area. Status in June 2002*. Orkustofnun report, in Icelandic, GrB/ArH/BS-2002/02, 31 p.

Bodvarsson, G: Report on the Hengill Thermal Area. Investigations carried out in the years 1947 to 1949. Section I.: *Yearbook, Association of Chartered Engineers in Iceland,* pp. 45-48, 1951.

Bodvarsson, G.S., Bjornsson S., Gunnarsson A., Gunnlaugsson E., Sigurdsson O., Stefansson V. and B. Steingrimsson: The Nesjavellir Geothermal Field, Iceland. Part 1. Field Characteristics and Development of a three-Dimensional Numerical Model. *Geotherm. Sci. & Tech.,* Vol. 2 (3), pp. 189-228, 1980.

Bodvarsson, G.S., Bjornsson S., Gunnarsson A., Gunnlaugsson E., Sigurdsson O., Stefansson V. and B. Steingrimsson: The Nesjavellir Geothermal Field, Iceland. Part 2: Evaluation of the generating capacity of the system. . *Geotherm. Sci. & Tech.,* Vol. 2 (3), pp. 229-261, 1980.

Bodvarsson, G.S.: *Recalibration of the three-dimensional model of the Nesjavellir geothermal field.* Report prepared for the Reykjavik District Heating, 111 p. 1993.

Bodvarsson, G.S.: *Update of the three-dimensional model of the Nesjavellir geothermal field.* Report prepared for Reykjavik District Heating. 1998.

Feigl, K.L., Gasperi J., Sigmundsson F. and A. Rigo: Crustal deformation near Hengill volcano, Iceland 1993-1998. Coupling between magmatic activity and faulting inferred from elastic modeling of satellite radar interferograms. *J. Geophysical Res.,* vol. 105, Ni. B11, 25655-25670. 2000.

Finsterle, S: *iTOUGH2 Users Guide.* Report LBNL-40040, Lawrence Berkeley National Laboratory, Berkeley, Calif., 1999.

Gunnarsson, A., Steingrimsson B.S., Gunnlaugsson E., Magnusson J. and R. Maack: Nesjavellir Geothermal Co-Generation Power Plant. *Geothermics,* Vol. 21, No. 4, pp. 559-583, 1992.

Haukwa, C.: *AMESH. A mesh creating program for the integral finite difference method: A User's Manual*. Lawrence Berkeley National Laboratory, LBNL-45284, 53 p, 1998.

Pruess, K.: Development of the general purpose simulator Mulkom. *1982 Annual Report. Earth Sciences Division,* Lawrence Berkeley Laboratory, Berkeley, California, LBL-15500, pp 133-134, 1982.

Pruess, K., C. Oldenburg, and G. Moridis, *TOUGH2 User's Guide, Version 2.0*, Report LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, Calif., 1999.

Saemundsson, K., 1967: Vulkanismus und tectonic des Hengill-gebietes in Sudwest-Island. *Acta Naturalia Islandica,* Vol II, no. 7.

Sigmundsson, S., Einarsson P., Rögnvaldsson S.Th., Foulger G.R., Hodgkinson K.M. and G. Thorbergsson: The 1994-1995 seismicity and deformation at the Hengill triple junction, Iceland: Triggering of earthquakes by minor magma injection in a zone of horizontal shear stress. *J. Geoph. Res.,* vol. 102, no. B7, pp. 15,151-15,161, 1997.

Tryggvason A., Rögnvaldsson S.Th. and O.G. Flovenz: Three-dimensional imaging of the P- and S-wave velocity structure and earthquake locations beneath Southwest Iceland. *Geophys. J. Int.,* vol. 151, 848-866, 2002.

Wessel, P., and W. H. F. Smith: *The Generic Mapping Tools (GMT), version 3.0 Technical Reference & Cookbook*, SOEST/NOAA, 1995.