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

The Reykjanes Seawater Geothermal System – Its exploitation under regulatory constraints

Omar Sigurdsson

HS Orka hf. Brekkustigur 36, IS-260 Reykjanesbaer, Iceland.

omars@hs.is

Keywords: Reykjanes, seawater system, high enthalpy, high pressure steam, drawdown, electrical power, constrains, sustainability, production strategy, environmental.

ABSTRACT

The Reykjanes high enthalpy geothermal system is located at the tip of the Reykjanes peninsula were the mid-Atlantic Ridge comes ashore in southwest Iceland. Its geothermal fluid has seawater salinity and originates from the seawater source underneath the peninsula. The first research drillings were made in the sixties and limited (50 kg/s) production was from the system in the eighties for a chemical plant. In 1998 research and preparation for a 100 MW generating power plant started and the plant came on line in May 2006. Now an enlargement of the power plant to 150 MW is underway that could be on line in 2011.

The general properties of seawater geothermal systems are addressed with reference to regular water systems. The high production impact (800 kg/s) in the beginning of operation is described and how it has affected the system. As environmental and other regulatory agencies have intermixed “sustainable development” with sustainable production and resource conservation, additional constrains are set on the production. To comply with these constrains the production strategy needs to be reevaluated and possibly changed. First steps in that direction have been taken with drilling into a high pressure steam zone (>55 bar) that is developing in the system. Finally, the future forecasts and goals are discussed.

1. INTRODUCTION

The Reykjanes high enthalpy geothermal system is located at the SW-tip of the Reykjanes peninsula where the mid-Atlantic Ridge comes ashore in southwest Iceland (Figure 1). In the last glacial period (12000-100000 years ago) the icecap covering Iceland extended far south along the mid-ocean ridge. At that time the geological formations were saturated with water of meteoric origin. As the icecap melted and retracted, seawater started to seep into the formations and replace the water. Evidences of the former water are now only found in crystalline inclusions. Land also started to rise and volcanic activity increased. The volcanic activity has been fracture intrusions and eruptions forming dyke swarms, which have supplied the heat sources to form the Reykjanes geothermal system.

The exploration of the Reykjanes system dates back to 1956 when the first well was drilled to 162 m depth and encountered a temperature of 185°C. The well produced 3-4 kg/s of a steam-brine mixture for the next years, but was plugged in 1962. The chloride concentration of the brine was about 25% higher than that of ordinary seawater and no noticeable change was observed in its chemical composition during the production (Bjornsson et al., 1971). The fact that the fluid produced was brine of seawater origin, but not meteoric water as commonly found in Icelandic hydrothermal systems, affected the course of later exploration and developments.

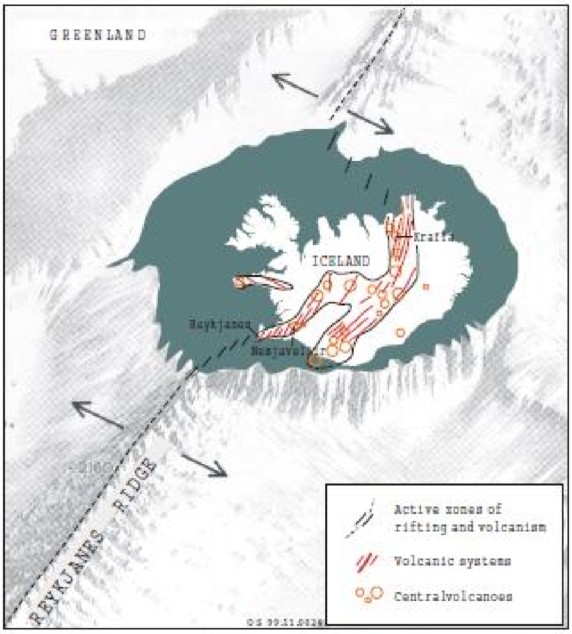

Figure 1: Iceland and its mid-ocean ridge. Location of Reykjanes shown.

Extensive investigation and drilling of additional 7 wells was carried out in the years 1968-1970. Most of the wells were shallow, but three of them reached depth greater than 1000 m with well 8 reaching 1754 m. This effort was done in relation to plans to produce 250,000 tons/year of not only common salt but various other sea-chemicals for export (Lindal, 1975). The investigation showed that the system would be suitable for development. However, the proposed sea-chemicals scheme did not materialize at that time but came into existence about 12 years later at a much smaller scale. In 1983 well 9 was drilled and was used along with well 8 for the sea-chemical plant. The plant was only in operation for few years and developments came to a halt for about 10 years.

In 1998 investigation started again with the drilling of well 10 and plans for electrical power generation. After discharge tests and bench-scale studies for material selection and scaling, a power plant was designed with reference to earlier experience of the geothermal system. In the years 2002-2006 wells 11 to 24 were drilled to obtain steam for a power plant that was constructed at the same time. The power plant came on line in May 2006 generating 100 MW_e from two 50 MW_e double flow turbines with seawater cooled condensers. Currently plans are to expand the electrical power generation by adding another identical 50 MW_e turbine unit and possibly yet another 30-50 MW_e low pressure turbine unit.

2. THE REYKJANES SYSTEM

The Reykjanes peninsula is the landward extension of the mid-Atlantic spreading ridge. The geology and surface distribution of the high-enthalpy geothermal system at Reykjanes is shown in Figure 2, and an aerial view in Figure 3. The surface is almost entirely covered by subaerial lavas of Holocene age; whereas hyaloclastite ridges of late Pleistocene age poke the lava fields, with the same NE-SW strike as the volcanic crater rows, faults and fissures (Fridleifsson and Albertsson, 2000). Parts of the hyaloclastite ridges and the lava fields are hydrothermally altered, centered within manifestations of fumaroles, mud pools and hot springs. The youngest fissure eruption dates back to 1226 at the crater row Stampar on the NW-side of Reykjanes, while the 2nd youngest is about 2000 year old. In Holocene time, at least four volcanic eruptions have taken place within this fissure zone. An older eruptive fissure zone is on the SE-side of Reykjanes (the Skalafell fissure zone), mostly involving early-Holocene lava eruptions. The faults and fissures have moved frequently in historic times, reactivating the hydrothermal surface manifestations, which are mostly located in between these two eruption zones.

Several surface resistivity soundings have been carried out at the Reykjanes field and its surroundings. The earliest one had Schlumberger configuration, but the later ones were TEM and most recently MT. The measurements delineated a low resistivity area interpreted as altered rock due to high temperatures. The interpreted low resistivity sheet has an aerial extension around 11 km^2 at 800 m depth (Figure 4). The shape of the surfacing of the resistivity indicates that the main upflow is along the older NE-SW eruptive fissure zone which is intercepted by a shorter N-S trending fracture in the central part of the field (Karlsdottir, 2005). A regular higher resistivity core, defining temperatures above 240°C, is only determined for few of the measurements. In Icelandic geothermal systems the forming of the higher resistive core has been assumed to indicate the diminishing of smectite minerals for higher resistive chloride-epidote minerals. However, drillings have proved higher temperatures where the higher resistivity core was not determined causing some controversy in the earlier resistivity interpretations. Drill cuttings have revealed that smectite can exist at temperatures higher than 240°C, even up to 280-290°C and then along with chloride. The change from the low resistivity sheet to the higher resistivity core is not as sharp as in geothermal systems with fluid of meteoric origin.

The recent MT-measurements strengthen the existence of upflow along the fissure zone (Figures 5 and 6), but the measurements are yet too scarce to delineate the deeper part of the system further (Rosenkjær and Karlsdottir, 2009). A deep low resistivity layer was not found with the MT measurements underneath the Reykjanes peninsula even though the measurements profiled over at least three known high enthalpy systems. Such a layer is commonly found inland at 3-5 km depth underneath high enthalpy systems and down to 14-18 km depth outside the geothermal systems. Therefore, it is suspected that this low resistivity layer ceases to exist when approaching the coastal areas. It had been suggested that features in this layer shape could define the deep upflow zones to the geothermal systems.

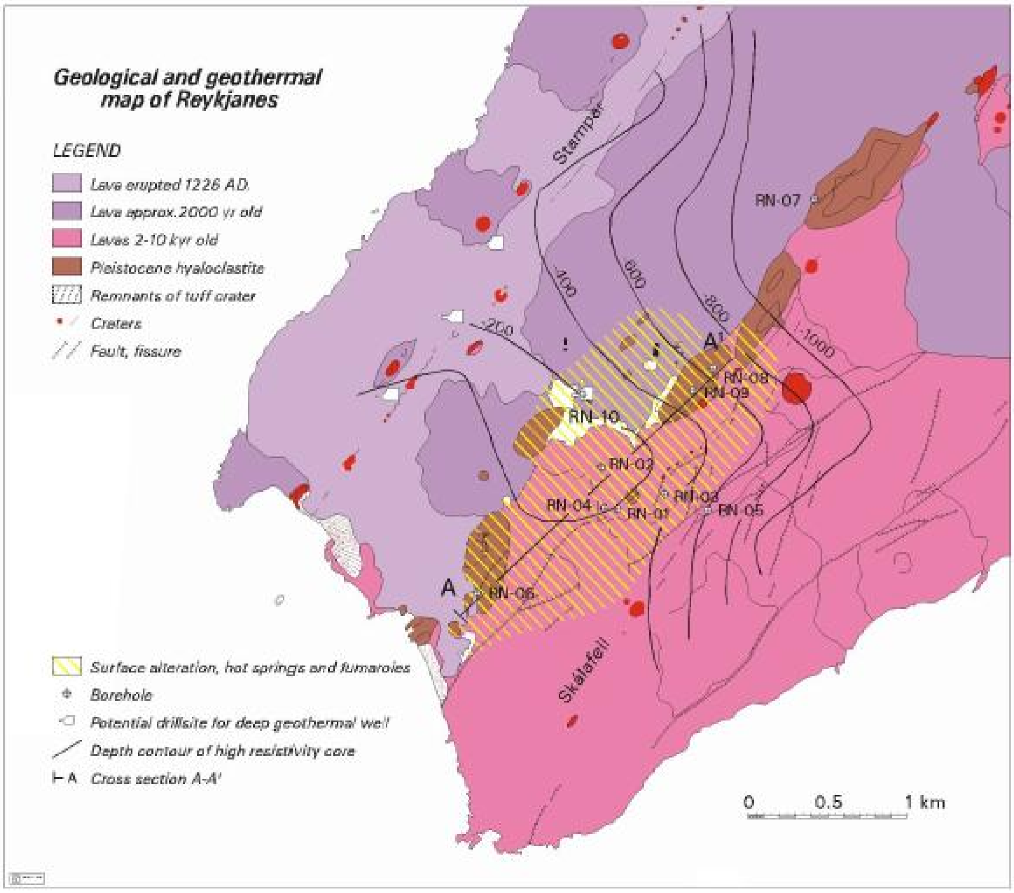

Figure 2: Geological map of Reykjanes (based on Sæmundsson 1997) showing some of the drill holes, depth contours to high resistivity core and hydrothermal surface manifestations.

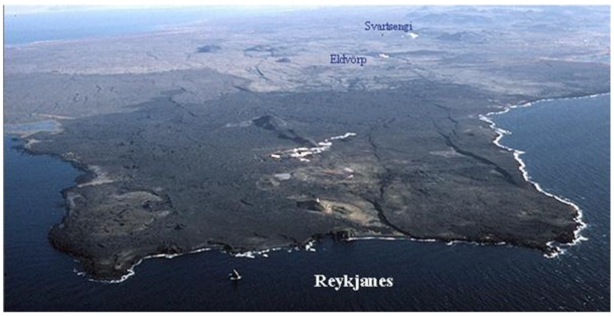

Figure 3: Reykjanes, the landward extension of the Reykjanes ridge. The fields Reykjanes, Eldvorp and Svartsengi can be seen.

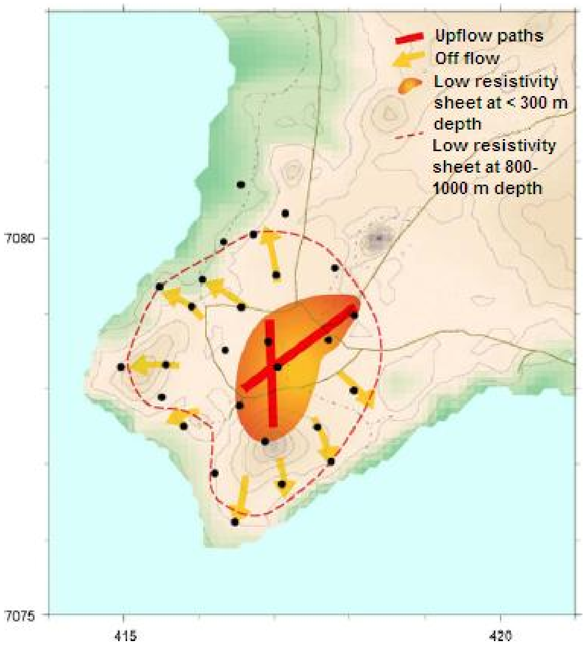

Figure 4: Aerial extent of the low resistivity sheet at around 800 m depth.

Calcite varies with depth but is most abundant in the uppermost 500-700 m. Calcite tends to precipitate out due to boiling when the geothermal fluid flows towards the surface. It seems likely that calcium rich rocks represent a region of initial boiling in the Reykjanes field (Gudmundsson et al. 1981). Further evidence for boiling in the upflow zone is the chloride concentration of the brine feeding the surface manifestations and the boreholes, but it increases with shallower depth. At 1000 m depth it was about 5 % higher than in seawater, at 300 m about 9 % higher and up to about 25 % higher at 100 m depth. Due to the upflow of hot brine and steam in the central part of the geothermal field a freshwater lens does not exist there. Such freshwater-seawater interface commonly exhibits classical coastal aquifers. However, the water table within the field is similar to the groundwater table surrounding the system. It follows that there must be some boundary or separation that prevents the cold water from invading the field. It has been argued that accompanying the circulation of cold seawater toward the field and down into the ground, there must occur substantial precipitation of secondary minerals (mainly anhydrite) at the boundary of the thermal system, forming an impervious cap. This will lead to the separation of the geothermal system from the surrounding colder seawater. This separation is considered most advanced close to the surface and to decrease progressively downwards. Mineral deposition sequences in voids indicate a young age and progressive heating (Franzson, 2004). In the upper part of the system zeolites are formed before wairakite and precipitation of anhydrite along with calcite could indicate temporary inflow of colder fluid into the system. Deeper the high temperature minerals epidote, wollastonite and amphibole are among the last to precipitate, indicating that no cooling has occurred in the system.

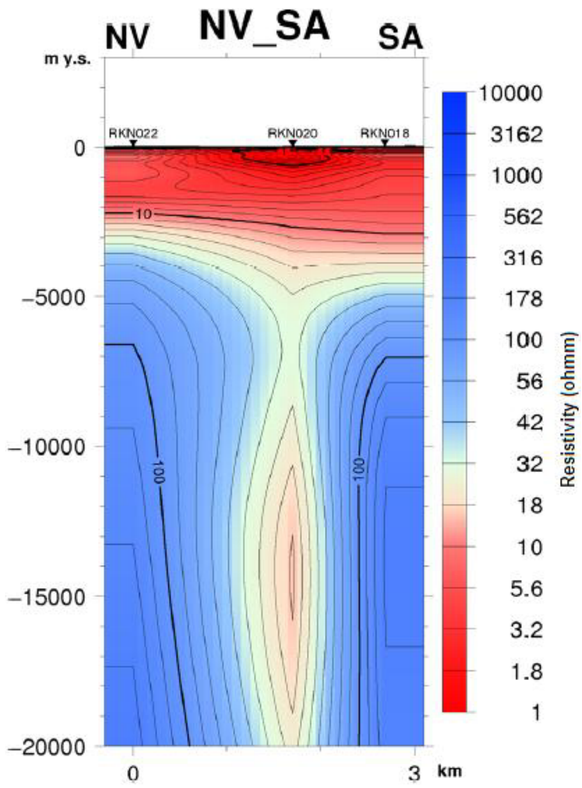

Figure 5: NW-SE cross section over the Reykjanes tip showing resistivity changes down to 20 km depth.

The Reykjanes field gives a unique insight into a submarine geothermal system. The geological succession depicts a steady buildup of volcanic strata within a submarine environment, where the lowest stratigraphic units are pillow basalt formations erupted at relatively deep waters. As eruptive units gradually buildup to shallower depths, the eruptive mode changes to more explosive type and tuffs become more dominant in the succession. At still shallower depths coastal environment is evidenced by reworked sediments eroded from the encroaching shoreline, and containing shallow water fossils. The most recent formations include sub-glacial hyaloclastite formations and sub-aerial lavas indicating the surfacing of this part of the Reykjanes peninsula. The stratigraphic succession is intruded by dykes which become more numerous in the deepest levels reaching there up to 60%.

The conceptual model of the Reykjanes system assumes a limited connection to the other known high enthalpy systems on the peninsula. The Svartsengi field, located about 15 km to the NE (Figure 3), has been in operation for nearly 35 years with drawdown of around 32 bar. In between is Eldvorp field, at some 8.5 km distance, with a drawdown around 21 bar due to the Svartsengi production. Little or no drawdown was observed at Reykjanes due to the Svartsengi production. The volcanic activity acts as a heat source for the system since considerable portion of the magma cools within the system as intrusions. Frequent but generally small earthquakes cause movements on the fractures and maintain good permeability. In the upper most

900 m the temperature and pressure follow the boiling point curve as scarce steam bubbles ascend from depths carrying heat upwards. Below 900 m depth the system is liquid dominated with temperatures up to 320 °C and possibly higher at greater depths. Possibly three fracture directions, that all intersects in the central part of the field, control the main flow paths in the system. Most active is the NE-SW eruptive fissure zone which is the active spreading zone with the hyaloclastite ridges like Raudholl. Then there is a possible short N-S trending fracture indicated by the resistivity measurements and location of feed points in the wells. Finally, there is a hint of a NW-SE transform fault near perpendicular to the spreading zone indicated by feed points and temperature distribution. The main upflow zone is inferred at the intersection of these three fracture zones (Figure 7).

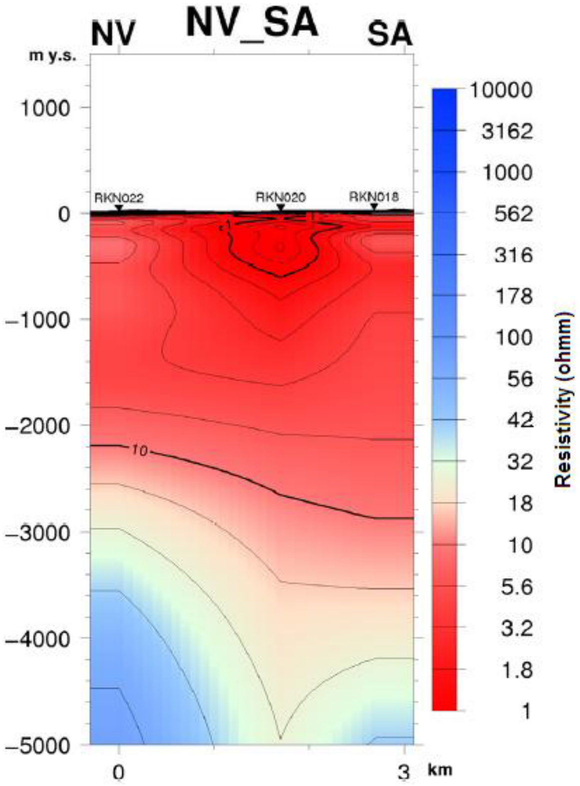

Figure 6: NW-SE cross section over the Reykjanes tip showing in more detail the resistivity changes down to 5 km depth.

3. PRODUCTION FROM THE REYKJANES FIELD

Production started in the 1970's with the discharge testing of the wells in the first drilling phase. The yearly production rates averaged in the range 35-50 kg/s. In the 1980's the production rates increased to 65-80 kg/s as steam and brine was supplied to a sea-chemical plant, a fish drying plant and a small turbine generator. After the operation of the sea-chemical plant stopped in the 1990's the production rates dropped back to 35-50 kg/s. In 1999 well 10 was drilled for the purpose of investigating the field for electrical generation and Hitaveita Sudurnesja, now HS Orka took over the responsibilities for the developments in the field. On the basis of the testing of well 10 and experience from the older researches, a 100 MW_e power plant was designed. In the years 2002-2006 additional 14 wells were drilled to supply steam for the power plant that was constructed in the latter half of that period. The plant came on line in May 2006 with full capacity.

The initial temperature conditions indicated that at top was a colder seawater system, then cap rock was encountered at 400-500 m depth and the first feed zone in the geothermal system encountered below about 750 m. From about 500-600 m the temperature followed the boiling point curve with depth down to 1200 m. Deeper the temperature was below the boiling point curve. Generally, the system was liquid dominated in 2006 before the commissioning of the power plant.

In the beginning of the production for the power plant the enthalpy of the fluid was around 1290 kJ/kg, corresponding to 290°C. The separation pressure is about 19.5 bar-a (211°C) giving a steam fraction about 21%. So the production rate jumped from less than 50 kg/s to 800 kg/s with the commissioning of the power plant. The impact of this sudden production increase caused considerable drawdown in the system, especially in the central part of it where the drilling density is highest (Figure 7). Figure 8 shows the pressure drawdown at 1600 m depth in some of the wells. In May 2009 the drawdown is about 32-34 bar in the central part of the production field and about 19 bar some 500 m away in an observation well (RN-16). The figure indicates that the drawdown is leveling off and possibly approaching some stabilization. This rapid drawdown in the early life of the plant production has raised some concerns, especially at regulating agencies. Such rapid drawdown and to this magnitude is not known for other Icelandic high enthalpy systems that have fluid of meteoric fresh water origin. The concern is partly due to the inexperience of producing seawater systems in comparison to water systems.

HS Orka has operated another power plant at Svartsengi some 15 km NE of the Reykjanes field for nearly 35 years. There the salinity of the geothermal fluid is about two third that of seawater. The temperature there is lower (240°C) and the drawdown is currently around 32 bar for net production of about 240 kg/s. There the drawdown has been sharp for some time when new stages have been added to the plant, but later reached some stability. Svartsengi is the only field in operation in Iceland that has some resemblance to the Reykjanes field regarding geothermal fluid and magnitude of drawdown. It is argued that the difference compared to water systems is caused by the origin of the geothermal fluid. When the cold seawater seeps through the rocks and approaches the heat source its temperature is raised until precipitation of anhydrite starts at moderate temperatures. This scaling is commonly more intensive at shallower depths than other type of scaling that can be found in water systems. Therefore, the natural recharge to the upper most 1000-1500 m is reduced for the seawater system in comparison with the water system while deeper the natural recharge can be similar. This leads to that greater drawdown is needed in the seawater system to induce the same amount of recharge as water system would obtain. On the other hand this self-sealing property of seawater systems can be advantageous when the system is produced for electrical generation. This larger drawdown can induce the forming of a steam cap at the top of the systems which can result in highly productive steam wells.

With the sharp drawdown in the Reykjanes field boiling has occurred and steam cap is forming in the central part of the field. The main feed zones in the Reykjanes system are commonly in the depth ranges 800-1200 m and 1900-2300 m depths. The upper range falls within the depth range where the temperature was initially at the boiling point curve. This has further enhanced the forming of the steam cap. Deeper the system is still liquid dominated. As the boiling has enhanced, the enthalpy of the production wells has increased, since most of them have connections to both the upper and deeper feed zones. Currently the average produced enthalpy is around 1500 kJ/kg and correspondently the mass withdrawal has been reduced. This has aided in the reduction of the drawdown rate. Furthermore, two relatively shallow production wells were directionally drilled into the steam zone in 2008. The pressure encountered at 1000 m in the steam zone was 53 bar (269°C). These wells have been put on line which has further reduced the mass withdrawal, now totaling less than 600 kg/s.

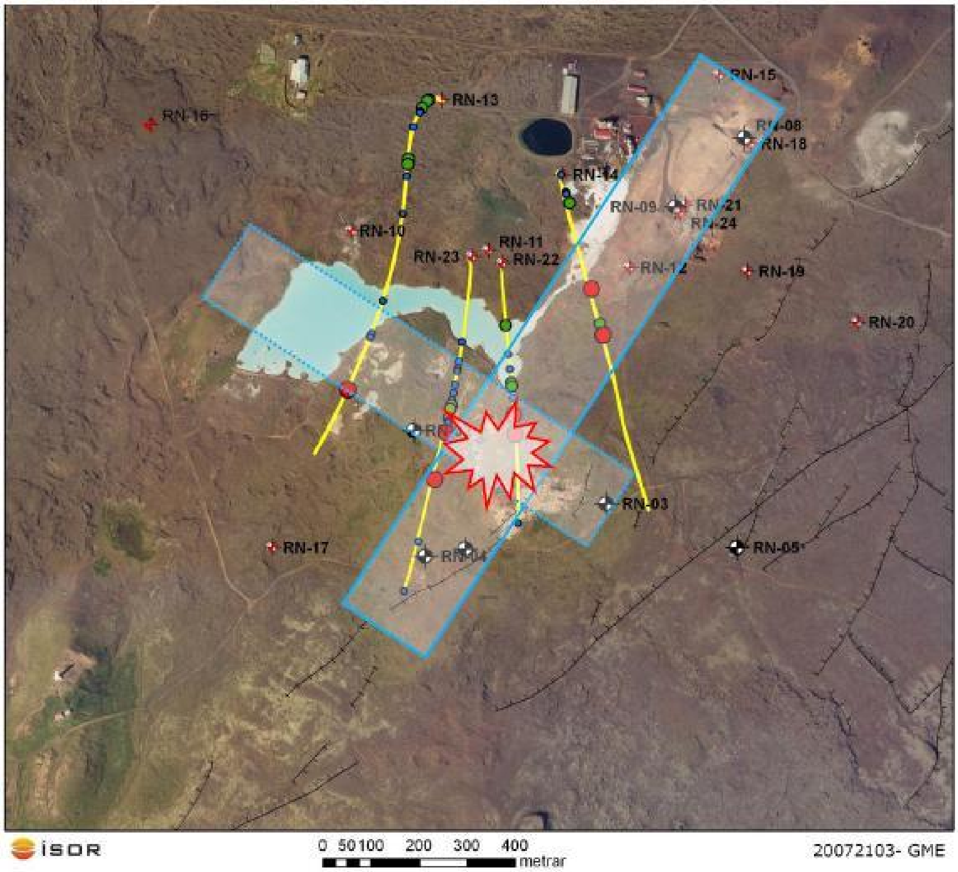

Figure 7: Main features of the conceptual model, two of the fracture zones (blue boxes) controlling the permeability in the production area. Highest inflow to the system at their intersection (star).

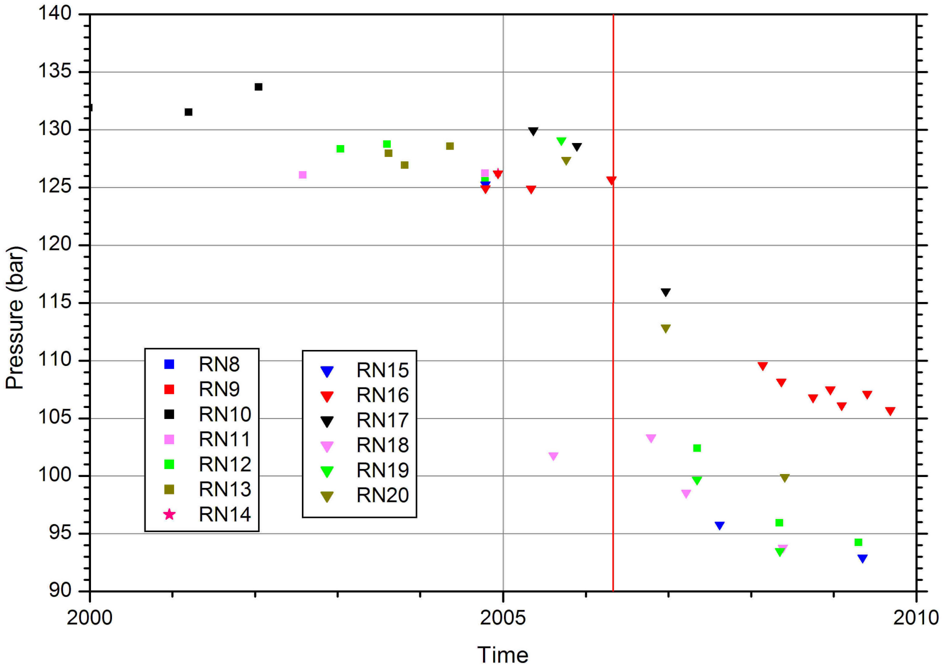

Figure 8: Pressure change at 1600 m in the Reykjanes field. The increased production starts in May 2006 (red vertical line).

4. CURRENT DEVELOPMENTS

Recently the environmental impact assessment was completed for the enlargement of the Reykjanes power plant by an additional 50 MW_e unit that would be identical to the other two units in operation. The addition would bring the generation up to 150 MW_e. Furthermore, it is possible to add a low pressure flash unit with an output in the range 30-50 MW_e. The low pressure unit is in design phase. It would take steam from the secondary flash of the separated brine from the other three high pressure units. Possibly it would incorporate a high pressure stage, allowing it to generate up to 50 MW_e during periods when some of the other units are being maintained.

In recent years the power plant operation permits, issued by government regulating authorities in Iceland, have been based on produced heat energy or heat power. Therefore, the production scenarios evaluated for the enlargement of the power plant refer to produced heat power from the geothermal system. The alternatives evaluated involve increased heat production of up to 400 MW_t, increased heat production in the range 250-300 MW_t, production within the current heat power limit (1000 MW_t) and finally a zero term. The zero term means that the production remains basically unchanged from what it is for the current power plant. The most heat production involves steam production from wells intercepting both the upper and deeper main feed zones, while the one for the less heat power requires that about two third of the additional steam would come from the upper feed zones or the steam cap. To stay within the current heat power permit would require a reevaluation of the production strategy.

The drawdown induced by the enlargement of the power plant has been evaluated by a numerical distributed parameter model (TOUGH2) (Hjaltarson and Juliusson, 2007 and Bjornsson et al. 2008). Figure 9 shows the estimated average drawdown by the model at the observation well in the field (RN-16). The match with observed data is good there, but the model underestimates the drawdown in the central part of the well field. Time has not allowed for recalibration of the model yet, but the model is considered representative for the current prevailing conditions in the system. Observations have indicated that the pressure in the central part of the well field follows the pressure at the observation well, but is about 12-14 bar lower. Furthermore, the model estimates that the drawdown is reduced by about 1 bar for every 25 kg/s reinjected to the system.

Reinjection, although planned from the early stage of production, has not been implemented, as studies on scaling have not been concluded. Also, the close proximity of the power plant to the sea score has allowed the effluent brine to be channeled to the sea. This has not been a problem as chemicals in the effluent have been within environmental and health limits. However, reinjection trial with a mixture of separated brine and condensate was started in middle of July 2009, as a mitigating measure against the drawdown. In the trial about 40 kg/s are injected to well 20 at temperature around 150°C. Well 20 is furthest to the east (Figure 7) and was reworked in 2008 by sidetracking towards southeast. The goal is that the injection could correspond later on to 30-50% of the mass withdrawal or at least to the additional mass withdrawal for the plant enlargement.

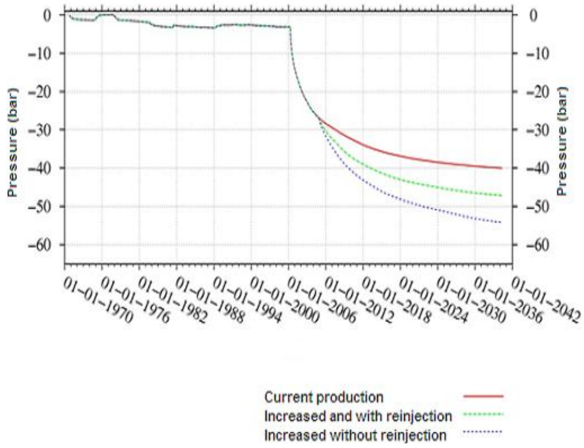

Figure 9: Average pressure drawdown at Reykjanes field for current production and increased production with and without reinjection.

5. DISCUSSIONS

In view of the current drawdown and with the estimated increased drawdown for the enlargement of the power plant has made regulatory authorities reluctant toward it. The drawdown would then be the largest observed in Icelandic geothermal systems. The knowledge on seawater geothermal systems is also limited compared to regular water systems making regulatory authorities more uncertain in their position. Governmental agencies are required to comment on the environmental impact assessment and have expressed opinions where sustainable production and resource conservation are in some instances intermixed with the thought of "sustainable development". However, sustainable production or resource conservation does not necessary need to apply for sustainable development of communities to take place. As sustainability has become a fashion word used extensively without clear definition, unrealistic constrains could be put on operators of geothermal resources in the future.

The current outlook for the enlargement of the Reykjanes power plant is that the limit for produced heat power could possibly be restricted to none or small increase. To comply with such restriction the production strategy would need to be reevaluated. For that situation about half of the generated electricity would need to be generated with steam from the steam cap. First steps in that direction have been taken with the drilling of two wells into the high pressure steam cap in 2008. The purpose is to get first estimates on the capacity of the steam cap that is developing. The enlargement could require drilling of about 7 additional production wells, thereof about 4 would need to be targeted towards the steam cap while the rest would be targeted to enlarge the well field.

If the solutions from the reinjection trials proof feasible, then at least two more injection wells are need. Location for a permanent reinjection site has not been determined yet, but a promising site could be at the outskirts of the field towards northeast. It would be in the direction of the NE-SW eruptive fissure zone. Subsidence has been measured at the Reykjanes field, but currently only preliminary results are available. The high production impact following the commissioning of the power plant and the sharp drawdown that it has caused has brought about subsidence that extends outward from the geothermal field. Some anisotropy is in its distribution as it extends more in the NE-SW direction along the eruptive fissure zone. Figure 10 shows an interpretation of InSAR ascending and descending interferogram for the time period 2005-2008 (Jonsson, 2009). The magnitude of the subsidence is about 9 cm (3.5 in) in the central part of the well field and diminishes away from the well field. The subsidence is measured in an area of more than 16 km^2 and has affected an area close to 30 km^2 as it extends out form the coast. These preliminary results can be interpreted such that the production is draining fluid from a much larger volume than earlier studies indicated. Rule of thumb calculations for generation capacity per aerial extension of the geothermal system are then supportive for the power plant enlargement.

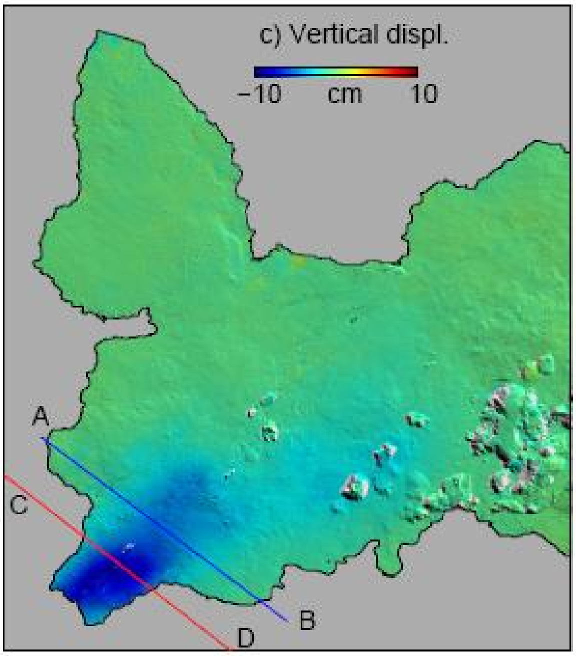

Figure 10: Unwrapped version of complex-value multiplication of one ascending and one descending interferogram resulting in a vertical displacement in cm (from Jonsson, 2009).

6. CONCLUSIONS

The Reykjanes power plant is generating 100 MW_e and environmental impact assessment has just been completed for enlargement to 150 MW_e. Another 30-50 MW_e low pressure unit is in the design phase. The estimated drawdown that could become more than 50 bar, would be the largest known in Icelandic geothermal system. Small scale reinjection trials have recently started but at larger scale it could mitigate the drawdown to some extent. Future exploitation of the geothermal system will have to compensate for that behavior. Furthermore, regulatory constrains could be imposed on the production with unforeseen results.

REFERENCES

Bjornsson, H., Thorgilsson, G. and Halldorsdottir, S., 2008: Reiknilíkan af jarðhitakerfinu á Reykjanesi. Spá fyrir 50 MW_e vinnsluaukningu frá árinu 2011. (*Numerical model of the geothermal system at Reykjanes. Prediction for 50 MW_e increased production from the year 2011*) (in Icelandic). Short report ISOR-08053, 70 p.

Bjornsson, S., Arnorsson, S., Tomasson, J., Olafsdottir, B., Jonsson, J., and Sigurmundsson, S. G., 1971: Reykjanes – Heildarskýrsla um rannsókn jarðhitasvædisins. (*Reykjanes - Final Report on Exploration*) (in Icelandic). Iceland Energy Authority, 122 p.

Franzson, H., 2004: Háhitakerfið á Reykjanesi (*The high temperature system at Reykjanes*) (in Icelandic). *Report* ISOR-2004/012, 68 p.

Fridleifsson, G.O. and Albertsson, A.L., 2000: Deep Geothermal Drilling on the Reykjanes Ridge Opertunity for International Collaboration. *Proceedings* World Geothermal Congress 2000, pp 3701-3706.

Gudmundsson, J.S., Hauksson, T. and Tomasson, J., 1981: The Reykjanes Geothermal Field in Iceland: Subsurface Exploration and Well Discharge Characteristics. *Proceedings* Seventh Workshop on Geothermal Reservoir Engineering, Stanford. CA (1981), pp 61-69.

Hjartarson, A. and Juliusson, E., 2007: Reiknilíkan af jarðhitakerfinu á Reykjanesi og spar um viðbrögð þess við 100 MW rafmagnsframleiðslu. (*Numerical model of the geothermal system at Reykjanes and predictions for 100 MW electrical generation*) (in Icelandic). *Report* ISOR-2007/025, 145 p.

Jonsson, S., 2009: Subsidence around the Reykjanes and Svartsengi Power Plants during 1992-1999 and 2003-2008 observed by InSAR. *Report* to HS, 42 p.

Lindal, B., 1975: Development of Industry Based on Geothermal Energy, Geothermal Brine and Sea Water in the Reykjanes Peninsula, Iceland. *Proceedings* Second U.N. on Development and Use of Geothermal Resources, **3**, pp 2223-2229.

Karlsdottir, K. 2005: TEM-mælingar á Reykjanesi 2004. (*TEM-measurements at Reykjanes 2004*) (in Icelandic). *Report* ISOR-2005/002, 23 p).

Rosenkjær, G.K. and Karlsdottir, K. 2009: MT-mælingar á Reykjanesi 2008. (*MT-measurements at Reykjanes 2008*) (in Icelandic). *Report* ISOR-2009/002, 45 p.