Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Turning Up the Heat

Aðalsteinn Möller [a*], Cansu Ari[b], Max Bilfinger[b] and Stephen Boyce[b]

[a] Veitur Utilities, Bæjarháls 1, 110 Reykjavík, Iceland

[b] Schlumberger Artificial Lift, Harlaw Industrial Estate, 1 Harlaw Rd, Inverurie AB51 4TE, United Kingdom

[*] adalsteinn.moller@veitur.is

Keywords: district heating, low temperature fields, electrical submersible pumps system, water level monitoring, high voltage, reservoir management

ABSTRACT

The presentation will discuss the application, benefits and challenges of using high voltage Electrical Submersible Pumps (ESPs) in geothermal wells. Despite the benefits of high voltage ESPs, Line Shaft Pumps have been the primary lift method of choice in Iceland up to this point. By using high voltage ESPs, the developer can achieve greater depths, increased efficiency, lower cost, higher operating temperatures, lower noise, faster installation (less downtime) and the 24/7 monitoring of downhole conditions. ESPs have a very large appetite for power, but also have the highest output of fluid versus all other lift types. Retrievable ESP packer technology also allows controlled production from various depths of the well.

Veitur Utilities is the largest utility company in Iceland. Veitur main responsibilities are distribution of hot water, electricity, potable water and sewage system throughout the Capital region as well as several municipalities both in the south and west of Iceland. Their distribution system is extensive; pipes and cables total 9,000 km in length, corresponding to the distance from Reykjavík to Shanghai. Veitur operate more than 80 geothermal wells producing up to 3200 l/s of geothermal fluid and 2300 l/s of heated ground water for district heating systems of more than 1,34 GWth for 13 individual district heating systems providing heat for more than 230.000 people. A majority of Veitur's wells are using Line Shaft Pump as the lift selection. However, beginning in 2018, Veitur started implementing Schlumberger ESP systems as a solution in Iceland. The first installation took place in Laugaland in S-Iceland in December 2018 following a detailed design, manufacturing and delivery process. A second installation took place at Bakki, S-Iceland early 2019.

The presentation will reveal multiple case studies with specific details surrounding technical design philosophy, depth, temperature, flowrate, installation date, accumulated production and ESP uptime. These case studies will highlight specific success stories, challenges and lessons learned during the planning and installation phases.

1. DEVELOPMENT OF GEOTHERMAL WATER PRODUCTION

The oldest sources of district heating in Iceland are from 1908. Then Stefán B. Jónsson in the Reykjahverfi area in Mosfellssveit harnessed a geyser called Amsterdamhver and led water through a pipe to his residential building for heating purposes. At similar time Erlendur Gunnarsson from Reykholtsdalur Borgarfirði also harnessed steam from Sturlureykjahver and led a pipe to his residential building for the same reason. Until then Icelander had only utilizes geothermal water for bathing and washing.

The district heating system continued to develop simultaneously in these places in the coming years. Deildartunga and Kleppjárnsreykir from 1920 and Álafoss in Mosfellssveit and by the end of the 1930s several dozens of buildings have been heated by geothermal district heating in Iceland.

Before the turn of the 19th century, people started drilling in hot springs for electricity production. The French are the first to have a hot water supply of 30 houses in the 14th century (Chaudes-Aigues).

Drilling for geothermal water in Iceland began in 1928 and lasted until 1930. Wells were drilled directly into geysers and hot spring that already produced geothermal water. The result was 14 artesian flowing wells producing geothermal water of 67-98°C depending on each well. Production rate went form 12 l/s to 24 l/s.

In 1930 a 2,7 km long 200 mm transfer pipeline and 2,3 km long district heating system from Laugarnes to Austurbæjarskóli and the surroundings supplying hot water for space heating to 58 houses. This construction opened up a new chapter for geothermal district heating in Iceland for the next half a century, until the 1990 commissioning of the Nesjavellir power plant. Hundreds or thousands of wells were drilled over this period and Iceland became geothermally heated, and oil and gas retreated. Today there are 975 wells listed for geothermal district heating in Iceland however, the number of active production wells is unknown since many are privately owned. Veitur are the largest utility company in Iceland owning over a hundred of district heating wells with 80 of them active production wells supplying geothermal water to over 200.000 people. Thirteen separate district heating networks spread across the island totaling 3000 km of pipes depend on their production which on a cold day can go up to 2900 l/s.

2. ARTIFICIAL LIFT

In Iceland, the earliest method of increasing well production is by airlift. Airlift is a method of pumping fluid out of wells and is widely used, mainly in the oil and gas industry today. Air is pumped with a thin pipe deep into the well, but by doing so, the air is mixed with the water and becomes less dense. The density difference between the air-water mixture and the water causes the air-

water mixture to be pushed to the surface along the well. The airlift method did not last for long since the compressed air increased the oxygen level of the water, leading to the severe corrosion of all steel pipes and parts in contact with the water.

Lineshaft pump. The line shaft pump is a vertical multi-stage centrifugal pump powered by a hollow shaft electric motor located on the well top. A shaft inside the production riser pipe connects a motor and a pump that is deep in the well. Between each riser pipe segment is a centralizer holding a lubrication pipe. On the couplings of the lubrication pipe is a radial shaft bearing holding the long axle shaft in place along the riser pipe, which is lubricated from a lubrication system located at the surface. The first installed lineshaft pump in Iceland was Swedish and was called Craelius from Svenska Diamat Berboring A.B. The pump was installed in a well at Rauðarárstígur in Reykjavík. A promising result led Hitaveitan to tender for more pumps, which was finally awarded to Floway and Fairbank Morse. Serious malfunctions and contamination of oil from bearing lubrication where challenging at this time. In 1966, entrepreneur and CEO of Hitaveitan, Jóhannes Zoega came up with an idea of using a material called Teflon invented by DuPoint and used by NASA. The Teflon bearing was water lubricated and could withstand the high temperature of the geothermal water.

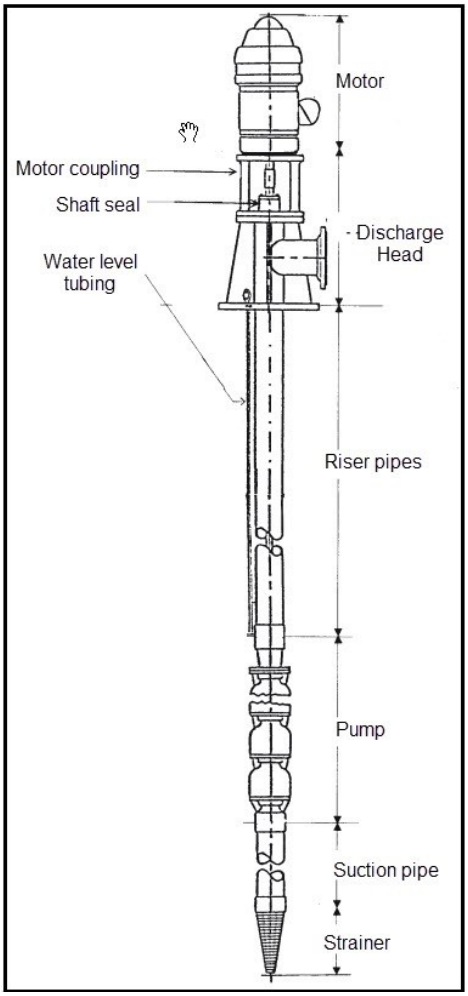


Figure 1: Lineshaft pump

This invention marked a new era for geothermal district heating systems and in the following years the lineshaft pumps became the industry standard and proved to be both reliable and efficient. By1990 the number of installations was close to one hundred spread across around Iceland. Even though the line shaft pump has been a major success for geothermal development in Iceland there are a few downsides that cannot been overseen. Pump depth is limited and when reaching 250 m below well top the calculation of thermal expansion, shaft expansion, riser pipe shortening etc. becomes complex and the required clearance between impellers and pump housing mandates a custom built pump with extended lead time and price. Cost of the riser pipe and shaft assembly is high since each pipe segment is only 3 m making the total number of couplings, centralizers, bearings, lubrication pipes, shaft couplings and shaft to be fabricated high. Mechanical loss of the long axle shaft can reach 20% if for deep installations. The complexity of the construction makes it both expensive and time consuming from a maintenance perspective. Lubrication system, shaft seals, motor bearing, lubrication pipe seal and motor coupling all require onsite maintenance. Pulling and installing a lineshaft pump into a well is time consuming and requires a specific knowledge and training that is not common in Iceland. Typical installation time is 5-7 days.

Electrical Submersible pump(ESP). Since the ESP came on the market in 1929, it has spread all over the world and is one of the most common solutions for artificial lift from wells, water tanks, sewage systems, oil wells, seawater and more. The main weakness for a traditional ESP for geothermal wells are the bulky electrical cables and low temperature rating of the motor. During installation of 400V ESP in a geothermal well a risk of cable fault is always present due to the debris of the wells casing and unprotected rubber insulation. The most common 400V ESP pumps are able to withstand 60°C and up to 80°C with a minor upgrade of o-rings and seals. This is widely used in low temperature fields and it may be assumed that hundreds of them are already installed. The benefit of these

pumps is low cost, simple installation and relatively low maintenance if water temperature is below 80°C. In many installations, the chemical content of the geothermal water affected the cable insulation and the cable splicing. This causes water to enter the motor, resulting in a short circuit. The chemical affecting the insulation has not been identified but is suspected to be H2S and CO2 which are present in most geothermal water. When Franklin Electric introduced the high temp 90°C motor, an important improvement took place for the geothermal district heating industry. These motors where limited to 30 kW and suited for smaller privately-owned wells but for Veitur the most common motor size is 100-150 kW. Other vendors provide larger sizes for temperatures below 85°C. Veitur have installed overall four such pumps in wells MG-04, MG-06, MG23, and MG-15 since 2018 the size range of 20-40 l/s,one of which had a major malfunction and was pulled for inspection. Veiturs short experience from these larger pumps have not indicated a reliable and efficient equipment, yet but further development may be needed regarding the installation process and cable design.



Figure 2: MG-23 installation of 400V ESP

High voltage (up to 5 KV) ESPs have come a long way from the systems described earlier. The main constraints in terms of temperature rating and corrosion susceptibility have been addressed by technology improvements and manufacturing methods. Material development for bearings and electrical insulation has found its way into the ESP industry, allowing for much widened operating envelope. Pump efficiencies have been optimized with the help of CFD simulations during the design process and casting methods as well as surface coating have complemented this process. High voltage ESPs selected are a multistage centrifugal, compression construction design with Abrasion Resistant (ARZ) bearings. ARZ pump technology offers an enhanced radial stability and resistance to wear, extending operational life beyond that of a standard pump. Compression pumps are used when operating outside the recommended pump range or/and the production of abrasives is a possibility. The compression construction design allows the pump to run outside the low end of the recommended operating range in “down thrust” area of the curve since the high load thrust bearing in the Protector is designed to mitigate the impact of these forces. In compression pumps, all impellers are fixed to the shaft, which minimizes the chances of abrasive particles getting in-between the shaft and the bearing, reducing shaft wear and improving run life for the system. Having relative benign fluid properties in terms of H2S and CO2 concentrations, carbon steel housings with Inconel shaft are considered adequate for most geothermal district heating application. Apart from absorbing the downthrust generated by the pump, the Protector section between pump and motor isolates the motor from well fluid while maintaining a pressure equilibrium. The Protector is a modular system of labyrinth type sections, which work on the principal of gravity separation of fluids of different density to segregate well fluids and motor oil. The employed protector comprises three labyrinth chambers (the second and third chambers provides redundancy) which are isolated from each other by a mechanical shaft seal above and below each chamber. A PEEK coated tilt pad thrust bearing is situated in the clean fluid at the base of the protector section where it is furthest away from well fluid. Self-lubricating polymer-lined radial bearings are located in each seal body and the base of the protector to optimize performance even in poor lubrication conditions and high temperatures.

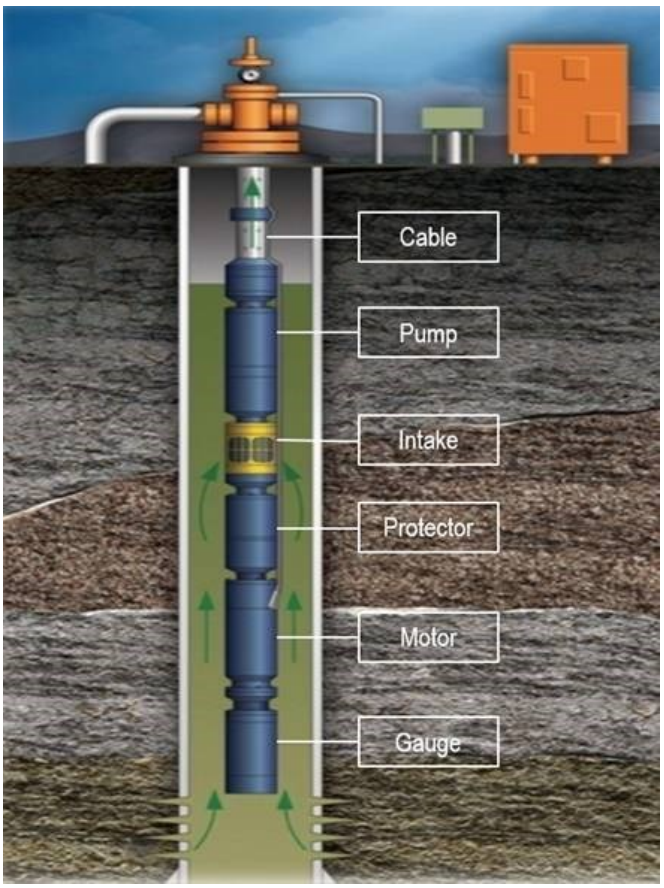


Figure 3: High voltage ESP system

The motors are two pole, three phase squirrel cage induction type with unvarnished polyimide magnet wire, designed to withstand a stator winding temperature up to 204°C. Oversizing the motor and operating it at a low load factor, can help to minimize the winding temperature. A PEEK coated tilt-pad thrust bearing support the weight of the rotor assembly while DP4 coated bushings and steel sleeves of the rotor bearings provide radial stability. Aflas elastomers are used throughout the assembly for o-ring seals. A downhole gauge attached to the base of the motor incorporates high-temperature microelectronics and digital telemetry to provide real time data on intake pressure, intake temperature, motor winding temperature, vibration and current leakage. This provides comprehensive data needed to protect the ESP system integrity and to optimize the well performance. Data communication and power supply of the gauge is over the ESP power cable using digital DC current modulation.

In 1981 Norðurorka installed the first high voltage ESP system in well TN-4 in Eyjafjörður. The ESP was a REDA M520 20Þ, installed at 390 m below welltop and producing 34 l/s with a 161 kW motor. Norðurorka had problems in the beginning with the REDA ESP probably due to lack of knowledge of this equipment as is common when adopting new technology. The ESP came without VSD or softstarter and Norðurorka ran the pump in start-stop mode to compensate the daily demand curve of the district heating system. Soon the motor failed and was replaced but other problems occurred, and the cable armor corroded due to non-airtight welltop and damaged the cable. The ESP system was replaced several time between 1981 and 2001 due to malfunctions but in the following years Norðurorka made adjusted of the operation pattern, limiting starts and stops to one or two per year and sealed the welltop. According to Norðurorkas district heating maintenance manager this extended the lifetime of the ESP significantly. Since 2008 the same pump has been in operation with scheduled maintenance stop in 2016 and was declared in good condition and is up and running today.



Figure 4: Nameplate of the TN-4 REDA ESP

Why high voltage ESP system was not developed further in Iceland for geothermal until 2018 when Veitur installed ESP for LL-06 is unknown to authors and is left unanswered in this paper.

2. CASE STUDIES

In 2018 Veitur purchased two high voltage ESPs for well LL-06 in Laugaland and BA-01 in Bakki, both in the southern region of Iceland and since January 2019 LL-06 was successfully commissioned, soon followed by BA-01 which marked a new era of geothermal district heating in Iceland. The promising cooperation of Veitur and Schlumberger led to a further development for Veitur and early 2019 two high temperature pumps where purchased for wells HS-08 and HS-09 in Hveragerði as a development project. Veitur put out an open tender later that year and two more pumps where ordered from Schlumberger for wells RV-41 and RG-20 making a total of six high voltage ESPs installed in the two years period of 2019 and 2020



Figure 5: High voltage ESP site locations

2.1 LL-06

Well LL-06 was drilled 2017 after a challenging selection of site location. Previous to LL-06 only well LWN-04 at Laugaland had proven to produce water of higher temperature than 70°C in this geothermal field. Temperature maping indicated that heat was present, but porosity had proven poor from previous production wells. Geoscientist believed going deeper could result up to a 120°C of porous rock. LL-06 was drilled only 30 m distance from LWN-04 to 1847m depth with a production casing down to 1195. Drilling process was complex due to nearby producing LWN-04 well. The result was not as Veitur had hoped for and production and temperature measurements indicated 97-98°C of 30l/s.

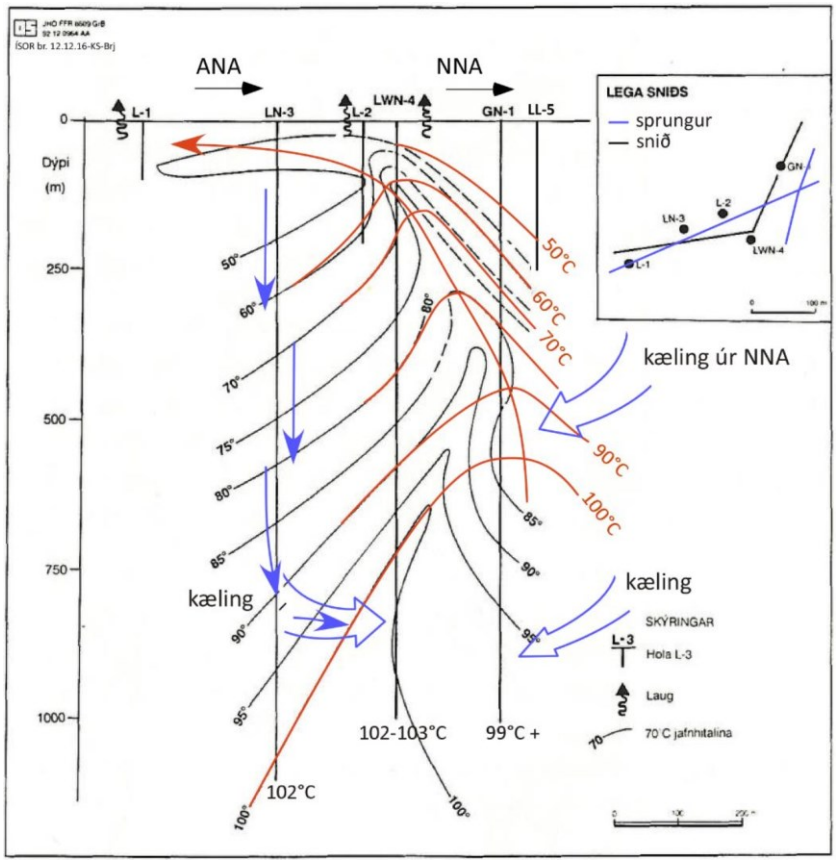


Figure 6: Temperature map of Laugaland geothermal field

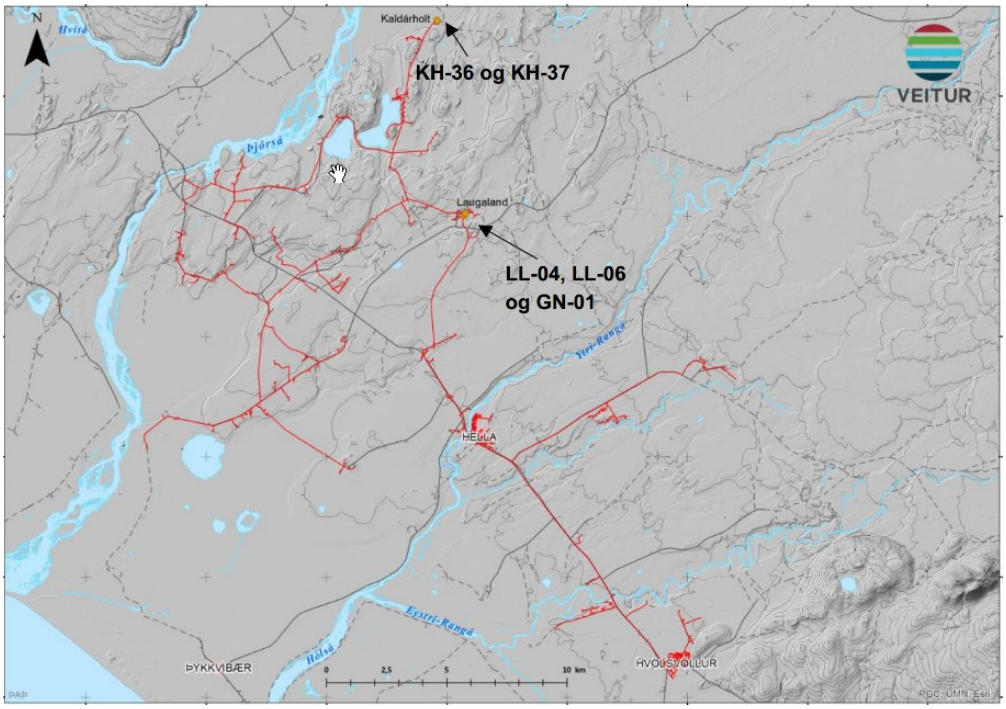


Figure 7: Overview of Rangárveita district heating system

The Laugaland geothermal field has a relatively low fluid inflow which is seen by the water level decline during production. Water level in LWN-04 goes from 50m below well top to 200m during winter season. For such application deep installation is required and in 2018 the first installation of a Schlumberger ESP was selected system by Veitur. Well LL-06 is completed with a 13-5/8" casing with an ID of 313.6 mm. The setting depth of the pump intake is at 265.6 m. The LL-06 pump design considered a fluid level variation between 40m and 200m with an inflow performance of 500 m3/d and anticipated production rates of 20 – 25 l/s at a manometric head of 260 m. The well is vertical at the pump setting depth and the equipment selection is listed below:

	LL-06 ESP Equipment
Pump	675 Series, J12000 - Compression construction, - CS housings, - Ni-Resist Stages, - SS head and base, - ARZ bearing configuration, - High strength Monel shaft, - Bolt on Intake
Protectors	540 Series, Maximus - CS housings, - CS steel body, - LSLSL chamber arrangement, - Inconel 625 shaft, - HL thrust bearing - Reda #6 motor oil,
Motor	562 Series, Maximus - Single Sections with 6 rotors - 225 HP, 2682 V, 51 A @ 60 Hz 100% - CS housings, - CS head & base - Un-varnished Kapton winding, - Reda #6 motor oil, - 400°F winding temperature rating
Main cable	RedaMAX 400 - AWG #4 - Round profile - Galvanised Armour - EPDM Insulation - EPDM Jacket - 5 KV Voltage rating - 400°F temperature rating
Motor lead extension	MaxLok400 - AWG #4 - Monel Armour - EPDM Insulation - Lead Jacket - 5 KV Voltage rating - 400°F temperature rating

Table 1:LL-06 ESP Selection

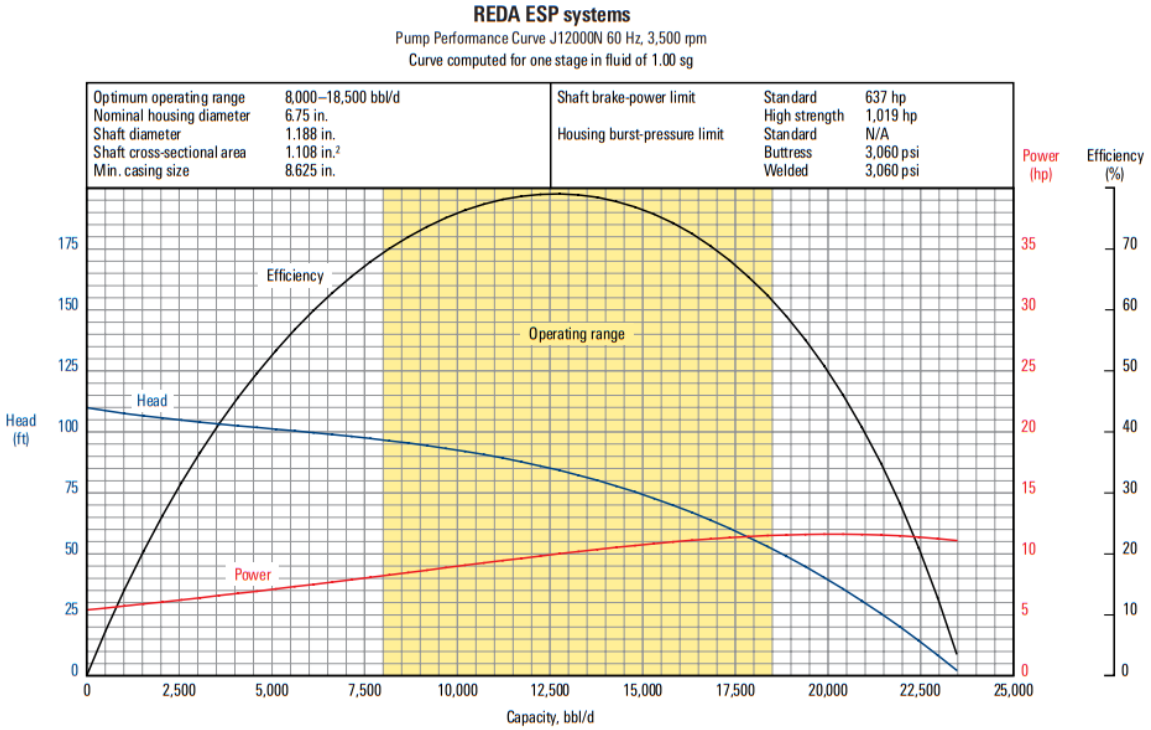


Figure 8: LL-06 Pump performance curve at 60 Hz

The recommended operating range of LL-06 at 60Hz is between 14,5 l/s and 34 l/s. The Net Positive Suction Head required (NPSHr) is shown in Figure 3. At 25 l /s (~ 400 GPM), the NPSHr is 28ft (~ 8.5 m). In terms of metallurgy, Carbon Steel housing, head and base were selected for this application.

The Protector selection is based on a modular system of labyrinth type sections which work on the principal of gravity separation of fluids of different density to segregate well fluids and motor oil. The proposed 562 series Maximus protector comprises three labyrinth chambers which are isolated from each other by a mechanical shaft seal above and below each chamber. The thrust bearing is situated in the clean fluid at the base of the protector section. A high load thrust bearing rated to 22,750 lbf has been selected to carry the impeller and shaft down thrust.

Self-lubricating polymer-lined radial bearings are located in each seal body and the base of the protector to optimize performance even in poor lubrication conditions and high temperatures.

The selected motor is a single 562 series Maximus motor with MaxLok pothead. The winding code provides a 60 Hz nameplate rating of 225 HP(168 kW), 2682 V, 51 A.

Main power cable is a three phase #4 AWG RedaMAX 400, which has been chosen to complement motor requirements and offer reliability in the down-hole operating environment. It is rated to 5000 Volts at 200°C maximum operating temperature. Each of the three EPDM insulated tinned copper conductors are a common overall EPDM jacket. Round profile interlocking galvanized steel armour provides mechanical protection and pressure containment for the power cable.

Motor Lead Extension (MLE) - A 562 series MaxLok pothead with #4 AWG flat cable has been selected. The cable comprises of three EPDM insulated copper conductors which are protected by a lead jacket and flat profile Monel armour. Both, pothead and cable are rated to 5kV, 205°C. The MLE design selected features a plug-in pothead which reduces ESP installation time, minimizing rig or service costs during the installation, as well as the risk of rain, snow or debris getting into the motor head.

Installation of LL-06 ESP was slow and had some major issues due to riser pipe coupling design. Installation during cold winter of Iceland lasted for 21 days with numerous stops which can be explained by Veiturs lack of experience in high voltage ESP system. The overall successful and since the pump was commissioned in December 2018 and production started in January 2019 it has run fluently and met its expectations. The well proved to produce 98°C water and production index was higher than LWN-04. Production rate of the Laugaland geothermal field and the Rangárveitur district heating system reached a new elevation. The downhole gauge provided real time information of the well allowing more aggressive production from the field without compromising sustainability or mechanical faults of the pump.



Figure 9: Installation of LL-06 ESP

During a cold period in the district heating system Rangárveita LL-06 ESP managed to race the temperature of the reservoir tank from 77°C to 80°C. In district heating systems higher temperature means lower fluid velocity since the demand is energy and can be explained by the following equation:

$$Q = \dot{m} * T1 - T2 * C_v$$

where $Q, \dot{m}, T1, T2\ and C_v$ are energy, mass flow rate, inlet temperature, return temperature and fluid specific heat, respectively.

The result of the higher temperature was a lower volumetric flow demand in the district heating system and the numerous pumping stations in the system where able to maintain the pressure at the people's houses. Past winters had both been exceptionally cold and the rapid increased number of users had put the district heating system to its peak performance.

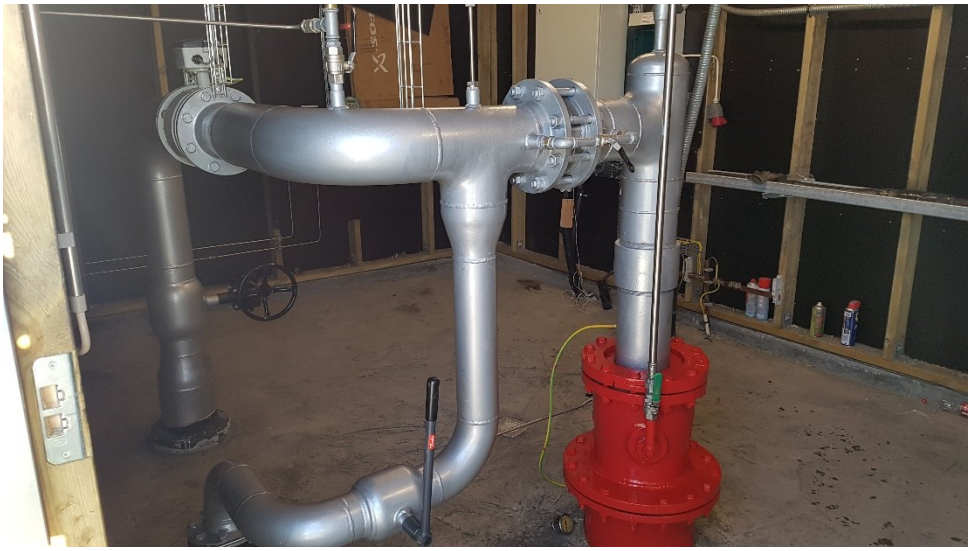


Figure 10: Well top at LL-06

2.2 BA-01

BA-01 is 885 m deep and was drilled in 1977 with a casing only down to 204 m. The well was artesian flow and has been in constant production for Þorlákshafnarveita since 1979 when the Þorlákshafnarveita was founded and started operation. The well produced up to 22 l/s of 110°C mixture of steam and water which was separated in an atmospheric gravity separator and water pumped by 11 km transfer pipeline to the municipality of Þorlákshöfn. Along with well HJ-01 the district heating system was able to produce up to 50 l/s.

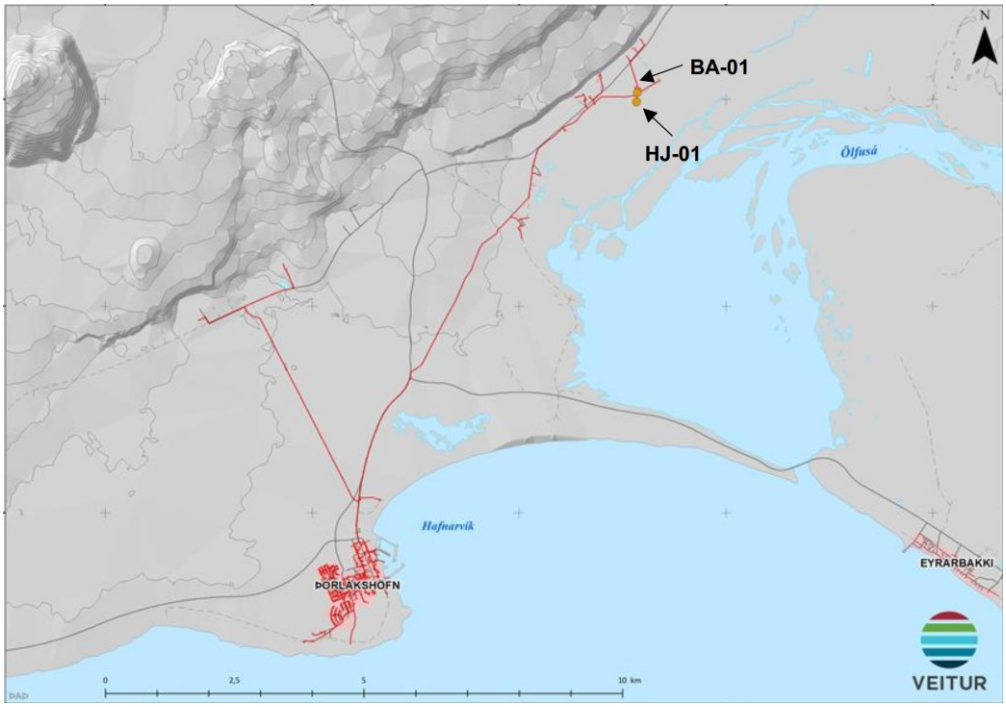


Figure 11: Þorlákshafnarveita district heating system

As in Rangárveita the demand for district heating has been gradually increasing for the past years and a decision of installing a high voltage ESP in well BA-01 to expedite the adoption of high voltage ESP. Water level of the well was unknow due to the artesian flow and the bottom temperature was estimated 120°C. Well BA-01 is completed with a 10-3/4" casing with an ID of 255 mm. The anticipated setting depth of the pump intake was set at 81 m. The BA-01 well benefits from a much higher inflow of 2300-2500 m3/d, providing an almost stable fluid level of 10 m. Expected production rates are 960 – 3500 m^3/d at a manometric head of 45 m and 58 m respectively. The well is vertical at the pump setting depth and the equipment selection is listed below:

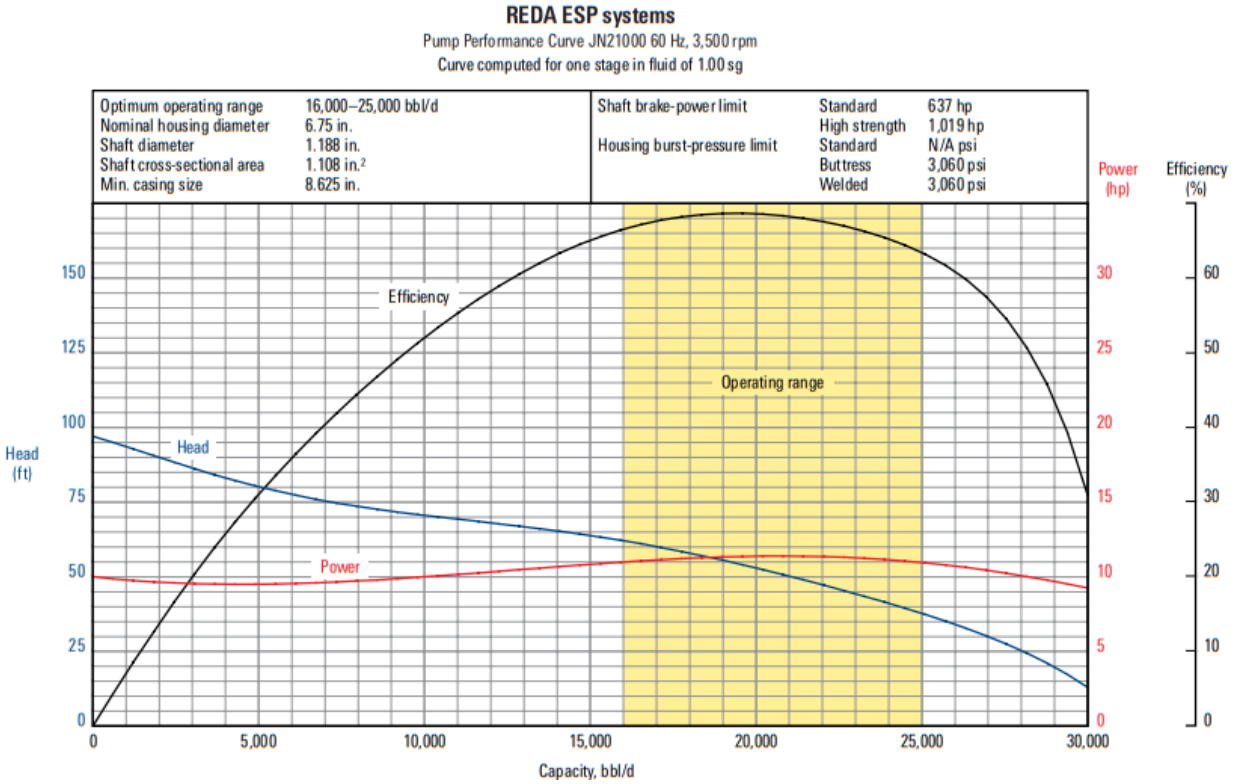


Figure 4: BA-01 Pump Performance Curve at 60Hz

	BA-01 ESP System
Pump	675 Series, JN21000, 5 Stages - Compression construction, - CS housings, - Ni-Resist Stages, - SS head and base, - ARZ bearing configuration, - High strength Monel shaft, - Bolt on Intake
Protetors	540 Series, Maximus - CS housings, - CS steel body, - LSLSL chamber arrangement, - Inconel 625 shaft, - HL thrust bearing - Reda #6 motor oil,
Motor	562 Series, Maximus - Single Sections with 2 rotors - 75 HP, 1272 V, 36 A @ 60 Hz 100% - CS housings, - CS head & base - Un-varnished Kapton winding, - Reda #6 motor oil, - 400°F winding temperature rating
Main cable	RedaMAX 400 - AWG #4 - Round profile - Galvanised Armour - EPDM Insulation - EPDM Jacket - 5 KV Voltage rating - 400°F temperature rating
Motor lead extension	MaxLok400 - AWG #4 - Monel Armour - EPDM Insulation - Lead Jacket - 5 KV Voltage rating - 400°F temperature rating

Table 2:BA-01 ESP Selection

The recommended operating range at 60Hz is between 2544 m3/d and 3975m3/d. The Net Positive Suction Head required (NPSHr) is shown in Figure 5. At 25 l/s (~400 GPM) the NPSHr is 15ft (~ 4.6 m).

Protector - The Protector selection is based on a modular system of labyrinth type sections which work on the principal of gravity separation of fluids of different density to segregate well fluids and motor oil. The proposed 562 series Maximus protector comprises three labyrinth chambers which are isolated from each other by a mechanical shaft seal above and below each chamber. The thrust bearing is situated in the clean fluid at the base of the protector section. A high load thrust bearing rated to 22,750 lbf has been selected to carry the impeller and shaft down thrust.

Self-lubricating polymer-lined radial bearings are located in each seal body and the base of the protector to optimize performance even in poor lubrication conditions and high temperatures.

Motor - The selected motor is a single 562 series Maximus motor with MaxLok pothead. The winding code provides a 60 Hz nameplate rating of 75 HP, 1272 V, 36 A.

Main Power Cable - The selected cable is a three phase #4 AWG RedaMAX 400, which has been chosen to complement motor requirements and offer reliability in the down-hole operating environment. It is rated to 5000 Volts at 200°C maximum operating temperature. Each of the three EPDM insulated tinned copper conductors are a common overall EPDM jacket. Round profile interlocking galvanized steel armour provides mechanical protection and pressure containment for the power cable.

Motor Lead Extension (MLE) - A 562 series MaxLok pothead with #4 AWG flat cable has been selected. The cable comprises of three EPDM insulated copper conductors which are protected by a lead jacket and flat profile Monel armour. Both, pothead and cable are rated to 5kV, 205°C. The MLE design selected features a plug-in pothead which reduces ESP installation time, minimizing rig or service costs during the installation, as well as the risk of rain, snow or debris getting into the motor head.

After a steep learning curve from the installation of LL-06 the riser pipe couplings where upgraded in BA-01 to a much higher quality and pipes and a modular pipe spinner was built by Veitur to gain the require torque. Installing the 80 m string took less than a day and the well was up and running 4 days after it was killed including deposit workover with a mobile rig.



Figure 12: Installation of BA-01

After commissioning the BA-01 ESP system production rate was set fixed to 25 l/s and well top pressure is kept at 2,8 barg to maintain liquid state of the geothermal fluid until the atmospheric steam separator. The deep well gauge attached to the motor has sent valuable information for reservoir monitoring. Both short term production tests up 40 l/s showed no drawdown of water levels in the well nor the constant 25 l/s over a longer period. A promising result from a successful ESP installation increasing the production rate of the Þorlákshöfn district heating system from 50 l/s to 73 l/s or 46%.

2.3 HS-08 and HS-09 High Temperature Hotline ESP

Hveragerði is a medium temperature geothermal reservoir with temperatures up to 180°C in some wells. Numerous wells have been drilled in Hveragerði since 1946 with various results. The high temperature of the field was a technical challenge to harness for district heating utilization. Calsium and Silica content is high and mineral deposits ar present if the fluid is flashed to a lower pressure state. For the past 20 years the pressure in the geothermal system has been declining gradually causing unstable production of the

two main production wells HS-08 and HS-09 that provide two phase fluid directly to a steam district heating system but also to a thermal station where the heat is transmitted to a closed district heating loop connected to majority of the facilities in Hveragerði.

Well HS-08 is located in Hveragerði at the geothermal park. HS-08 was drilled in 1989 only to 254m with a casing down to 118 m.. In 2011 Veitur addressed the possibility of installing a line shaft pump in HS-08 due to the frequent disturbance of the artesian flowing well. Research work design lead to a conclusion that the most promising design was an installation of line shaft pump to a 100 m depth. A deeper installation was not considered due to the thermal expansion. To reduce thermal expansion, 80°C return water from the thermal station was pumped down the well. A 6 m long perforated mixing pipe was attached to the bottom of the pump to ensure adequate mixing of the two fluids and to maintain a 140°C production temperature. Early 2017 the pump was installed successfully and produced for 7 months when at the pump broke loose from the riser pipe and fell into the bottom of the well. Inspection of the riser pipe and broken fragments did not lead to a solid conclusion, but lack of control and protection functions was suspected. A new pump was installed to 110 m in 2018 and control functions where improve but early 2019 the pump malfunctioned again. Pulling the pump displayed the same broken pump as before.



Figure 13: Second fragments of HS-08lineshaft pump

A decision was made to develop a high voltage ESP solution for HS-08 and for HS-09 with Schlumberger. Previous projects had proven successful and the cooperation between the two companies gave Veitur confidence that a solution was possible.

With reservoir temperatures around 180°C wells HS08 and HS09 required further design considerations compared to the conventional ESPs previously discussed. As this is considered a development project two separate strategies are being pursued:

1. The adaption of a conventional ESP system by upgrading several elements including the bearings, shaft seals and motor windings to withstand higher temperatures.
2. Utilisation of Reda Hotline ESP system.

For both cases, the centrifugal pump part of the ESP system will be identical, the differences are found in the construction of the protector and motor. As the rotating and stationary components inside the pump are assembled to very tight tolerances particular attention was paid to the material selection of the pump components. The pump design assumes a dynamic fluid level of 20 to 100 m and an inflow performance of 500 to 1000 m3/d/bar. To prevent cavitation and recommended installation depth is 200 m at this temperature. Expected production rates are approximately 1100 to 3300 m3/d depending on the season which resulted in the selection of a 675 series, J21000 pump with 17 stages. The recommended operating range at 60Hz is between 2544 m3/d and 3975m3/d. Net Positive Suction Head required at 25 l/s is ~ 4.6 m.

The Hotline ESPs have been specifically developed for Steam Assisted Gravity Drain (SAGD) applications where the ESP is deployed in a horizontal section of the well bore. Many of the Hotline ESP features have been employed to address the challenges specific to this environment, resulting in a fully encapsulated motor and seal assembly. While this type of ESP system is perfectly suitable for Geothermal wells, the requirement to operate the motor in a horizontal position is usually not given. As such, the conventional ESP system has been enhanced by utilising certain components from the Hotline product range, in order to reduce the complexity of the system whilst maintaining the same reliability.

The protector works on the same modular principle with three labyrinth chambers as previously described, however the elastomer shaft seals have been replaced with Inconel metal bellows, polymer lined radial bearings with Tungsten Carbide bearings and the pads of the thrust bearing are coated with silicon carbide instead of PEEK.

The high temperature enhancements for the motor include “mine-duty” windings with a thicker insulation of the magnet wire, Silicon Carbide thrust and radial bearings and snap-rings on each rotor to prevent thermal growth of the rotor assembly. High temperature Chemraz elastomers are used instead of Aflas. The motor lead extension (MLE) plugs into the motor head through a Hotline style pot head connection.

The fundamental difference of the Hotline system is its integrated motor which combines the protector, motor and gauge functions into a single assembly. The integrated motor is comprised by a Shaft Seal Module (SSM) with 4 sealing chambers above the motor, the motor, monitoring section and the bellows compensator and filter assembly below the motor. The MLE, pothead and pumps have also been developed to cope with the high temperatures inherent to thermal applications. The monitoring section works with a CTS (Cable-to-Surface) configuration to establish communication between the sensors located in the motor and the electronics at surface.

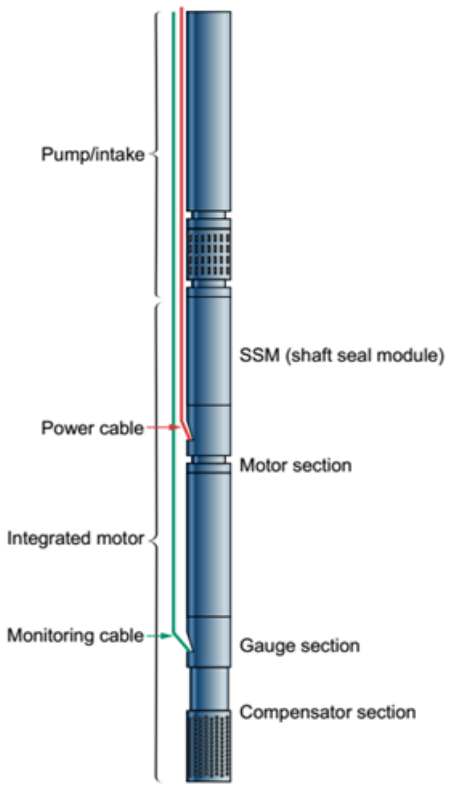


Figure 14: Hotline scematic

Before installation of the ESP to the wells Veitur had to prepare the wells for two reasons:

1. The casing of both wells only reaches down to ~120 m. The risk of rocks falling loose and jamming the pump is high.
2. Both in HS-08 and HS-09 inflow vanes have been detected by temperature measurements at 120 m depth and 250m. As mentioned earlier the casing reaches only down to 118 m and recommended installation depth is below the inflow a risk of insufficient flow across the motor for cooling purposes is present.

A solution to both items was developed. A 8-5/8” hanging liner was designed and lower down to 216 m depth. This liner maintains the required flow across the motor as the fluid from the shallower vain travels outside of this liner below the motor and protects it from falling rocks from the open hole sections. In addition to this the wells where deepened by 20 m with a 6-1/4” drill bit. The liner is welded on a collar special flange was designed for the 8-5/8” liner to hang from a collar that sits on a groove in the flange allowing the master valve to be in a closed position if the ESP is pulled.

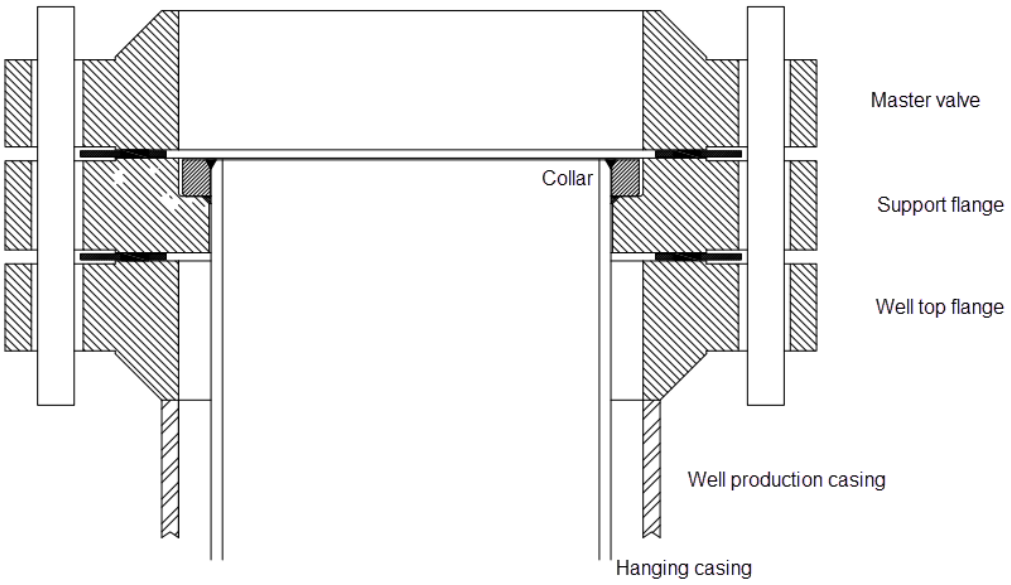


Figure 15: Hanging casing

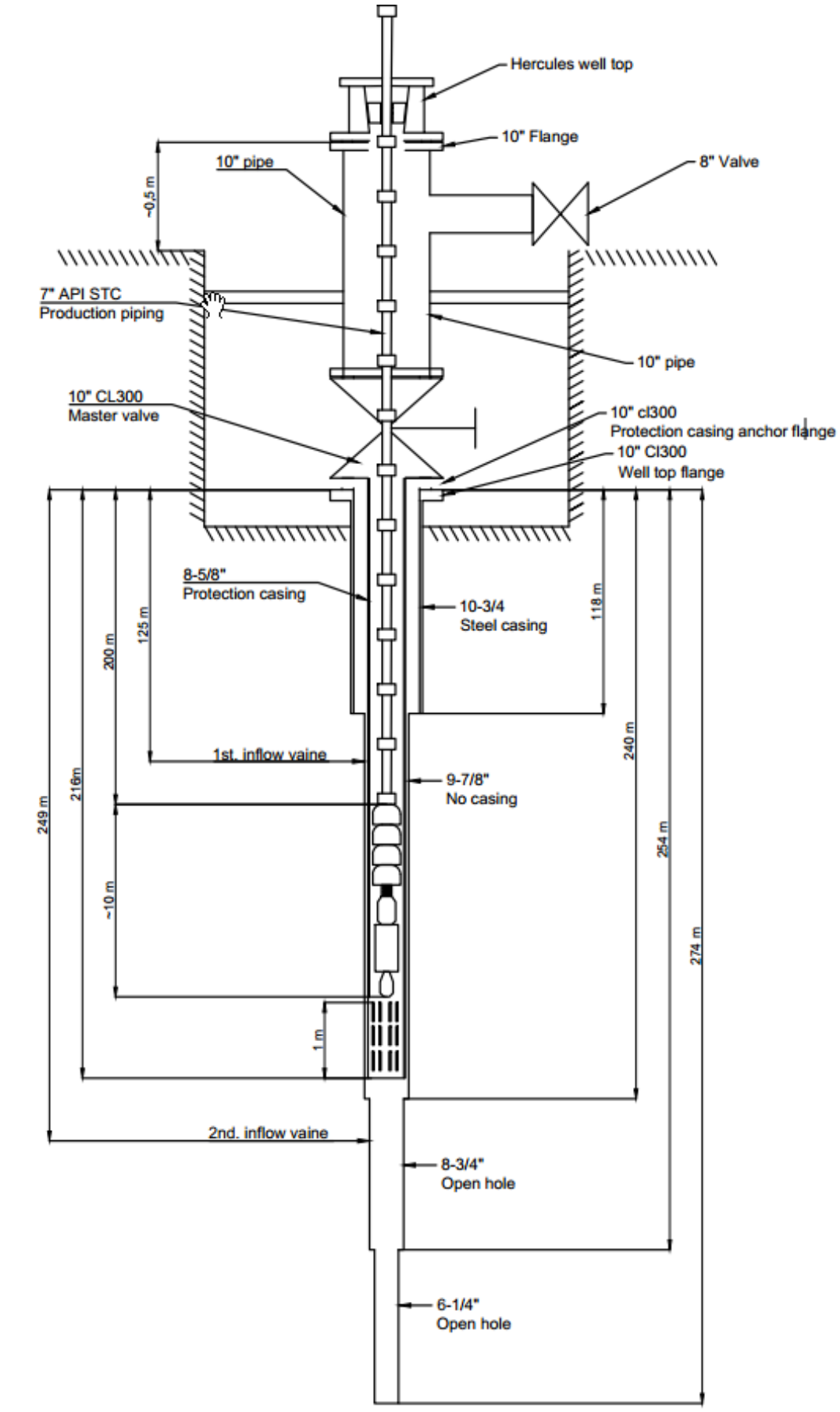
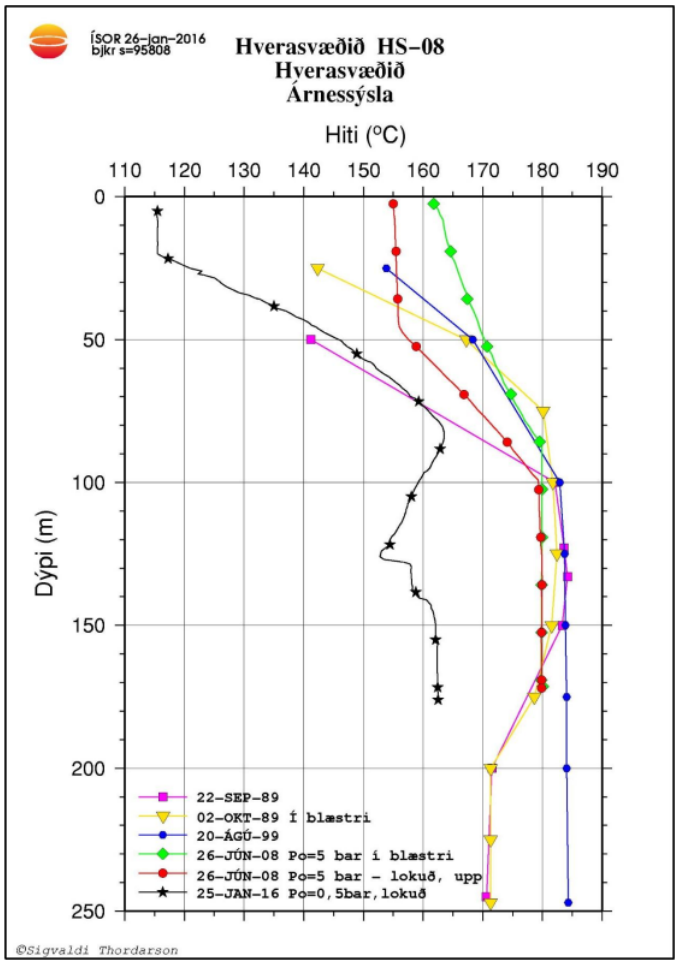


Figure 16: HS-08 ESP well design



Mynd 1. *Hola HS-8. Hitaferlar.*

Figure 17: Temperature measurement of HS-08

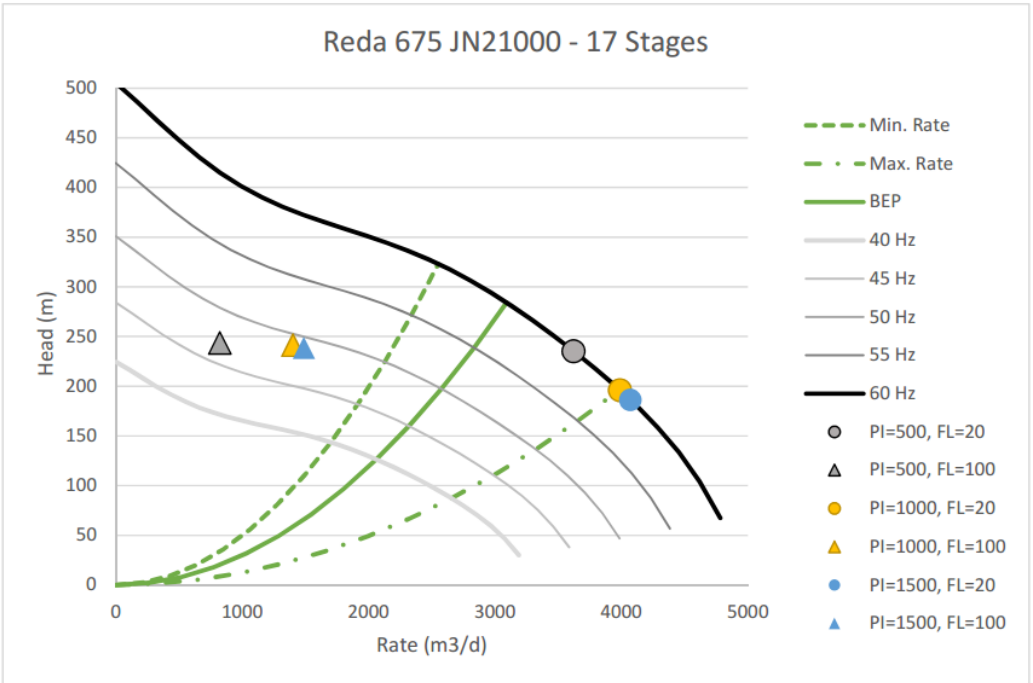


Figure 18: HS-08 Multy Frequency Pump Curve

	HS-08 ESP System
Pump	675 Series, JN21000, 17 Stages - Compression construction, - CS housings, - Ni-Resist Stages, - 5530 Impeller material - CS head and base, - ARZ-SS bearing configuration, - Keyless sleeves - Inconel 625 shaft, - Bolt on Intake
Protetors	-Integrated Shaft Seal Module
Motor	562 Series, Hotline - Single Sections with 6 rotors - 225 HP, 2682 V, 51 A @ 60 Hz 100% - CS housings, - CS head & base - Un-varnished Kapton winding, - SLK Ceramic bearing - Purified Reda #7 motor oil, - 572°F winding temperature rating
Main cable	RedaLEAD 450 - AWG #4 - Flat profile - Galvanised Armour - EPDM Insulation - XLPE Cushion - 5 KV Voltage rating - 450°F temperature rating
Motor lead extension	HotlineSA3 - AWG #4 - Monel Armour - PRN Insulation - Lead Jacket - 5 KV Voltage rating - 550°F temperature rating

Table 3: HS-08 ESPselection

2.4 RV-41

RV-41 is the hottest well of the Elliðárdalur geothermal reservoir and was drilled in 1984 to 1605 meter with a casing to 434 m. Today Veitur operate 9 production wells including RV-41 at Elliðárdalur, most of them above 85°C with flowrate of 20-50 l/s. The distance of RV-41 from the nearest transmission line was considered to far to be ever connected until 2018. Veitur Elliðárdalur geothermal field is a small area which is sensitive to production. Special attention is necessary for the water level not to drop and therefore an ESP with a downhole base gauge for real time monitoring a suitable solution. Another factor supporting an ESP for the area are the noise restrictions. RV-41 is located less than 10 m from an office space in a which makes a lineshaft pump with a surface motor unattractive option. The welltop had been unprotected in open air for decades and a building was needed for the surface equipment since the well is located in a public space with unlimited access.

The selected ESP for GV-41 has been designed for a fluid level of 10 - 60 m with an inflow performance of 6 - 16 l/s/bar. Expected production rates are 12 – 22 l/s at a minimum head of 96 m and 211 m respectively. The selected pump is an 11 stage J12000N powered by a 84 KW motor. Setting depth and casing size are identical to RG-20, however the lower production rates allow for a smaller tubing size of 7”.

	RV-41 ESP System
Pump	675 Series, J12000N, 11 Stages - Compression construction, - CS housings, - Ni-Resist Stages, - CS head and base, - ARZ bearing configuration, - High strength Monel shaft, - Bolt on Intake
Protetors	540 Series, Maximus - CS housings, - CS steel body, - LSLSL chamber arrangement, - Inconel 625 shaft, - HL thrust bearing - Reda #6 motor oil,
Motor	562 Series, Maximus - Single Sections with 3 rotors - 83.9 KW, 2248.2V, 30.6 A @ 60 Hz 100% - CS housings - CS head & base - Un-varnished Kapton winding - Reda #6 motor oil - 400°F winding temperature rating
Main cable	RedaMAX 400 - AWG #4 - Round profile - Galvanised Armour - EPDM Insulation - EPDM Jacket - 5 KV Voltage rating - 400°F temperature rating
Motor lead extension	MaxLok400 - AWG #4 - Monel Armour - EPDM Insulation - Lead Jacket - 5 KV Voltage rating - 400°F temperature rating

Table 4: RV-41 ESP Selection

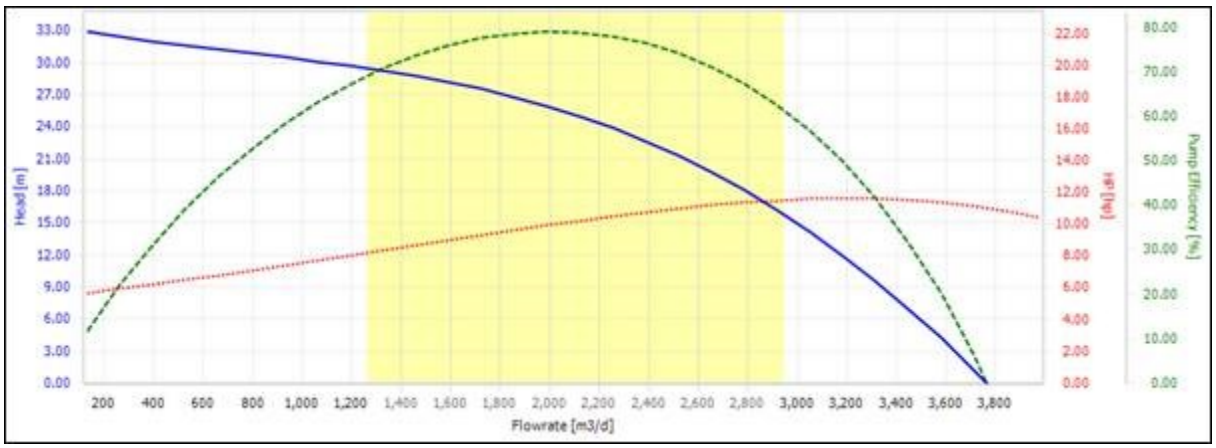


Figure 19: RV-41 Single Stage Performance Curve at 60Hz

In terms of material selection and construction the pumps are similar to LL-06 and BA-01. A variation being the stage count and stage geometry. The Protectors are literally identical while the motors vary in size to accommodate for the different power requirements.

2.6 RG-20

RG-20 was drilled in 1963 down to 765 m with a 13-3/8" casing to 86m and has been one of the most valuable well of the Laugarnes geothermal reservoir producing more than 56 l/s of 130°C water. Laugarnes geothermal field is located in Reykjavik and is considered one of the most valuable reservoirs due to it´s high temperature and convenient location. Already installed at 168 meters depth is an 8", 9 stage line shaft pump with a 150 kW motor. For RG-20 ESP installation was considered feasible for the following reasons:

1. The production index of the well indicates that short time production can be increased to 80 l/s
2. The installed pump is 20+ yrs. old and soon needs to be replaced
3. Space is limited for the transformer and VSD inside the well top building. The surface equipment can be located in a nearby(20m) pumping station



Figure 20: RG-20 line shaft pump

For RG-20 the design assumes a static fluid level of 35 - 73 m with an inflow performance of 12 - 19 l/s/bar. Expected production rates are 50 – 80 l/s at a minimum head of 98 m and 178 m respectively. Well RG-20 is completed with a 13-3/8" casing with an inner diameter (ID) of 317 mm. The anticipated setting depth of the pump intake is at 200 m. Production tubing will be 9-5/8". The selected pump is a 5 stage N1400NA powered by a 420 kW motor.

In terms of material selection and construction the pumps are similar to what has already been described in LL-06 and BA-01. A variation being the stage count and stage geometry. The Protectors are literally identical while the motors vary in size to accommodate for the different power requirements.

	RG-20 ESP System
Pump	1000 Series, N1400NA, 5 Stages - Compression construction, - CS housings, - Ni-Resist Stages, - CS head and base, - ARZ bearing configuration, - High strength Monel shaft, - Integral intake
Protetors	540 Series, Maximus - CS housings, - CS steel body, - LSLSL chamber arrangement, - Inconel 625 shaft, - HL thrust bearing - Reda #6 motor oil,
Motor	562 Series, Maximus - Single Sections with 8 rotors - 419 KW, 3873.4 V, 88.1 A @ 60 Hz 100% - CS housings - CS head & base - Un-varnished Kapton winding - Reda #6 motor oil - 400°F winding temperature rating
Main cable	RedaMAX 400 - AWG #4 - Round profile - Galvanised Armour - EPDM Insulation - EPDM Jacket - 5 KV Voltage rating - 400°F temperature rating
Motor lead extension	MaxLok400 - AWG #4 - Monel Armour - EPDM Insulation - Lead Jacket - 5 KV Voltage rating - 400°F temperature rating

Table 5: RG-20 ESP Selection

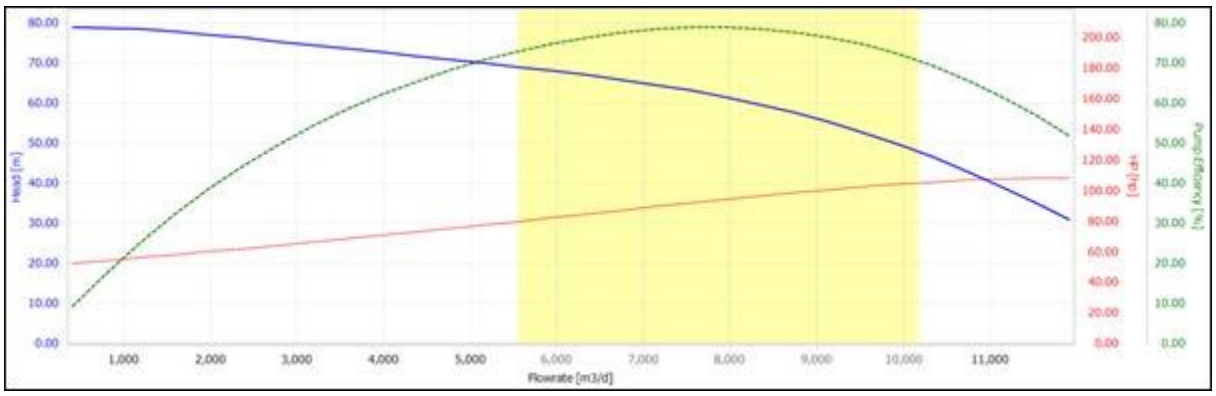


Figure 21: RG-20 Single Stage Performace Curve at 60Hz

3. CONCLUSIONS

The overall the experience from high voltage ESP has been positive for Veitur. The previous installations required thousands of engineering hours but as the number of ESP system increases the hours get less and less making the ESP an efficient and suitable solution for geothermal.

The downhole base gauge is a significant improvement for sustainable reservoir management which plays a bigger role every year as the demand for hot water increases but the reservoirs stay the same. The price of drilling for hot water increases every year and license for geothermal exploration become slow and costly procedure. Optimizing your reservoir is the most efficient way of operating a geothermal district heating system.

The improvement of the riser pipes design has large impact of both availability of the pump and operation cost. With pipe spinner technology installation depths will become less of a challenge and cost is reduced significantly.

For geothermal field located in suburb areas noise requirements are met with high voltage ESP system since the motor is submerged. A low electrical buzz is present from the VSD sine valve filter but is significantly less than an surface AC motor

The lineshaft pump was a key role in the development of geothermal in Iceland earlier but has stalled for the past 20 years. With high voltage ESP technology new possibilities lie ahead.

REFERENCES

Orkustofnun(National Energy Authority) 2019, *Borhole directory*, accessed 26.07.2019, https://orkustofnun.is/borholuleit

Lýður Björnsson, Saga Hitaveitu Reykjavíkur (2007)

Árni Gunnarsson, Jón Eggertsson, Snælaugur Stefánsson, Hitaveituhandbók Samorku (1992)

Kristján Sæmundsson, ISOR, Staðsetning holu LL-06 í Laugalandi í Holtum(2016)

Simon Klüpfel, Hendrik Tómasson, Sandra Ósk Snæbjörnsdóttir, Sigrún Tómasdóttir, Þorlákshafnar- og Ölfusveita Vatnsvinnsla 2018, OR(2019)

Bjarni Kristinsson, Benedikt Steingrímsson, Holur HS-08 og HS-09 í Hveragerði Hita- og þrýstimælingar í janúar 2016, ÍSOR(2016)

Aðalsteinn Möller, Arnar Freyr Sigmundsson, Hveragerði Rekstur Borholna og endurbætur á Gufuveitu, Frumhönnun, áfangaskýrsla 2, Verkís(2011)