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# Extending the lifetime of geothermal lineshaft pumps

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## ABSTRACT

Geothermal power plants rely on the hot fluid flow from below the surface to generate clean, sustainable, energy. In high enthalpy fields, artesian well flow is common and does not require artificial lift. In a growing number of geothermal fields, artificial lift is required to deliver fluid to the power plants. Today, Ormat operates approximately 150 production wells with artificial lift technologies, and that number is growing every year. Ormat's geothermal portfolio is currently 1,015MW, and approximately 75% of the production wells use artificial lift (the majority are Line Shaft Pumps), representing the largest fleet of geothermal production pumps in the world. The magnitude of these machines, set hundreds of meters below surface, makes the importance of minimizing failures and extending their mean time between failures crucial for a geothermal power plant's financial success. Over the years Ormat gained substantial experience and implemented many strategies to minimize geothermal pumps operation and maintenance expenses, reduce downtime, maximize reliability, while also maximizing well production across our geothermal fleet. With such a large variety of geothermal systems in operations, Ormat is experiencing a rise in the lifetime of pump systems (now 6 to 7 years on average), with some pump systems operating more than 15 years without replacement. This paper will present and review the main strategies that proved to be most successful by Ormat's operation and engineering teams; from the development of new products, validation testing, operational procedures, and data analysis that provided meaningful insights to a standardized control logic of geothermal production pumps.

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## 1. INTRODUCTION

Extending the lifetime of machine such as a geothermal lineshaft pump may seem like a daunting task. Most of the machine is not accessible, making maintenance and failure analysis significantly more complicated. However, Ormat's reliance on the geothermal line shaft pumps as a driving power of up to 75% of its geothermal portfolio leaves no choice but to approach this task with all available resources. One of the inherent challenges in attempting to increasing the lifetime of all pumps across the board is the difference between geothermal reservoirs, and thus the operating conditions of the pumps which deeply affect the best solution for extending the lifetime of the specific pump.

Ormat's engineering and operation teams have many years' worth of experience in the operation and design of geothermal lineshaft pumps. Over the years, each plant has developed its own local operational procedures, which varied according to local conditions and specific operators' knowledge and experience. When creating a generalized approach, it was critical to create a uniform set of operating instructions on one hand, but on the other hand, keep all vital local knowledge regarding site-specific operating conditions. This balance, between the will to provide a general solution to all pumps, and accounting for each reservoir's specific operating conditions is a core issue in all the strategies reviewed in this paper. Ormat's team identified which parameters in the design and operation of geothermal lineshaft pump can be standardized across the board, and which must be kept dynamic, to allow for local variations.

In this paper the terms "production pump" and "geothermal line shaft pump" will be used interchangeably, as the absolute majority of Ormat's geothermal production pumps are lineshaft pumps.

## 2. PERFORMANCE MONITORING

One of the key strategies to extend the lifetime of any machine is to closely monitor its performance. All machines, including geothermal lineshaft pumps, will fail eventually. Failures can vary between minor, which result in a short downtime before resuming operation, to catastrophic, which in some cases require replacing the entire pump.

In the specific case of geothermal lineshaft pumps, the equipment that is installed in the well is not accessible from the surface. Maintenance or repairs cannot be performed without removing the assembly, which is not financially feasible. The cost of removing and reinstalling the assembly can be higher than the cost of the equipment itself, so it is typically preferred to reinstall new equipment rather than attempting to repair used equipment.

This raises the importance of closely monitoring the performance of the pumps, to avoid undesired operating conditions that can damage the pump. Performance monitoring is also important in predicting imminent pump failure to prepare for pump replacement and minimize downtime.

One of the primary but preventable failure modes of a lineshaft production pump is rotor/stator interference. Geothermal lineshaft pumps are designed to have some axial clearance between stator and rotor, usually referred to as "axial play", see Figure 1. Due to the length of the lineshaft, the magnitude of thermal expansion and shaft stretch due to hydraulic thrust is large. The amount of space for an impeller to travel axially inside the bowl is limited and contact with either the top of the bowl or bottom of the bowl will damage the pump. If the contact, known as “topping” or “bottoming”, is severe enough and/or for long enough, the result will be catastrophic failure of the pump.

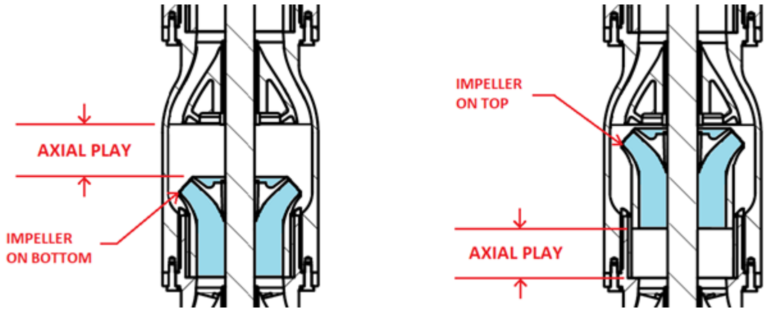


**Figure 1 - "axial play" in a geothermal lineshaft pump**

To avoid topping, fluid temperature is closely monitored especially upon commissioning. The sudden increase in temperature can cause impeller topping due to thermal expansion. In order to minimize the sudden change in temperature, often the lineshaft pump assembly is preheated by either injecting hot brine from a neighboring pumped well or allowing the well itself to flow artesian through the pump at a low flow rate for a limited amount of time.

To avoid bottoming, discharge pressure is closely monitored. Higher than normal discharge pressure moves the operation point of the pump leftward on its Q-H curve. The higher head in this condition results in higher thrust and shaft stretch. If high enough head is reached, the impellers may bottom.

Suction pressure is closely monitored to avoid cavitation which generally occurs due to an operation of the pump at a low suction pressure. The result of cavitation is the creation of a local two-phase flow in the pump, which when returns to a single-phase flow with the increase of static pressure can induce rapid erosion and excessive vibration of the pump parts (Gülich, 2008). Severe cavitation, or other unique reservoir conditions effected from suction pressure, can also "vapor lock" the pump, reducing flow to zero. If this zero-flow condition is not identified and corrected, the pump shaft may seize, and the result would likely be catastrophic failure of the pump.

Total Dynamic Head (TDH) of the pump is producing is calculated through differential pressure in the pump, temperature, flow rate, and motor speed to determine performance against the theoretical curve. Correct performance is known as “on curve.” A deviation from the curve TDH is known as “wear factor.” Wear factor is useful for detecting lost pump stages, erosion/corrosion, scale build up, and other problems with the pump. Wear factor in conjunction with flow rate and suction pressure is useful in differentiating pump performance decline vs well or reservoir decline. Wear factor is also useful in detecting problems with instrumentation.

In addition to hydraulic performance of the pump, electrical performance of the motor is closely monitored. Power consumption, motor current, motor temperatures, vibration of the motor bearing, and vibration of the above ground assembly are being recorded continuously. Power consumption and motor current are very useful for detecting rotor interference and lubrication problems. Power consumption and motor current in conjunction with flow rate are useful for differentiating pump normal deterioration vs a more acute and sudden damage to the pump. Vibration and motor temperatures are useful for detecting imminent motor, mechanical seal, or other supporting systems failure, which helps minimizing downtime.

When integrated, this in-depth information provides the trained eye a full picture of the pump, auxiliary systems, well integrity, and reservoir performance.

### 2.1 Motor Performance Monitoring and Maintenance

In addition to the insight the motor’s readings can provide on the pump and reservoir condition, the motor’s performance is closely monitored to extend the lifetime of motors as much as possible and be as prepared as possible to failures. Performance monitoring of motor is done using the methodology of performance monitoring that was developed over the years for other surface equipment such as turbines, drive systems etc. Performance monitoring of the motor follow standard machinery performance monitoring and maintenance, and therefore allow for planned maintenance such as bearing replacement, oil replacement and other activities. Performance monitoring include following trends of bearing vibration, spectral analysis of bearing vibration, and other standard bearing performance monitoring actions. This enables the detection of a wide array of potential problems that relate to the motor: from alignment and motor shaft problems to mechanical seal potential problems.

### 2.2 Recent Developments

In recent years Ormat invested a lot of resources in the performance monitoring of production pumps. Many measurements that were once taken manually are now measure automatically and continuously. In some cases, the automation was simple as replacing a local indicator to a transmitter, while other cases, such as pump suction pressure measurement required the design and development of new above-ground support systems.

2.2.1 Suction pressure manifold system

The continuous indication of pump suction pressure is vital for real time pump performance monitoring, as well as monitoring reservoir conditions.

Downhole pressure is measured with "bubble tubes" – 1/4" capillary tubes that run down along the column pipe assembly and are typically terminated at the top of the pump bowl unit. At the surface, bubble tubes are connected to $N_2$ tanks and pressure instruments. Measuring the $N_2$ pressure on the surface, with the knowledge of the bubble tube length enables a simple and reliable suction pressure measurement. Similarly, if downhole scale inhibitor injection is needed, these same tubes will be used, however they will be terminated below the pump.

The bubbler pressure reading is performed manually, by an operator first purging the bubbler line with $N_2$, then waiting for the pressure to stabilize, then reading and recording the pressure of the $N_2$ at the tank outlet. A similar operation is required to ensure the integrity of the tubes used for scale inhibitor injection. Purging and checking the pressure on the tube used for scale inhibitor ensures the tube is intact, and scale inhibitor is being delivered to the correct location below the pump. Because tubes break and plug from time to time, spare tubes are always installed with the pump. When a broken or plugged tube is identified, it is important this tube be taken out of service in a timely manner and replaced with a spare tube.

The manual purging, measurement, and changing tubes was cumbersome to operations personnel. To alleviate this burden on operations, Ormat developed an automated manifold system, remotely controlled from the control room, to perform all required purging, measurements, and switching lines as needed.

2.2.2 Performance monitoring software

An additional effort to aid with the performance monitoring effort is via software. In recent years Ormat has been developing software tools that automate the analysis and integration of all data collected measured in a lineshaft production pump.

These tools are programmed to identify events that may lead to a future problem in the pump. This set of events was defined based on years' worth of operational experience and failure analysis of line shaft production pumps. However, as extensive as the experience that led to the development of the automation of event identification, history shows that there are always outlying events, that do not follow the pattern that has been identified in the past. For this reason, the software tools do not only seek a combination of readings that indicate an event, but also follow changes in single readings and provide an alarm if there are any unexpected changes.

At this point, we must acknowledge the prevalence of commercial preventive maintenance software tools in the industry. Ormat chose to develop its own tool due to the combined effect of two factors: (a) the extent of customization that would have to be done on any commercial tool to account for the above-mentioned set of predefined events and (b) the small number of available measurements would reduce the confidence in any result gained from statistical \ big data analysis.

Over the years, in addition to studying all production pump failures, and the events that preceded them, Ormat has been studying the effect of production pump failures on the power plants, and vice-versa. The knowledge gained was implemented in all procedures and the aforementioned software tools.

## 3. INTRODUCTION OF NEW TECHNOLOGY

Some failures can be prevented via preventive maintenance, improved operational procedures etc. however, in some cases we understood that we were limited by the pump's capacity. With the ever-growing demand for more flow, introduction of new technology helped us increase the envelope of performance without compromising the safety margins for a long-lasting operation of the pump. Some of the new developments have been covered in a previous paper (Akerley et al 2021) and shall therefore be reviewed only briefly here.

### 3.1 Extended lineshaft

Years old industry standard lineshafts were redesigned to have larger diameter to accommodate higher loads and therefore allow for the pumping of larger flows from a given well. This development was done in a close collaboration between Ormat and its vendors, to assure the same standards of manufacturing and reliability from the first installation. This development allowed for larger safety margins in the operation of once risky to impossible pump constructions, and thus contributed for the longevity of these pumps.

### 3.2 Position Sensor

Ormat has developed a novel sensor that indicates in real time the axial position of the pump's rotor, relative to the stator. This sensor sheds light on previously unmeasurable phenomena. The sensor can provide operations teams a "last chance" warning before a catastrophic failure occurs if all other measured signals and warnings failed to do so. This sensor also provided some invaluable information on transient phenomena in the pump that are otherwise undetectable. After the first generation of this sensor proved itself as described above, a second generation is now under development, with the emphasis of increasing accuracy, reliability, and ease of use for field operators.

### 3.3 Optimization of Pump Design

Ormat designs all the parts of the pumps, including the hydraulic parts – bowls and impellers. When a new model is designed its system requirements are comprised from many years of experience, including all the lessons learnt from previous failures. All design aspects are considered when designing a new model: construction materials, required lifetime of the pump, mechanical and hydraulic design etc. In most recent models Ormat engineering team has successfully increased hydraulic efficiency by 4-5% and reduce hydraulic thrust by 25%. The former can save ~300MWh annually across the fleet, while the latter greatly reduces the chances of a bottoming (see Figure 2) catastrophic failure, since the reduced hydraulic thrust causes a smaller elongation of the shaft.

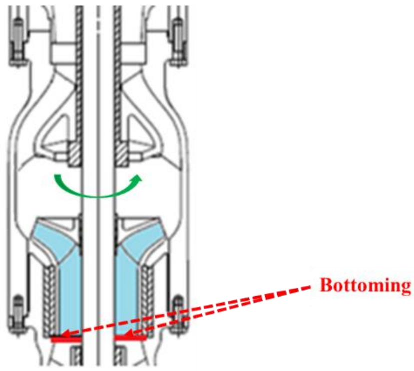


**Figure 2 – Illustration of a Bottoming event**

## 4. STANDARD CONTROL LOGIC

Geothermal lineshaft production pumps are large, complex machines. The exact operation of each pump differs due to the ever-changing plant and reservoir conditions, which cannot always be controlled. Historically, each pump was operated with its own set of unique instructions, that naturally differed between each pump and plant, both in core issues such as logic and in non-standard terminology, tag numbers, P&ID etc.

This type of operation lasted for many years, and heavily relied on the experience of operators on the field. To reduce the dependance on specific operators' knowledge, and to create a uniform language for production pumps control, thus increase serviceability and maintainability, Ormat initiated the standard control logic for production pumps. Instead of each pump being operated as a standalone machine, all pumps are operated under the same framework, saving a lot of engineering and operators' time, and inherently preventing potential misunderstanding when transitioning between different systems. In addition to the operation of the pumps themselves under a standard logic, all production pumps auxiliary equipment (motor cooling systems, oil delivery systems etc.) is also operated under a standard framework, with all that is implied from it. It is important to differentiate between the standard control logic and the software tools described in section 2.2.2. The former is in charge of online performance and can take actions, while the latter tracks trends over time, and provides warnings and recommendations for preventive actions.

Hot brine flow is the driving power of any geothermal power plant. Therefore, the control logic of production pumps affects the entire operation of the plant. The intrinsic connection between the pumps and the plant necessitates their control logic philosophy to be insentiently connected. As such, the control of brine valves is a part of production pumps control logic, to ensure a correct and coherent operation.

An important part of the control logic is determining the set points which trigger alarms \ stop the pumps at once. For some measured variables, such as pressure, flow etc. there is no sense in determining generic setpoints, while for others, such as motor bearing temperature, there is a lot of sense in doing so. Therefore, all readings were classified as generic or dependent on specific pump parameters. For the latter, this dependence was carefully and unambiguously defined (e.g., minimum flow is %X of rated flow etc.). The standard and comprehensive set of protections allows for a standard approach while also ensuring that no protection is overlooked\missed during the design of a new pump. In addition, all software updates for the controller are now seamless, as they all operate under the same framework.

The production pump control logic does not only operate the pump in steady state, it also manages commissioning, planned and emergency stops (either those that stem from the control or those initiated by human operators). As is the case with many machines, commissioning and stopping a geothermal lineshaft pumps is in many cases a delicate process, which requires a lot of attention, a relatively large number of failures that occurred during transient processes. Considering the complexity of the commissioning process, and the high cost of commissioning failure, the standard control logic commissioning procedure relies on input from operators in the field, to incorporate the best of both worlds – computer standard control, and human detection of potential problems.

We will now demonstrate one of the events that the standard control logic prevents – pump operating at shutoff. Operating at shut off (no flow, high pressure) is strictly forbidden for any centrifugal pump, let alone a large geothermal lineshaft pump. There are many dangers in operating the pump in shutoff, but for a geothermal lineshaft pump the most severe risk is bottoming (see Figure 2 above). The reason that operating at low (or no) flow may lead to bottoming is that in all models used by Ormat, the maximal hydraulic thrust is obtained in zero flow, see Figure 3 below. The hydraulic thrust can increase by a factor of 150% between the pumps' rated flow and zero flow. As a result, the pump's shaft will further stretch, which in some cases may lead to a dangerous contact between the rotating impeller and stationary bowl – bottoming.

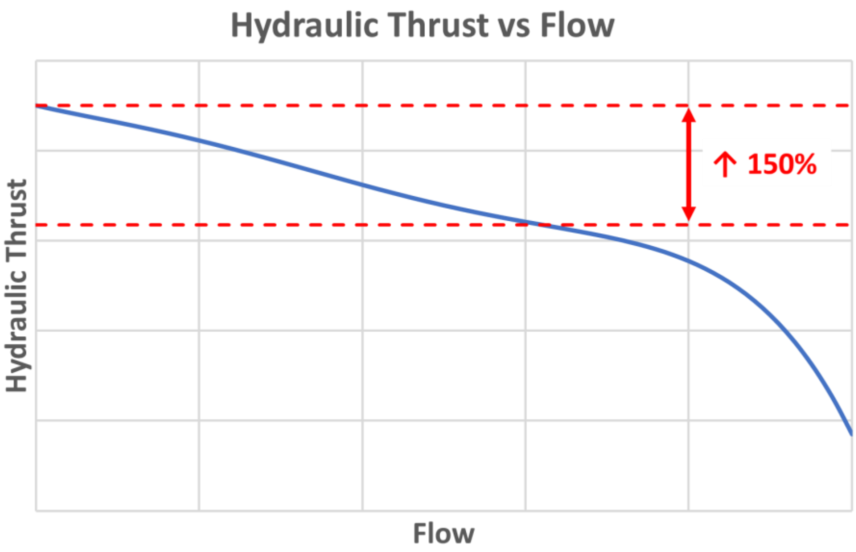


**Figure 3 - Typical hydralic thrust vs. flow curve**

To prevent any case of shutoff, the standard control philosophy will raise the following alarms, which will precede any shutoff event:

- Low flow
- High discharge pressure

In addition to alarms, if any of the above will go beyond an additional setpoint, the pump will automatically stop, according to a predefined procedure.

## 5. OPERATION AND COMMISSIONING PROCEDURES

Part of the standardization efforts described above concern the operational procedures during installation, commissioning and operation of the pumps. In this section it is very important to consider the large variance in the installed pumps in Ormat's fleet. All standardization efforts must consider this variance, in order to not disregard the subtleties of each specific well.

We will now describe some of lessons learnt during installation and the required steps to implement these conclusions.

### 5.1 Parts & Tools

It has been identified that to ensure streamlined installation, a special care must be taken with all the parts involved in an installation. The following items were identified as critical

- All required parts & tools must be on site prior to installation
- Parts need to be organized for installation in dedicated groups, according to installation procedure
- Prior to shipment to the site, QA must be completed as preparation to the installation
- Any deviation from the formal drawings in BoM issued by the engineering department must be approved in advance
- The usage of refurbished parts is allowed, but extra care must be taken in their QC, handling, and refurbishment process
- All the above refers both to parts dedicated to installation *and* spare parts

### 5.2 Preinstallation

The event preceding an installation, alongside the correct preparation for an installation can greatly affect its eventual success. Below is some of the important elements that must be considered prior to any geothermal lineshaft pump

- The pump and well work symbiotically. Therefore, to ensure a problem-free operation of the pump, the well must be thoroughly checked prior to installation. Specific test (caliper log, TPS, bit run etc.) will vary according to findings from previous installations to reduce risks during installation and future operation
- A conservative approach towards any doubt must be utilized. In some cases, the smallest seemingly negligible defects can cause an entire pump to fail, with extremely high costs. Ormat adopts this approach even in cost of stopping all operations until a satisfactory decision has been reached regarding a potential problem
- Any issues that arose during previous pumps removal must be discussed, and any concerns that may arise must be treated as described above
- It is important to note that any action during pump removal can affect the installation. For example, difficulties in installation were experienced due to an error during the seemingly simple process of cutting the old motor cables
- All personnel involved in installation must partake in a coordination meeting that will emphasize all the specifics that must be taken into consideration in this specific installation.

### 5.3 Personnel

A geothermal lineshaft installation is in many cases a complex operation that involves personnel from multiple disciplines, in in some cases multiple companies. As ultimately the work of all personnel on site affects the proper installation of the pump, Ormat has identified that a clear "chain of command" is crucial for a streamlined and error-free installation. Determining the personnel responsibilities and their exact scope of work is crucial. Additionally, Ormat identified that a daily meeting of all team leaders in which the job manager updates all in any changes, conducts an update to risk analysis, and trains them if there are any processes with which they are not familiar. This helps avoiding any problems that arise from misunderstandings.

### 5.4 Commissioning

As described above, in the past, pump operation and commissioning process would vary between pumps, between plants, between shifts, and was mostly based on the specific operator's knowledge and experience. In recent years Ormat standardized operation and commissioning processes, as much as possible given the differences between different location. Additionally, "high risk" wells were identified across the fleet. "High risk" wells are wells in which a pump with challenging operation is installed (high setting depth, high abrasives content on commissioning etc.) or those that have a large impact on the plant generation. Any changes in the operation of the pumps in "high risk" wells is closely monitored by engineering and operation supervisors.

Additionally, as described above, Ormat has gained invaluable information on transient processes which occur during pump commissioning. Understanding these phenomena helped Ormat issue safer commissioning procedures, for all wells in general, but specifically for high-risk wells.

## 6 CONCLUSIONS

Ormat is deeply reliant on the safe operation geothermal lineshaft pumps for the continuous operation of its power plant around the world. Therefore, extending the lifetime of these pumps is a high priority effort for the company. We described the different strategies that were implemented by Ormat to prevent premature failures in these pumps. The efforts described in this paper are continuous, and therefore are never completed. Some important milestones were reached, yet the effort to continue extending the lifetime of the pumps does not cease, we always aim for a higher MTBF, and always strive to better ourselves.

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