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Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

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A STUDY ON OPERATION AND MAINTENANCE OF FLASH STEAM GEOTHERMAL POWER PLANTS: REYKJANES POWER PLANT

Fardaneh Ravazdezh
Renewable Energy Organization of Iran
Dademan Blvd., Shahrak-e Ghods
P.O.Box 1468611387, Tehran
IRAN
fardaneh.ravazdezh@gmail.com

ABSTRACT

For a geothermal power plant to operate prosperously, series of activities starting from optimum design and installation to efficient monitoring of operation and maintenance (O&M) should be carried out precisely. Experience acquired during real O&M of a geothermal power plant gives a practical insight into observing the quality of material and equipment, optimal repair and replacement, troublemaking factors affecting the power plant's performance and management of failure incidents by utilizing suitable devices.

In this report operation and maintenance procedures of Reykjanes power plant in SW-Iceland is analysed. Most maintenance practice done in this power plant is preventive maintenance done on basis of routine and annual outage period maintenance. Efficient planning of outage minimizes tasks and time needed for scheduled and forced activities and consequently maximizes the reliability and availability of the power plant. The O&M team running both Svartsengi and Reykjanes power plants have gained valuable know-how to maintain reliability, availability, maintainability, and other critical performance factors at a satisfactory level so that electricity productivity and economic profitability of the power plants are guaranteed.

This study presents common problems occurring in the running of a geothermal power plant and their solutions, as well as analysis of outage period including required actions for each component of the power plant, manpower and cost breakdowns.

1. INTRODUCTION

It is a fact that geothermal energy plays a significant role in the Icelandic energy sector, generating 68% of the primary energy and 29% of the total electricity in the country. The first geothermal power plant started operation in 1969 and since then seven power plants with a total capacity of 663 MWe have been installed and operated, making Iceland one of the leaders in the geothermal sector (Ragnarsson, 2015). Developing a geothermal power plant and producing electricity is costly. For a power plant to be prosperous in a competitive energy market, innovatory steps should be adopted. The best way to lower the costs is to reduce the amount of losses in the process of generating energy in the power plant, i.e. electricity, which is achieved by boosting reliability and availability of the power plant through optimal O&M procedures.

The development of a trustworthy O&M plan relies on optimizing the methods and practices based on specific characteristics and requirement of the operating geothermal power plant.

The term maintenance refers to any activities carried out on an asset in order to ensure continuous performance of its intended functions, repairing any equipment that has failed, to keep the equipment running or to restore it to a favourable condition (Kachru, 2007). There are different methods how maintenance tasks can be planned and scheduled. These methods have been categorized in various manners according to different sources. However, main procedures are classified as *Corrective Maintenance* (also referred to as reactive) that aims to take corrective action when a failure occurs, *Preventive Maintenance* that includes activities to avoid failures based on a specific time-based routine, *Predictive Maintenance* that in some studies is considered as an independent type while in others has been seen as a subcategory of Preventive Maintenance using techniques to predict failures and problems based on equipment condition, and lastly *Reliability Centred Maintenance* (Proactive view) which allocates priorities to components and focuses on mitigating the need for maintenance (root-cause finding) (see Sullivan et al., 2010; Kahn, 2006).

Emphasis on allocating financial and human resources in O&M has been drastically increased in power plants by growing awareness on its importance. For example, in most geothermal power plants over a quarter of the total workforce in the process industry is dedicated to maintenance work (Adale, 2009). However, not many studies have been carried out regarding O&M of geothermal power plants. Studies in this field could accumulate unrecorded experience of Icelandic geothermal operators and maintenance experts to assist new generation of operators predicting probable failure modes and reduce or stop potential troubles and damages which might occur during the design and various operation stages.

Methodology of this study was to collect secondary data from related reports and papers, documents from the Dynamic Maintenance Management (DMM) used at the Reykjanes power plant, SW-Iceland, as well as conduct interviews with power plant managers and make several visits during the annual outage activities, recording procedures. The operation of the major equipment and maintenance undertaken in Reykjanes flash steam power plant is reviewed as a case study. Furthermore, analysis of operation indexes is carried out. Major problems that the equipment may encounter as well as the effective maintenance processes to prevent or correct those problems are investigated. Finally, all activities in an annual outage maintenance period are recorded and categorized. An analysis of actions, manpower and cost breakdowns are presented. The data of the Icelandic geothermal power plant gathered in this study can be used to improve the O&M procedures in other geothermal power plant all around the world.

2. BASIC GEOTHERMAL CYCLE

Geothermal systems can be grouped into several categories. The main source of geothermal energy production are hydrothermal systems that are driven by natural flow of hot water. Other systems include enhanced geothermal systems (EGS) and hot, dry rock (HDR) (DiPippo, 2008).

Geothermal power conversion systems are typically divided into three basic systems:

- Flashed steam/dry steam condensing systems in which resource temperature range from about 320 to 230°C.
- Flashed steam back pressure systems in which resource temperature range from about 320 to 200°C.
- Binary or twin-fluid systems (based on the Kalina or the Organic Rankine cycle) in which resource temperature range between 190 and about 120°C or less.

In addition to three basic power conversion systems mentioned above, so-called hybrid systems are in use which are in fact a combined system comprising two or more of the above basic types in series and/or in parallel (Elíasson, et al., 2011).

2.1 Geothermal power plants worldwide

In 2014, 612 power plants worldwide with a capacity of 12.8 gigawatt (GWe) produced 74 terawatt-hours (TWh) electricity (Bertani, 2015). At the end of 2014, top 5 countries with the largest amounts of geothermal electric generating capacity were the United States (3.5 GW), the Philippines (1.9 GW), Indonesia (1.4 GW), Mexico (1.0 GW), and New Zealand (1.0 GW). The majority of installed capacity (7.8 GW) and 63% of the global geothermal generation is represented by 237 flash steam plants. The main geothermal field/plant operators in 2014 were US-based Chevron and Calpine (1.3 GW each), followed by EDC of the Philippines (1.2 GW), the Mexican state utility CFE, Italy's Enel Green Power (1 GW each), and the US-based Ormat (0.9 GW) (Bertani 2015).

Capital cost of a typical condensing flash geothermal power plant with 1–100 MW size and capacity factor of 60–90% has been estimated to be 1900-3800 USD/KW (Ren21, 2015). In Figure 1, the percentage of each type of geothermal power plant in electricity production is shown.

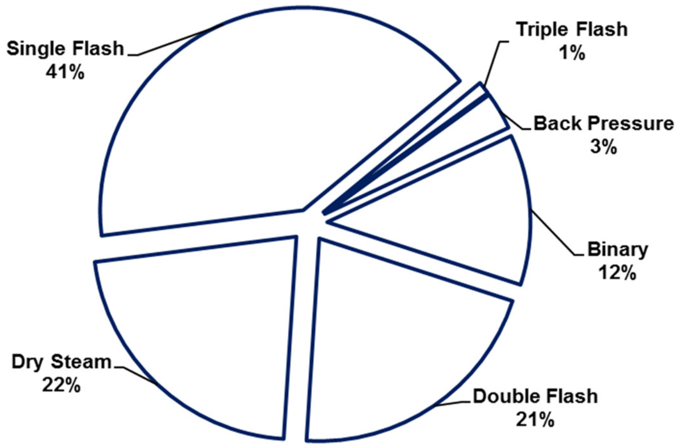


FIGURE 1: Share of each type of geothermal power plants in global electricity production

2.2 Geothermal flash steam power plants

DiPippo (2008) defines single-flash power plants as power plants that utilize the flow of steam between two pressure levels to generate electricity by rotating a turbine. The term flash refers to the pressurized liquid that is flashed into a steam and liquid mixture by reducing the pressure of the liquid below the saturation pressure of water for a given temperature. In double flash cycle, the design differs in a way that a flasher has been added resulting in a low pressure steam line to the turbine, in addition to the high pressure line from the separator.

Flashing can occur in the reservoir, in the production well, in the gathering pipes leading to a steam separator or at the separator inlet. With extended exploitation of the reservoir over the power plants lifetime, reservoir pressure drops, causing the flashing to "move back" and occur in the production well or the reservoir itself. To maintain reservoir pressure, re-injection of fluid into the reservoir is common.

2.3 General description of Reykjanes power plant

Geologically, Reykjanes geothermal area is the landward extension of the mid-Atlantic spreading ridge. There is a history of episodic hot spring activities from early times (Fridriksson et al., 2010). The geological succession depicts a steady build-up of volcanic strata within a submarine environment (Franzson, 2004). Exploration of the area started in 1956 when the first well was drilled. The field was investigated extensively in the years 1968-1970 when 7 exploration wells were drilled (Gudmundsson and Hauksson, 1981).

FIGURE 2: Svartsengi power plant

Reykjanes power plant (Figure 2) is located 55 km away from Reykjavik city at the southwest tip of the Reykjanes peninsula. The geothermal area is one of the hottest in use for power production in Iceland, with downhole temperatures reaching up to 320°C. The geothermal fluid in the Reykjanes reservoir is a 32,000 ppm of total dissolved solids (TDS) (Thórólfsson, 2005). Drilling for power production commenced in 1998. Until today 34 wells have been drilled in total and 18 of them are contributing to steam provision with an average temperature of 290°C down the wells.

This single-flash condensing type geothermal power plant was commissioned in 2006 with a total capacity of 100 MW and with approximately 96 MW net electrical output to the grid. Design of the power plant has two major unique features; one is having one of the highest turbine inlet steam pressure in the world (18 bar) in order to impede the silica scaling in exposed components. Another specific feature of the plant is the use seawater for cooling excluding cooling towers.

Both Reykjanes and Svartsengi power plant are run by HS Orka, hf. This is a privately owned company who has developed geothermal and other renewable energy applications since 1975. This company is responsible for the production and sale of electricity and heat in the Reykjanes Peninsula area. Future plans for developing the power plant include adding 30-80 MWe to the capacity in two phases, a 50 MW double flow condensing unit and a 30 MW low pressure turbine.

3. OPERATION AND MAINTENANCE

In general terms, operation and maintenance are the decisions and actions taken regarding the control and upkeep of property and equipment. These are inclusive but not limited to the following:

1) Actions focused on scheduling, procedures, and work/systems control and optimization; and
2) Performance of routine, preventive, predictive, scheduled and unscheduled actions aimed at preventing equipment failure or decline with the goal of increasing efficiency, reliability, and safety (Sullivan et al., 2010).

Focusing on the operation aspect, the performance status of any kind of power plant and working equipment in their cycle of electricity production can be evaluated by inspecting current states of key parameters such as separator inlet pressure, turbine inlet pressure, steam flowrate, non-condensable gas content and others in a geothermal power plant. By means of using various instruments, compiling all detailed performance recorded in control systems and precisely analysing the gathered data, operators can determine the power plant functionality.

Today, almost all geothermal plants are using the SCADA (Supervision, Control and Data Acquisition) system for plant operation control. The following parameters are vital for plant operation (Woodworth, 1988):

a) *Operator training:* The operation personnel should understand the operating system. Especially if modern power plants are remotely controlled, the ability and knowledge of the operators determine the smooth operation of the machinery.
b) *Technology*: Nowadays a plant can be controlled and operated remotely with a few well-trained personnel using a SCADA system. The plant should update its equipment on a regular basis to the latest technology for better production.

c) *Operation manual:* A manual is a guidebook for an operator. It gives full information and necessary steps about the operating and control systems of the plant including start-up, normal operation, shut-down and emergency procedures.

To investigate a flash steam geothermal power plant operation performance, it is necessary to recognize basic elements of the cycle.

3.1 Basic equipment of a geothermal flash steam power plant

3.1.1 Steam production, collection and transmission

High-temperature wells, wellhead valves, controls and piping system are key elements to provide steam for the power plant. Pipelines transport the fluids that will be used to generate electricity and convey the waste fluids to their destinations. The main factors involved in pipeline design are pressure drop due to flow in the pipeline, heat losses to the environment as well as structural strength of the pipeline systems (Pálsson, 2010).

3.1.2 Separator

A steam separator, either vertical or horizontal installed depending on design specification or owners´ experience of the power plant, is a device used to separate water from steam in a two-phase flow so that only steam is sent to run the turbine.

The earliest method to separate steam and water is passing the mixture into a large drum, called a *knock out drum*. Flashing occurs due to the drop in the fluid pressure and the less dense steam will rise up while the denser water will fall down to the bottom of the drum.

Currently, the *cyclone separator* is the most popular design. Separation process is carried out by generating centrifugal force on the mixture entering the separator by using a tangential or spiral inlet to the cyclone. As the fluid rotates, the liquid with higher density will move outward and downwards while the steam which has lower density will move inward and upward. Finally, a stream of steam flows through turbine and water stream (brine) will be utilized or disposed in later steps (Zarrouk and Purnanto, 2015).

3.1.3 Steam turbine and auxiliaries

Steam turbines are turbo-machines that transform the thermal energy of steam into mechanical energy. In the first step the thermal energy of the steam is converted into kinetic energy by letting the steam expand, and secondly by momentum exchange to transform the kinetic energy into mechanical energy, through turning of the turbine wheels.

The basic components of a steam turbine are rotor blades, stator blades (nozzles), diaphragms, seals, bearings and casing. Bearings support the moving part of the turbine, i.e. rotor and seals are used to prevent leakage of the turbine. Stator blades are located on diaphragms which transform thermal energy of the steam into kinetic energy. The rotor supports the moving blades that convert the kinetic energy to mechanical energy. The casing holds the diaphragms, seals the rotor and protects the whole turbine from the environment.

There are two different types of steam turbines, so-called *Impulse* and *Reaction* turbines. In Impulse turbines pressure drop occurs only across the stator blades and not through the rotor blades whereas in reaction turbines, pressure drop is divided between both stator and rotor blades.

Moreover, steam turbines can be categorized as *Condensing* and *Back-pressure* turbines. In condensing turbines, a condenser is used to create a vacuum in the outlet of the turbine, steam expands until pressure drops to values lower than the atmospheric pressure. Back-pressure turbines, on the other hand, let the steam down to atmospheric pressure or higher. This allows to release steam directly to the atmosphere (Gunnarsson, 2013).

3.1.4 Gas extraction system

In geothermal steam there are always traces of non-condensable gases (NCG). The amount is usually in the range of 0-3% of the separated steam flow. Since the gas is non-condensable it must be removed out of the condensers, otherwise it will simply build up there, blocking the heat exchange between the cooling water and the steam. The purpose of the gas extraction system is to collect the NCG from the condenser and release to an exhaust at atmospheric pressures. Steam ejectors and liquid ring vacuum pumps are the most common types of equipment used in gas extraction systems though their selection depends mostly on the gas content in the steam (Teke, 2011).

3.1.5 Condenser

After flowing through the turbine, the steam continues its pathway to the condenser. One of the functions of the condenser is to reduce the pressure at the turbine outlet and thus extract more energy from the steam flowing from the turbine. In order to create water circulation from the condenser and reduce the pressure, pumps are used which are equipment of major electrical internal consumption. There are 2 types of condensers available: *Surface condenser systems* in which vapour condenses on coolant pipes and *direct-contact condensers* which mix cooling water with the utilized steam in an open chamber (NREL, 2010).

3.1.6 Cooling system

A cooling water system is composed of the cooling tower, the main circulation water pumps, the cooling pumps and the system of auxiliary pumps.

Cooling systems can be: 1. *Once-through* systems that take water from nearby sources (e.g., rivers, lakes, aquifers or the ocean), circulate it through pipes to absorb heat from the steam in the condensers and discharge the now warmer water to the local sources or 2. *Wet-recirculating (closed-loop)* systems that reuse cooling water in a second cycle rather than immediately discharging it back to the original water source or 3. *Dry-cooling* systems that use air instead of water to cool the steam exiting the turbine. A cooling tower is a specialized heat exchanger in which two fluids (air and water) are brought into direct contact with each other to accelerate the heat transfer.

There are two basic types of cooling towers, *Direct (open)* and *Indirect (closed)*. Direct (open) cooling tower exposes the cooling water directly to the atmosphere whereas Indirect (closed) cooling tower circulates the water through tubes located in the tower with no contact to the atmosphere (Sullivan et al., 2010, Union of Concerned Scientists, 2015).

3.1.7 Silencer

The main purpose of silencers is the reduction of noise level in the environment. Silencers are comprised of a chamber for receiving the spent fluid in the power plant and a lower outlet for the brine flows. The chamber has an upper outlet to release the geothermal vapour (Thórólfsson, 2010).

3.1.8 Electrical system

The electrical system is a complex unit of the power plant consisting of generator, transformer, transmission line, circuit breakers, switchgear/substation, instrumentation system, protection system, and control system (Kebede, 2002).

Generator & transformer
The generator of a geothermal power plant converts mechanical energy to electrical energy, comprising a stationary part: stator windings, as well as the moving part: the rotor with its field winding and excitation system and the prime mover with its associated auxiliaries. Step-up transformers are utilized to bring the low voltage level generated in the generator to the voltage level of the transmission lines.

Control system
To make sure the power plant is operating at optimum performance, the control system collects signals from connected units, analyses them and makes them transparent by visualization systems such as state-of-the-art SCADA systems either on site or in the control room.

The control system configuration of a modern power plant is based on advanced electronics. Some key components are the SCADA system, computers, modem, transmitter, receiver, programmable controllers etc. which are interconnected by fiber optic cables. In addition to the plant system, other systems such as the, fire protection, compressors, etc. can be integrated into the control system (Magnússon and Gunnarsson, 1989). Figure 3 shows one of the SCADA screens of Reykjanes power plant.

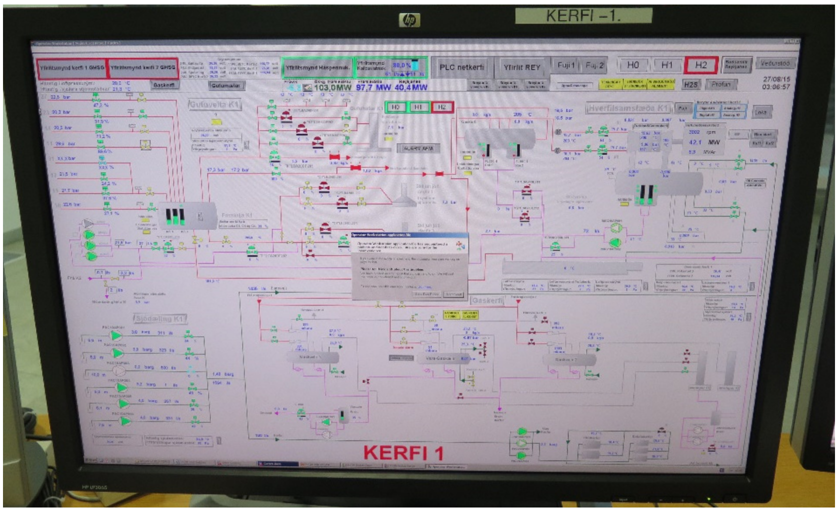


FIGURE 3: A SCADA screen in Reykjanes power plant

The most controlled parameters encountered in the flash steam cycle are flow, level and pressure. Level is measured as a distance or as a difference in pressure by the transmitter and the output of the controller is a position command to the control valve, the final acting element (Avilés, 2011).

Protection system
The protection system of a geothermal power plant ensures that all mechanical and electrical parts of the system are working flawlessly. It is designed to minimize damages due to any fault or error in the performance of the power plant. Electrical protection equipment reduces the consequences of electrical failures and plant damages. Based on the type of equipment and its importance, different types of protection relays can be used. Relays are designed to carry the fault current without damage and withstand the voltage without damage to the insulation. Nowadays, microprocessors based protection relays are becoming popular. A microprocessor-based relay also provides back-up protection. Hence it is more reliable, accurate and fast responding (Kebede, 2002).

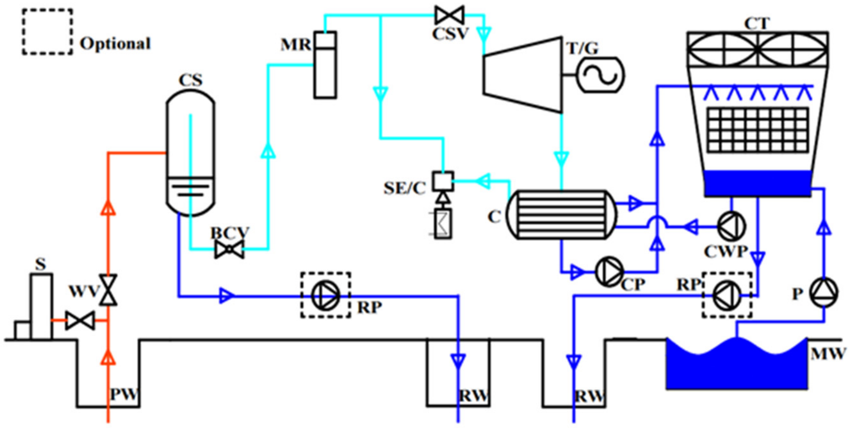
Safety devices which trigger the stoppage of parts of the installation or modify the operating regime according to abnormalities in certain parameters are among others:

- Automatic valves at wellheads for closure in case of sudden pressure loss;
- Safety valves on the geothermal circuit to limit the effect of an unexpected pressure increase;
- Circuit breaker in case of an electrical fault in a pump.

Other equipment partly protecting the geothermal loop are settlers and filters removing solid particles.

3.1.9 Reinjection system

Initially, the purpose of re-injection had been simply to dispose the low temperature water from the power plant after the energy extraction by returning some or all of it back into the geothermal system. This process also provides additional recharge which increases the production capacity, lowers the impact on the environment, reduces pressure decline due to mass extraction, enhances thermal extraction from reservoir rocks, offsets surface subsidence etc. The reinjection system usually includes water collection pipelines, injection pumps, injection pipelines, injection wells and a control system (Axelsson, 2008). Figure 4 illustrates a typical configuration of a single-flash geothermal power plant (Moon and Zarrouk, 2012).



PW	Production well	WV	Wellhead valve	S	Silencer
CS	Cyclone separator	BCV	Ball check valve	MR	Moisture remover
CSV	Control / stop valve	T/G	Turbine / generator	SE/C	Steam ejector/condenser
C	condenser	CT	Cooling tower	CWP	Cooling water pump
CP	Condensate pump	RP	Reinjection pump	RW	Reinjection well
P	Pump	MW	Make-up water		

FIGURE 4: Typical configuration of single-flash geothermal cycle (Moon and Zarrouk, 2012)

3.2 Operation of the Reykjanes power plant

Reykjanes power plant generates electricity during the whole year except for annual outage maintenance (one week for each 50 MW unit) and during 0 to 10 hour stops due to failures. Thus, with 100 MW of nominal capacity, an average of 815 GWh of electricity is produced annually. Electricity demand is not variable or seasonal due to a base-load contract with the aluminium smelter industry.

The local weather is characterised by high humidity, rain and salinity from the ocean. Three types of fluids are available in this power plant, high temperature geothermal fluid, seawater and fresh water. Originally, the fresh water supply was intended for a cooling tower which was never installed. It is now used for fresh water supply of the power plant facilities.

As shown in Figure 5 electricity production is subject to strong fluctuations in the past 5 years which are a result of major overhauls of unit 1 in 2011 and for 5 weeks in unit 2 in 2012. There was also a decrease in power of the geothermal wells during 2013 and 2014. In 2010, the production was maximal.

Two single-flash steam condensing units of 50 MW are working independently with one separator, one moisture separator, and one condenser each. Flashing process usually happens inside the production wells below 1000 m depth. Two-phase geothermal fluid (steam and mineral-rich brine) with 22-40 bar wellhead pressure and average temperature of 290°C is gathered and directed by 6000 m pipelines toward two horizontal separators (Figure 6) with inlet pressure of around 18 bar, 210°C and 25% steam quality. Density difference and gravity lead the steam and brine into different chambers in the separator.

Steam flows from the separator station to the moisture separator station located 1200 m away. Pipes which transport the steam from the separator to the moisture eliminator perform the role of a second separator. Pressure drop along the way to the turbine unit is around 1 bar. Fine droplets of water that might have formed in the pipelines are removed when the steam passes through the moisture separator. The saturated steam (18 bar and 207-208°C) is expanded and runs with a flowrate of 80.3 kg/s into each of the two double flow, top exhaust reaction turbines.

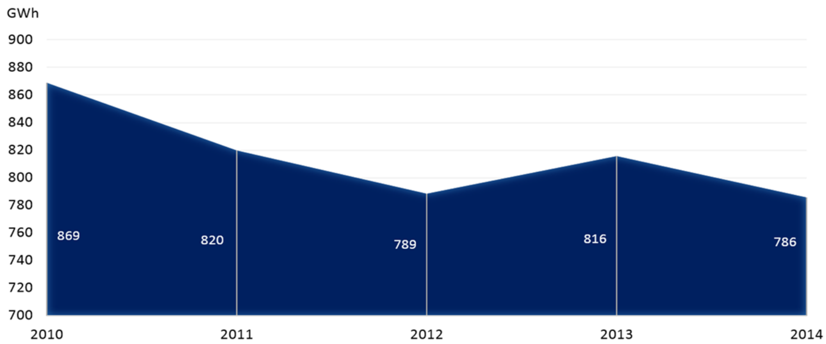


FIGURE 5: Annual electricity production trend in Reykjanes power plant

The steam enthalpy at the turbine inlet is about 2,800 kJ/kg and steam passes through the 14 stages of the turbine and leaves it with a pressure of 0.1 bar and 42°C. This significant expansion is accompanied by a decline in enthalpy of about 627 kJ/kg and hence this energy is transformed into shaft work by the rotating turbine blades which move with a speed of 3000 rpm. The turbine efficiency has been calculated to be about 80%. At the turbine exhaust, the steam enthalpy is found to be around 2.170 kJ/kg and wetness is about 18%. Rotor and stationary blades are made from alloy Steels and the outer casing is made of welded Carbon Steel plates.

FIGURE 6: Horizontal separators the power plant

The turbines are directly coupled to the 3-phase horizontal cylindrical revolving field synchronous Fuji generators with a brushless exciter (62.5 MVA) and totally enclosed water-air-cooled (TEWAC). Air is recirculated into the TEWAC machine by air to water heat exchangers. It generates 16.5 kV voltage with a power factor of 0.8. Output voltage is increased by step-up transformers in substation inside the power plant with switchgears (circuit breakers) to connect it to grid (16.5 to 132/230 kV).

A surface condenser is connected to the exit of each of the turbines and 1600 l/s of cold seawater is pumped into the condenser coming from 4 boreholes of 50-60 m depth. Lava layers are used as natural filters to purify the cold sea. The more vacuum pressure in the condenser the more efficient is the turbine. Eventually the condensate leaves the unit toward a mixing vessel with a remaining temperature of 38°C. Seawater used for cooling, condensate and most part of the brine from the separator are collected in the mixing vessel to be released into the ocean. The mixed fluid in the mixing vessel has a flow rate of 1900 l/s, atmospheric pressure and a temperature of 55-60°C. Auxiliary coolers of the turbine-generator are also cooled by seawater. The heat-exchangers tubes are all made of titanium.

On the other side of the condenser, the NCG is vacuumed to gas ejectors in the gas extraction system which is connected to the outlet of the condenser in order to discharge them to the atmosphere. Pressure of the NCG when leaving the condenser is low and requires 2 stages of steam ejectors (totally 3 steam

FIGURE 7: Silencers of the power plant

ejectors: one ejector for each turbine and one spare) to increase its pressure to 1200 mbar before being vented through the chimney to the atmosphere. After each steam ejectors the steam remaining in the NCG is condensed by a cooling system. Small parts of brine are transported to the silencers shown in Figure 7 and the power plant has the permit to release the brine into the sea.

A part of the brine from separator is mixed with the condensate in order to reduce the brine temperature and dilute it before reinjection to reduce the risk of scaling in the reinjection well.

The level of brine in the separator is controlled. When the level of brine is too high, brine mixes with the steam which is critical for the turbine performance and if the level of brine is too low, steam exists in the brine that causes bubble collapse and eventually a water hammer or a wave shock in the pipelines.

In a normal operation, the valve in the silencer is slightly open and if the level of brine exceeds a specific level this valve will open more and increase the flow of the brine towards the silencers. The power plant flashing brine silencers are large basins with aluminium tops, constructed from concrete with epoxy coated rebar. The aluminium top separates the brine drops from the steam in order to minimize brine carry-over. The brine in the basin boils and the aluminium top is a lid with vent holes. The basins are designed to enable a maximum flow of 300 kg/s.

The reason for not reinjecting all brine is that only one reinjection well exists on the power plant. This well had not been used for reinjection at first but due to its position close to other production wells it became a reinjection well because it could not produce. In a few months 4 new reinjection wells will be on operation which allows the reinjection of more fluid back into reservoir as well as decreasing the risk of pressure drawdown. The new reinjection wells are located 2000 m away from production area and are around 2500 m deep which is about 900 m deeper than the old reinjection well.

A lubrication system is located in the basement adjacent to each of the two units. This system supplies oil to the turbines and generator bearings for lubrication and contains a tank, a pump, a cooler, filters, and accumulators.

The power plant is equipped with centrifugal water and oil pumps which range in size from 270 kW to 1.0 kW. Each unit has three auxiliary cooling water pumps and 3 hot well pumps (only 1 is working). The auxiliary oil pump (AOP) and emergency oil pump supply oil to the turbine bearings and control oil. The AOP supplies oil during unit start-up when the turbine speed is low and during unit shut-down. The emergency oil pump is a DC motor-driven pump used to supply oil during power black-outs.

The power plant has 4 valve houses (A, B, C, and D), two of them (1 for each unit) next to the separation station containing steam control valves. Two other valve houses are next to the silencers containing valves to control the brine. Steam pressure control valves let the steam be released to the atmosphere if the pressure is above a set point but other regulatory of pressure is controlled by the turbine itself. The most critical valves in the power plant are:

- *Turbine main stop valve (MSV):* is open during normal operation and closed under stop and failure conditions; closes very quickly if it receives trip signal and closes automatically stopping the turbine from over-speed.
- *Main control valve (GV):* is for speed and power control of the turbine. This valve is regulated by the governor of the turbine and power settings intervene if the speed of the turbine is not within the correct range to be synchronized with the grid.
- *Pressure or Vent control valves:* is a steam pressure regulatory valve regulating the exact amount of steam needed by the turbine control valves.

The most significant control equipment used in Reykjanes power plant consists of:

- *In the steam gathering system:* wellhead control valve that opens remotely during the start-ups and lets two- phase fluid from the wells flow through the control valves to the silencers where steam is vented to the atmosphere. Additionally, each well has pressure and flow sensors;
- *In the separator:* a level control sensor that prevents brine from mixing into the steam pipe;
- *In the turbine:* valves MSV and GV which were mentioned earlier are controlling steam flow and load;
- *In the generator:* an automated voltage regulator (AVR) adjusts the voltage, the frequency and the current to operational limits;
- *In the condenser:* condenser basin level control to keep level of condensate in the condenser within a specific range.

In Figure 8 a process flow diagram of the power plant is shown presenting important operating parameters and components.

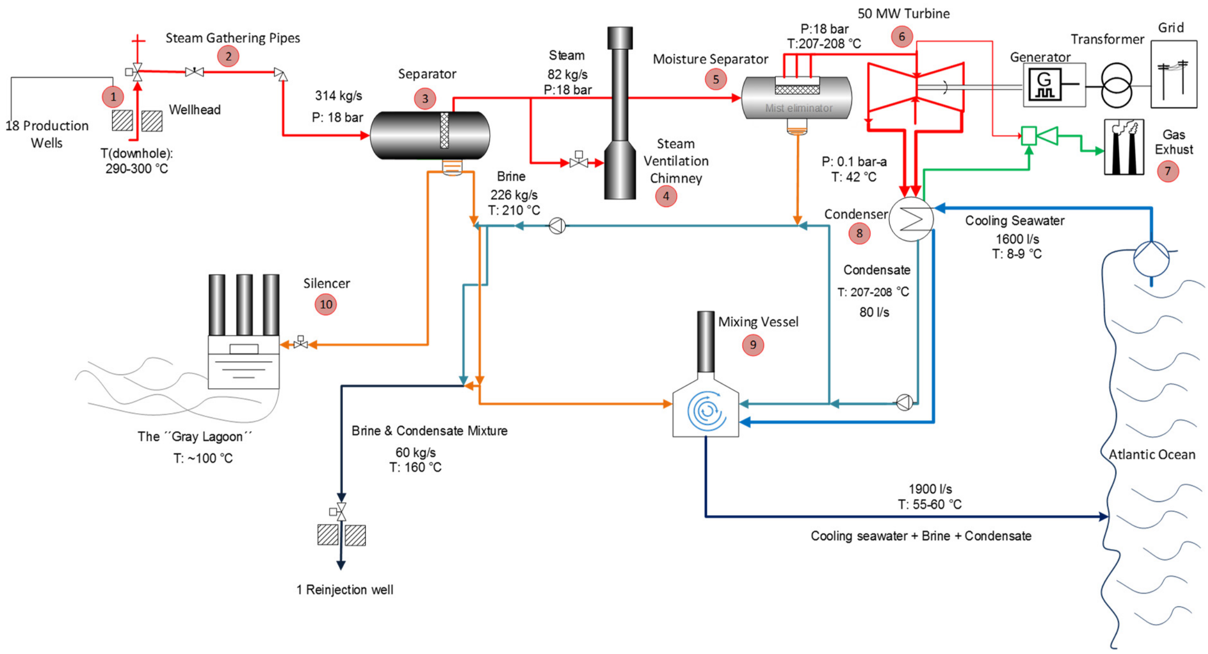


FIGURE 8: Process flow diagram of Reykjanes power plant

Number of major equipment in the Reykjanes power plant is shown in Table 1.

TABLE 1: Total number of components

Total wells	Exploration wells	Production wells	Reinjection wells	Separators	Moisture separators	Turbines	Generators	Transformers	Condensers	Gas ejectors	Cooling towers	Pumps	Motors	Valve houses
34	12	18	4 (new) 1 (old)	2	2	2	2	2 Main 6Auxiliary	2	3	-	~30	~30	4

4. MAINTENANCE PROCESS

According to the Oxford dictionary maintenance is defined as the process of keeping something in good condition. To narrow down the concept, maintenance refers to all actions that should be taken to prevent a device or component from failing or to repair normal equipment degradation experienced with the operation of the device to keep it in proper working order.

In the design life of most equipment, they require periodic maintenance. Belts need adjustment, shaft alignment needs to be maintained, proper lubrication of rotating equipment and replacement of non-functioning elements are required and so on. In addition to waiting for a piece of equipment to fail (corrective maintenance), preventive maintenance, predictive maintenance or reliability-centred maintenance are utilized (Sullivan et al., 2010; Tessema, 2002).

4.1 Maintenance methods and procedures

Maintenance methods have been categorized variously by different studies. In almost all the papers and studies, corrective, preventive and predictive maintenance have been identified. Although in all sources first type of maintenance is referred to as corrective or reactive maintenance, they differ in categorizing preventive and predictive maintenance. Some scholars regard predictive maintenance as a subcategory of preventive maintenance while others see predictive maintenance as an independent category. Nevertheless, the definition of these procedures is almost the same (Sullivan et al., 2010; Adale, 2009; López, 2008; PECI, 1999; Bore, 2008; Márquez, 2007).

4.1.1 Corrective (reactive) maintenance

Maintenance which is classified as corrective is performed only when the equipment or system fails to function. The damaged equipment will then be repaired or replaced.
Corrective action can either be deferred or immediate. Deferred maintenance is delayed for any reason and is assumed to have little impact on system performance, immediate action is executed as soon as a failure has been detected.

At first sight, this method seems the most cost effective because the manpower and their associated costs are minimal especially for new equipment. But in real practice, when equipment fails, labour costs associated with repair will probably be higher than normal because the failure will most likely require more extensive repairs or if it is a critical piece of equipment that needs to be back on-line quickly, maintenance overtime costs will have to paid. Lost revenues due to non-production, safety issues for equipment and for staff caused by failures can be added to pitfalls of this method.

4.1.2 Preventive maintenance

Preventive maintenance, as the name indicates, includes activities for prevention of failures. Inspecting and diagnosing breakdowns before occurrence aiming to preserve and enhance equipment reliability to prolong lifetime of the power plant components closer to design are considered as preventive maintenance. Preventive maintenance activities include equipment checks, partial or complete overhauls at specified periods, oil changes, lubrication and so on. In addition, workers can record equipment deterioration so they know when to replace or repair worn parts before they cause system failure.

Some scholars have divided preventive maintenance to time-based (periodic) and conditioned-based procedures (predictive) maintenance assuming predictive maintenance as a subcategory of preventive procedures. Time-based preventive maintenance refers to procedures done based on calendar intervals, after a specified number of operating cycles or a certain number of operating hours while conditioned-based maintenance consists of programmes measuring equipment condition on a regular basis, track the measurements over time and take proper action when measurements are about to exceed the equipment operating limits.

4.1.3 Predictive maintenance

Seeing predictive maintenance as a main category and third type of maintenance, it is defined as the establishment of a baseline performance data, monitoring performance criteria over a period of time and observing changes in performance so that failure can be predicted. Basically, predictive maintenance differs from preventive maintenance by basing maintenance need on the actual condition of the machine rather than on some schedule (Sullivan, et al., 2010). On the down side, to initially start predictive maintenance is not inexpensive and needs training of in-plant personnel to effectively utilize predictive maintenance technologies. Common predictive technologies are as follow:

Infrared thermography (IR): Process of generating visual images that represent variations in IR radiance of surfaces of objects. The primary value of IR is thermographic inspections of equipment to locate problems so that they can be diagnosed and repaired such as transmission lines or rotating equipment problems. Thermography can be used to define temperature profiles indicative of equipment operational faults or failure.

Oil analysis is used to define three basic machine conditions related to the machine's lubrication or lubrication system. Firstly, it is the condition of the oil, secondly lubrication system condition and finally the machine condition itself (machine wear).

Ultrasonic analysis or ultrasounds are defined as sound waves of a frequency above 20 kHz which are used to detect airborne ultrasound. Most rotating equipment and many fluid system conditions will emit sound patterns in the ultrasonic frequency spectrum. Changes in these ultrasonic wave emissions are reflective of equipment condition such as component wear or leaks.

Vibration analysis used for vibration detection of rotating equipment via sensors to quantify the magnitude of vibration or how rough or smooth the machine is running.
Motor analysis provides all the answers required to properly characterize motor condition electrically or mechanically.

Performance trending maintenance activities by utilizing already provided instrumentation to determine the health/condition of the related component.

In Table 2 Common predictive technology applications in different components of a power plant are been shown (Sullivan et al., 2010)

TABLE 2: Common predictive technology applications

Technologies / Applications	Pumps	Electric Motors	Diesel Generators	Condensers	Heavy Equipment/ Cranes	Circuit Breakers	Valves	Heat Exchangers	Electrical Systems	Transformers	Tanks, Piping
Vibration Monitoring/Analysis	X	X	X		X						
Lubricant, Fuel Analysis	X	X	X		X					X	
Wear Particle Analysis	X	X	X		X						
Bearing, Temperature/Analysis	X	X	X		X						
Performance Monitoring	X	X	X	X				X		X	
Ultrasonic Noise Detection	X	X	X	X			X	X		X	
Ultrasonic Flow	X			X			X	X			
Infrared Thermography	X	X	X	X	X	X	X	X	X	X	
Non-destructive Testing (Thickness)				X				X			X
Visual Inspection	X	X	X	X	X	X	X	X	X	X	X
Insulation Resistance		X	X			X			X	X	
Motor Current Signature Analysis		X									
Motor Circuit Analysis		X				X			X		
Polarization Index		X	X						X		
Electrical Monitoring									X	X	

4.1.4 Reliability centred maintenance (proactive)

Basically, Reliability Centred Maintenance (RCM) methodology deals with some key issues that are not taken into consideration by other maintenance programs allocating priorities to components considering financial and personnel limitations as well as importance of the equipment. It recognizes that equipment design and operation differs and that different equipment will have a higher probability to undergo failures from varying degradation mechanisms. RCM sometimes is seen as an umbrella term of proactive maintenance which aims to emphasize on proper installation and precision rebuild Failed-parts analysis such as Root-cause failure analysis, Reliability engineering, Rebuild certification/verification, Age exploration and Recurrence control to extend machinery life (Chalifoux and Baird, 1999).

Table 3 presents results of a case study comparing costs of different maintenance strategies (Sullivan et al., 2010):

TABLE 3: Case study comparison of four maintenance programs

Maintenance method	Cost ($/Horsepower/year)
Reactive maintenance (breakdown or run-to-failure maintenance)	18
Preventive maintenance (time-based maintenance)	13
Predictive maintenance (condition-based maintenance)	9
Reliability centred maintenance (proactive)	6

4.1.5 Optimum maintenance strategy

To decide which of the methods discussed above should be employed by a power plant maintenance team (Figure 9) could be based on criticality/impact and vulnerability/risk analysis. Corrective maintenance should be the strategy of choice only if the risk of failure is very low and if the consequences of failure are fairly mild or where preventive maintenance measures are not available.

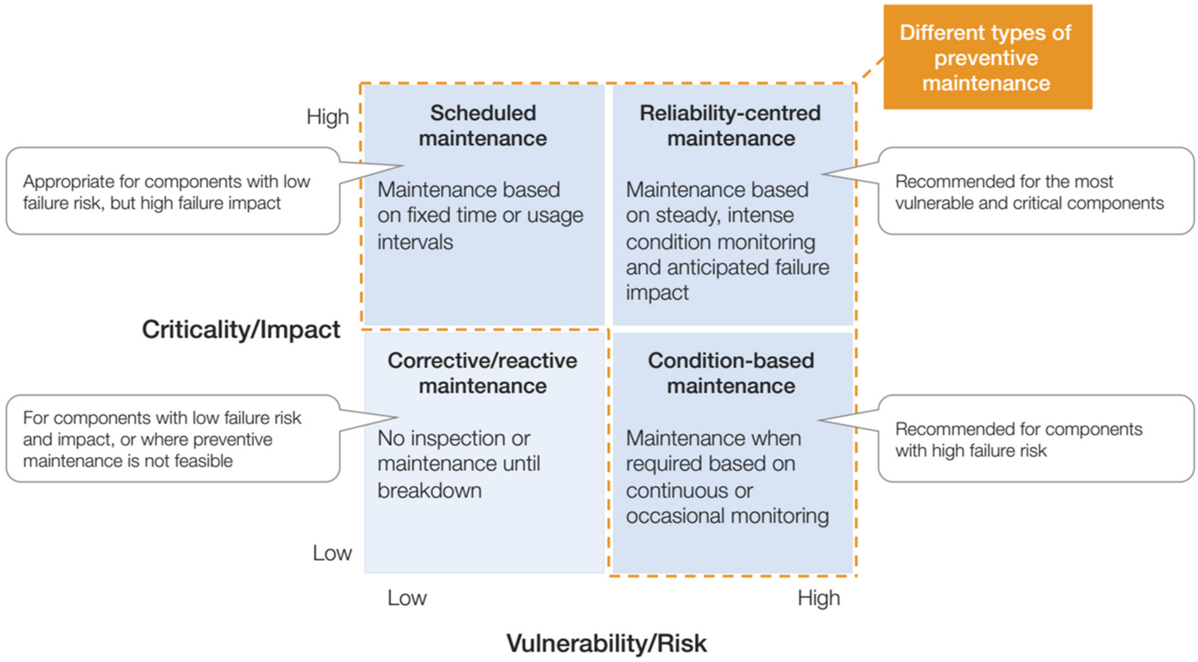


FIGURE 9: Selection of optimum maintenance methods (World Economic Forum, 2014)

Scheduled (time-based) maintenance is the strategy of choice when failures are costly or safety is critical and when the failure rate is fairly low but tends to increase over time.

Condition-based or predictive maintenance is a strategy that triggers maintenance activity when the asset's condition falls below a certain threshold. The aim is to time the maintenance work optimally so that it is not performed more often – and hence more expensively – than necessary and in a way that it can be undertaken at a convenient time when the service will be disrupted the least.

Reliability-centred maintenance considers not only the asset's current condition but also the likely consequences of failure. The main aim of this strategy is to reduce the overall risk and impact of unexpected failures i.e. to ensure high reliability. To put in a nutshell, maintenance methods need to be customized for each asset and correct combination of strategies should be applied for each component of the power plant (World Economic Forum, 2014).

4.2 Overhauls (outages)

Unit overhaul is carried out annually or after every two, four, five etc. years of continuous operation depending on maintenance management of the power plant. This maintenance usually takes some weeks to complete depending on which unit is being maintained. For this type of maintenance, it is necessary to optimize time and costs and to plan all steps in advance including preparing tools, possible spare parts and hiring external personnel to carry out the work if needed, because downtime affects plant operational availability, reliability and eventually prosperity of power plant regarding produced electricity.

4.3 Dynamic maintenance management (DMM)

In order to arrange a maintenance schedule, a maintenance management programme is used to help define coordination, control, planning, implementing and monitoring of the necessary activities required for each component of the plant. For this purpose, CMMS (Computerized Maintenance Management Systems) have been developed to fulfil all maintenance tasks flawlessly. DMM software is one of the CMMS methods that have the following common functions: Machine history, preventive maintenance schedules, work orders, condition monitoring, condition based flagging, time accounting, fault reports, improved safety, expense tracking, procurements, trending and performance reports (Adale, 2009).

4.4 Geothermal power plant maintenance system

Geothermal power plants can make substantial savings by practising effective maintenance of equipment. Annual O&M cost is estimated to be 1-4% of the capital cost of a typical geothermal power plant with 50 MW capacity.

However, the maintenance process is very case-dependant, considering the nature of the geothermal system in the area, chemical and state properties of fluid, geographical setting such as weather, age of power plant etc.

Most maintenance activities are done in a geothermal power plant targeting and combating scaling in pipelines, cracking in metal parts or pipes, corrosion, erosion and failure in component pipes due to nature of the geothermal fluid result in damage in equipment, plugging in pipes, more pressure drop due to friction and less energy to be converted in the turbines (Elísson, 2013).

4.5 Maintenance of Reykjanes power plant

In this section, maintenance activities carried out for each component in Reykjanes power plant are described. Methods to gather information on operation and maintenance of the Reykjanes power plant in this report have been analysis of secondary data from related reports and papers, documents from the Dynamic Maintenance Management (DMM) of the power plant as well as interviews with power plant staff in addition to visits during the annual outage activities and recording maintenance procedures in one-week outage of one unit of the plant. So all accumulated data were utilized to have a general overview of how the operation and maintenance of Reykjanes power plant is accomplished.

The maintenance team of Reykjanes power plant uses a DMM software since the commission of the power plant. The DMM software is interconnected to SCADA screens to control all procedures. SCADA screens present Process Flow Diagram (PDF) including piping, instrumentation, utility connections and power layout with equipment identification including pumps, valves, ancillary fittings as well as measurements and control of points and loops. Maintenance actions are triggered by equipment condition, run time or a fixed schedule (Tessema, 2002). The DMM software interface consist of following tabs: logbooks, availability of unit, documents (manuals), reports of O&M, equipment with KKS (Kraftwerk Kennzeichen System) for coding all components, work orders, green book (reports on wastes of the plant), Gantt charts and instruments in each of which comprehensive data on operation and maintenance have been embedded.

In Figure 10 recorded work orders in the DMM system of Reykjanes power plant during the year 2014 have been categorized. Table 4 shows performance and cost data on Reykjanes power plant that will be used in the next sections.

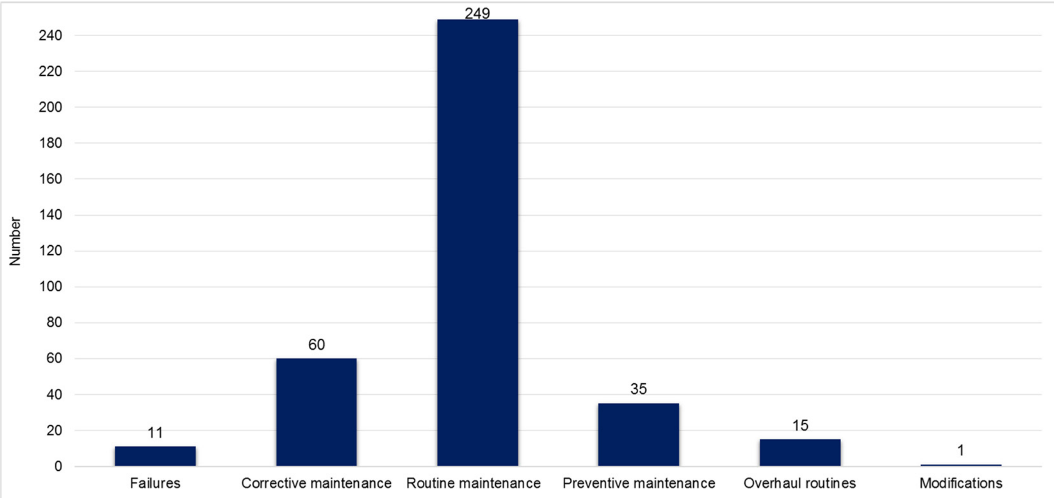


FIGURE 10: Total work orders in DMM system in 2014

TABLE 4: Data gathered of Reykjanes power plant

Total number of stops	15	(time)
Total stop (outage) time (unavailable time)	336	(hours)
Scheduled outage time	224	(hours)
Unscheduled outage time	112	(hours)
Total routine (day) maintenance time (For one unit: 50 MW)	2300	(hours)
Total maintenance overtime (For one unit: 50 MW)	440	(hours)
Net electrical output	96	(MW)
Total electricity generated	786000	(MWh)
Electricity price	3	(ISK/KWh)
Total sold electricity (income)	235.8	(Million ISK)
Total cost of lost production	27	(Million ISK)

4.5.1 Maintenance staff

The O&M team of the power plant consists of 12 (marine) engineers working in shifts at both Svartsengi and Reykjanes power plants. Routine inspections, preventive and predictive maintenance activities are done during the daily maintenance shifts. Work that might involve considerable scheduling effort like overhauling the plants and well workovers is done in cooperation with the in-house team. Some tasks are outsourced to local contractors.

In normal operation time during a month, operators work as dayshift operators in the plant for one week, one week as part of the maintenance team and have one week off.

Three operators who work during the dayshift have different responsibilities. Two of the operators monitor the power plant and investigative protection and safety and the third one is responsible for minor maintenance, lubrication etc. The first two operators stay at Svartsengi power plant at night for emergency maintenance.

4.5.2 Power plant RAM (Reliability, Availability, Maintainability)

It is true that a power plant is a system of interdependent subsystems and that, if one of the subsystems fails, the entire power plant may be at risk of shutting down. Reliability is used to express and quantify the unplanned maintenance needs of a power plant measuring how often a plant is available in comparison to the total number of hours the plant would be available with no unexpected maintenance. Reliability of an ideal power plant is 100%.

By means of Equation 1 and data presented in Table 4, reliability of the Reykjanes Power plant in 2014 has been calculated to 98.7%.

$$Reliability = \left(1 - \frac{hours\ unavailable\ caused\ by\ unscheduled\ outages}{total\ hours}\right) \times 100 \qquad (1)$$

Availability is a measure of how often a unit is capable of providing service. In most cases, equipment must be shut down for maintenance to be performed. It may be extremely reliable but it is unavailable during the time it is shut down. Availability can be improved by maximizing uptime (reliability supplemented or enhanced by redundancy) and minimizing downtime (high maintainability). Availability considers both scheduled and unscheduled maintenance and compares to an ideal situation with no maintenance outages at all. By means of Equation 2 as well as data from Table 4 availability of Reykjanes power plant in 2014 has been calculated to be: 96.1% which is higher than average availability of geothermal power plants reported to be 90% (EERE, 2015).

$$Availability = \left(1 - \frac{hours\ of\ unscheduled\ outages + scheduled\ hours}{total\ hours}\right) \times 100 \qquad (2)$$

Maintainability is used to express the cost of maintenance. This includes the cost for parts and servicing. Material management in Reykjanes power plant is maintained within the accounting system and regular status checks are made on the inventory. This system has proven to be working well so there is no plan for changing inventory system (Figures 11 and 12).

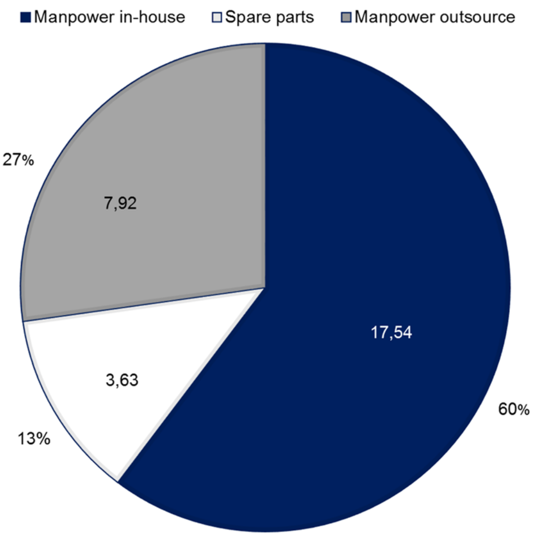


FIGURE 11: O&M annual cost breakdown for 50 MW unit (Million ISK) (2014)

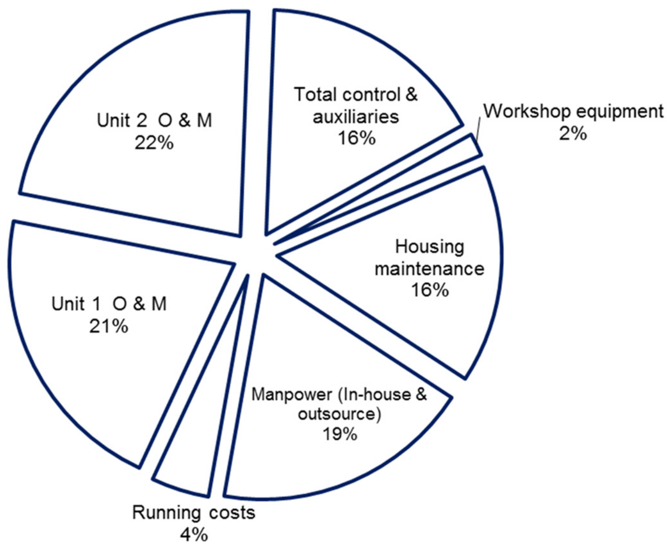


FIGURE 12: Annual O&M and Control cost of total 100 MW (2014)

Combining these considerations, RAM looks at how often you can use the equipment and how much it costs to keep it in operating condition (HPAC Engineering, 2013; Michael Curley, 2013; Marini, 2006). Other important parameters based on IEEE 762 Standard from the power plant have been calculated.

By means of Equation 3 as well as data from Table 4 the Net Capacity Factor (NCF) of Reykjanes is calculated to be 89.7% which is higher than the average worldwide capacity factor of single-flash dry-steam plants (80,1%) (Moon and Zarrouk, 2012).

$$Net\ Capacity\ Factor(NCF) = \frac{Actual\ Energy\ Generated}{Maximum\ Possible\ Energy\ could\ have\ generated} \quad (3)$$

By means of Equation 4 as well as data from Table 4 the Scheduled Outage Rate (SOR) of Reykjanes is calculated to be 2.55%. The lower this index is, the better. It is worth mentioning that from the total of 15 times of the plant stops, 8 times have been caused by steam supply failures, 4 times by maintenance work and 3 times by transmission lines and grid failures.

$$Scheduled\ Outage\ Rate(SOR) = \frac{Total\ hours\ unit\ is\ out\ of\ service\ due\ to\ scheduled\ maintenance}{Total\ hours} \quad (4)$$

And finally by means of Equation 5 as well as data from Table 4 Forced Outage Rate (FOR) of Reykjanes is calculated to be 1.2%. This indicator should be as low as possible and is supposed to be less than the SOR.

$$Forced\ outage\ Rate(FOR) = \frac{Total\ hours\ unit\ is\ out\ of\ service\ due\ to\ unexpected\ failures}{Total\ hours} \times 100 \quad (5)$$

4.5.3 Maintenance procedure for each component

Most maintenance procedure in Reykjanes power plant involves preventive maintenance although corrective actions are sometimes inevitable. It has been tried to prioritise corrective steps, especially regarding the price of electricity since during a power plant stop, the power plant owner is required to purchase and provide electricity for contracted sales (aluminium industry) and if the timing is not suitable, electricity could have to be bought for higher prices than necessary.

Maintenance is carried out weekly, monthly and annually. Inspection of power plant component (preventive and predictive maintenance) is the main activity during annual outage. Each unit of 50 MW takes one week outage per year and the time between outages of each unit is at least one week to do necessary preparations. Major activities done during this period will be discussed step by step by following the steam route flow from the wells to the powerhouse equipment.

Steam gathering and pipes

Each wellhead is equipped with a control valve in order to regulate the flow from the wells to meet the power plants' requirements. The valve actuator is a hydraulic cylinder. This valve has been designed by engineers of the power plant and are set up as a large needle valve (choke valve) which does not stick due to scaling and does not suffer from erosion. They are remotely controlled although position of the valves does not change regularly.

Drain valves are open during warm-up of pipeline in the start-up process and are closed before taking the full pressure. Besides, these valves are used during tracer test flow measurement and for collecting the fluid samples. Figure 13 shows the repairing process of brine pipelines (cleaning).

Scaling problems however, are prominent in the level-control valves for the brine in the separators. The scaling in wells and wellheads of Reykjanes power plant consists mostly of metal sulphides but not silica (Figure 14). Silica scaling can be found downstream in separators and brine pipes.

FIGURE 13: Pipeline and valve maintenance

FIGURE 14: Cleaning scaling in pipes

In the past, brine valves were prone to get stuck and valve stems wore down too quickly but both problems were solved by modifying the control valves.

In the annual outage maintenance period, valves are taken out, opened and depending on their condition they are cleaned, repacked and reinstalled or they are replaced if needed.

Other main maintenance tasks in outage period is stopping the leakage in steam pipes which can be caused by different reasons, but mainly by H_2S cracking and bad quality of steel or improper welding. Regarding maintenance of the pipe insulations, they are changed only if they are damaged due to leaks from the steam pipes.

Separator
Horizontal separators have been installed in Reykjanes power plant which are considered to be safer regarding earthquakes. In the first years of operation they faced scaling problems. The scaling was gradually reduced by pressure drop and a change in the chemistry of the geothermal system. Moreover, some minor cracks have been observed only in the upper part of some pipes while in the separator vessel itself no cracks have been identified. Generally, inlet pipes that connect to the separator are a critical point affected by high manganese content in the steel (Thórólfsson and Einarsson, 2015).

FIGURE 15: Separator inspection during outage

In the annual outage maintenance periods, the separator is cooled down by an air pump to allow visual inspections, taking pictures of the centre chamber and steam outlet, checking for stuck valves and scaling (Figure 15).

In general, maintaining high pressure in the separator inlet reduces scaling in the vessels. In addition, corrective procedures are done if necessary such as repairing or replacing. For instance, in the 2015 outage, a leakage in the brine outlet pipe from the separator caused by a faulty welding was fixed. Also as droplets of brine fall down to the bottom in two rows of the chevrons inside the separators, they needed cleaning.

Moisture separator
Steam from separators flows towards a moisture separator unit, passing through the stainless steel mist eliminator pads.

The moisture separator is a unit highly prone to cracks. About 400 kg of condensate is drained through the moisture separator per hour, carrying about 1 kg/h of dissolved solids compared to 80 kg/s of condensate from the condenser that carries only 0.1 kg/s of solids (Thórólfsson and Einarsson, 2015).

A recent incident was related to the mist eliminator which is made of 316 Stainless Steel. It had deteriorated and cracked caused by pressure fluctuation due to an electricity grid failure. The cut mesh pieces went into the steam line and into the steam inlet strainer, broke the strainer and into the turbine. It was not realized at the time and after 3 years of operation the maintenance team found the damage of the turbine blades during an overhaul. Eventually one row of turbine blades was replaced. The wire mesh was improved from 316 to duplex Stainless Steel which lasts for 3 to 4 years. During the maintenance outage period the mist eliminator pads are inspected visually and pulled by hand to check if they are deteriorated as shown in Figure 16.

FIGURE 16: Moisture separator inspection during outage

Steam turbine

As the most significant part of the geothermal power plant, the turbine is also the most complicated and sensitive equipment in terms of operation and maintenance. Thus, in addition to periodic inspections in routine maintenance procedure, a specific overhaul period is assigned just for the turbine and its auxiliaries. Main components of the turbine that are monitored in the maintenance procedure are the rotor, stationary blades (nozzles), lubrication system, sealing, packing and casing parts, bearings, steam traps and steam strainers. The turbines in Reykjanes power plant have been designed for easy and fast maintenance, blade carriers are bolted into the turbine casing so they can be removed quickly for cleaning.

The turbines have built-in protection systems against vibration, over-speed, eccentricity, axial movements and differential expansion as well as control of lubrication oil temperature, bearings temperature and turbine gland (seal) pressure. Sensors are installed in all bearings to monitor vibrations in the turbine. A portable vibration meter is available to record the vibration of pumps and smaller rotating units.

In the last stage of the turbine, there is 18% moisture at the end of the blades where they are exposed and hit by liquid drops. The blades have a strip made of a special hard metal, Stellite, which is a cobalt-chromium alloy designed for wear resistance.

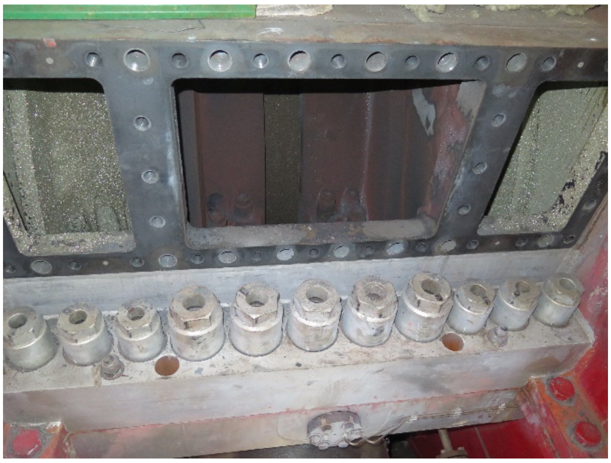


FIGURE 17: Visual inspection of inlet nozzles of turbine for scaling

In the annual outage, turbine maintenance involves a visual inspection of scaling in the inlet chamber and the inlet nozzles of turbine. Photos are taken and compared to photos taken in previous years to decide on a date of the next major overhaul (Figure 17). Also the pressure in the head of the nozzles is measured to track how the inlet pressure increases with time due to scaling. In 2012, damaged blades of the rotor were changed which were broken due to the incident in the mist eliminator, that was mentioned above (Figure 18).

During the 5-year major overhaul, that takes 5 weeks' time, turbines are dismantled, bolts are loosened, casings are opened, all parts are cleaned, scaling is removed, and blades are repaired if necessary. If blades are damaged they can be replaced with spare turbine rotors.

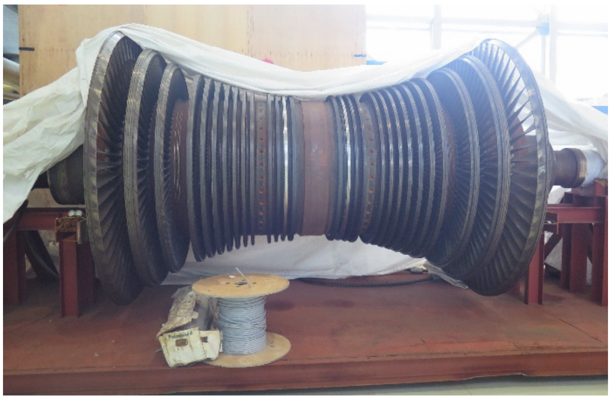


FIGURE 18: A repaired steam turbine rotor

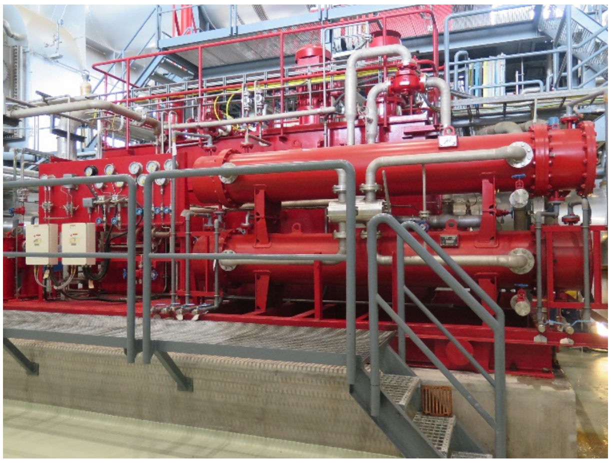


FIGURE 19: Lubrication system of the Reykjanes power plant

Turbine auxiliaries

Steam traps are automatic valves that drain condensed steam (condensate) from a steam space while preventing the loss of live steam. Droplets are formed by heat transfer especially during start-up time when pipes are still cold. Number of steam traps for one unit is 22.

Excluding design problems, two of the most common causes of trap failure are under-sizing and dirt. Under-sizing increases the work load on single traps. In some cases, this can result in blowing of live steam. Dirt is always being created in a steam system and excessive build-up can cause plugging. Steam traps are periodically checked to avoid failures.

Steam strainers are another turbine auxiliary that captures any foreign materials like rocks at the inlet of the turbine. Maintenance procedure in outage involves opening and taking out the foreign material.

Lubrication system as one of auxiliary systems of the turbine. It has pumps, motors, tanks, filters and pipes and circulates oil through all components that need lubrication (Figure 19). The turbine and generator rotors weigh 28 and 15 tonnes, respectively, rotating at 3000 rpm. Normally, circulating oil does not require frequent replacement, instead samples of oil are taken for analysis every 2 or 3 months. Separators in the oil system and micro filters as they are installed in lubrication system of Reykjanes power plant are not very common in geothermal power plants but, since engineers of this power plant are marine engineers, they used the same equipment applied in lubrication system on ships. However, this extra equipment is beneficial for the system in a way that oil can be used for 10 to 15 years. When the turbine starts to work, the first component that starts is the auxiliary oil pump and the jacking oil pump that lifts the rotor in the bearings. So when the turbine reaches working speed they can stop, and the main oil pump, mounted on the turbine shaft, takes over.

Generators

Prevalent failures of the generator and electrical systems can be rotor vibration, loose stator coils, arcing of switch gears, failure of motors and failure of transformers (Bore, 2008). Yet, these failures have occurred rarely in Reykjanes power plant. The only experienced failure has been a house load transformer which broke down due to defective manufacturing.

Plant generators are one of the least problematic equipment in the power house, working since 2006 without breakdown. They do not require complex maintenance, only the bearing system is constantly monitored and lubricated. The hydrodynamic bearings are also reliable pieces. Preventive maintenance of generators involves controlling and protecting it against any failure caused by internal factors of the power plant or from the grid.

In major overhauls, the disassembly and internal inspection of mechanical components of the generator is necessarily carried out according to the manual. Electrical tests consist of insulation condition assessment, cleaning and testing.

Generator grounding and its fault protection, excitation system, thermal and fault protection of stator of generator, rotor field protection, breaker failure protection, protection against loss of fields, over-excitation, unbalanced currents, motoring overvoltage, fluctuation in frequencies etc. are common protection considerations of generators (Aguirre, 2010).

Condenser and cooling system

The surface condenser used in this power plant is much more expensive than direct contact condensers, although it is less vulnerable to scaling. In addition, with having the clean condensate from the surface condenser which is used to dilute the brine for reinjection, less scaling problems occur in the reinjection pipes. There are six condensate pumps, three for each unit that increase the pressure of the condensate from 2 to 20 bar. To protect the unit, the water level inside the condenser as well as the pressure and temperature of the steam exhaust of the turbine is controlled.

The maintenance process of the condenser has been proactive to begin with by considering the fluid salinity of the area during the design phase and by choosing the surface condenser type. Visual inspection for foreign objects in the condenser and cleaning scaling in the pipes is usually not carried out annually. This is usually done on a biannual basis or only in the major 5-year overhaul (Figure 20). The steam condensate is corrosive because of its low pH. However, when it is mixed with brine no corrosion occurs anymore. Oxygen in the condensate is the cause of corrosion which does not happen in surface condensers. By selecting the type 316 Stainless Steel for condensate pipes and vessels, this problem is also prevented. The seawater pipes, transporting cooling water, are made by fibre glass or composite and the tubes in the condensers are titanium which is more expensive yet more reliable in cycles using seawater.

FIGURE 20: Inspection of the condensers

Temperature sensors in the low temperature side of the condenser last many years but in the high temperature (steam) side the sensors should be replaced after 4 or 5 years and need more frequent calibration during the annual overhaul.

Common problems of cooling towers such as scale deposits or clogged spray nozzles, that require maintenance, do not exist in Reykjanes power plant because of the usage of a once-through cooling system that takes water from the sea. Cooling water supply for condenser is not directly taken from the sea but from ashore wells. Regarding cooling water, generally no trouble has occurred in condenser performance due to cooling water so far. Biological bacteria and sea animals could gradually plug up the pipes of the condenser. Inspection, cleaning and effective filtration are actions that should be done.

Gas extraction systems

Currently 0.7% of the steam consists of NCG in Reykjanes power plant of which 98% is CO_2 and 2% H_2S. Comparing to other geothermal power plants, this amount of NCG is very low. However, even very little amounts of H_2S in the system can cause huge problems for the equipment. After the separation of steam and brine, the proportion of NCG increases in the steam and high partial pressure of H_2S causes cracks in vulnerable pipes (Carbon Steel pipes).

FIGURE 21: Steam ejector

FIGURE 22: Cleaning pipes of silencers by hydro-blast pumps

FIGURE 23: Power plant pumps

Since steam ejectors have no moving parts and due to their simple construction, this is a relatively low-cost component, easy to operate and low in maintenance efforts (Green and Perry, 2008).

Typical steam ejectors components are nozzles, intercoolers, control valves, and isolating valves. During outage maintenance only nozzles and control valves are disassembled to check for cracks (Figure 21). Outlets of the moisture separator and the main steam line between the moisture separator and the turbine are most vulnerable to cracks because of the high temperature and high H_2S concentration. Significant part of the 2015 annual outage corrective maintenance procedure consisted of repairing at least 4 steam leaks in pipes caused by H_2S corrosion.

Silencers

Silencers in Reykjanes power plant take a part of the brine from the separator depending on the status of the level controls in the separator. Inside the silencers the flow is directed downwards through vertical pipes into a water tank inside the silencer vessel 3 m below water level. In systems including brine, the main problems coming up in silencers relate to scaling and corrosion. During annual outage the silencers pipes are washed by hydro blast pumps to prevent or clear blockage (Figure 22).

Pumps and motors

One of the special design features of Reykjanes power plant is that brine flows through the system by utilizing the separator pressure as well as taking advantage of gravity, so that no pumps are needed for brine circulation and problems of scaling in brine pumps, which is a common problem that does not occur in this power plant. Two condensate pumps, three auxiliary cooling water pumps for oil, and the generator in main power house are shown in Figure 23.

Maintenance of pumps and motors by minimizing the vibration plays a vital role in the performance of the whole system and also influences the lifetime of their related auxiliaries like bearings, couplings and others. Shaft alignment of the pumps is done by a laser alignment tool.

Motors, if bearings are lubricated properly, can work for a long time without any mechanical problems. On the other hand, there is a number of common electrical failures in motors that need protective actions by monitoring critical parameters of motor performance such as phase overcurrent, negative sequence, ground fault, stall or locked rotor, over-temperature of stator winding and vibrating sensors (Aguirre, 2010).

Air cleaning room
This unit serves for removing any trace of H_2S from all electrical rooms by filtering H_2S from the air to avoid corrosion of electrical components such as computers, electronic and low voltage electrical systems. Hydrogen sulphide combined with humid air corrodes copper. All sensitive equipment has to be kept in a room where H_2S gas has been cleaned from the ambient air.

FIGURE 24: Air cleaning room

This room consists of drawers that are filled with chemical air purifier material, based on potassium permanganate, providing optimum adsorption and oxidation of a wide variety of gaseous contaminants (Figure 24). The air flows through drawers and ventilators and then to the electrical rooms and then circulates again. There are six filtering units for six electrical rooms, each of which works with an electrical blower to circulate the air. Maintenance of the ventilation system is rather straightforward including replacement of the air purifier material when its colour changes and reshuffling the drawers. The more H_2S in the air in a power plant, the faster the deterioration of the air purifier material will be.

Electrical rooms
Electrical rooms contain PLC units, electrical protection systems (breaker system), optical fibre connections, power breakers for generator and Earthing system, cable room, batteries for DC systems, backup for power cut and generally all the devices and circuits required for automatic control. There is a copper plate hanging in each electrical room to monitor if there is any stain of corrosion on it in order to make sure that the ventilation system is working properly (Figure 25).

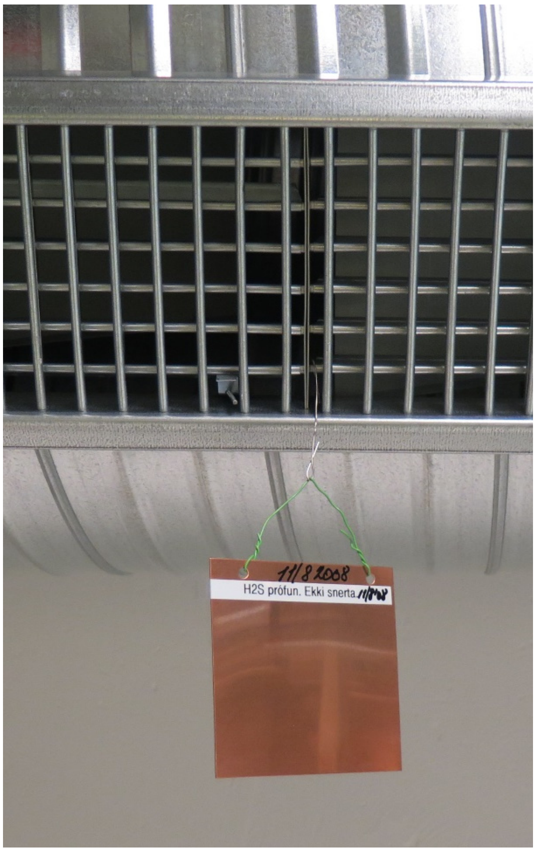


FIGURE 25: Copper plate for monitoring corrosion

In the 2015 annual overhaul, some minor modifications were made for this unit and basically all tests needed in the electrical system, such as load test of DC system, were carried out. Cables are long lasting components and do not need any specific maintenance.

Control system and instrumentation
The control system of Reykjanes power plant is an open system, i.e. the SCADA system, which is used for monitoring the operation. In the control room there are direct boards of switches for manual control of all components and parameters of two turbine units and turbo-generators such as opening and closing of valves, motors, pumps, temperature and pressure control, trip switches etc. (Figure 26).

FIGURE 26: Main control room

All control panels are supplied by the turbine manufacturer since it is common practise to purchase turbines together with their control system. Although it might look outdated and bulky, no corrective maintenance has been required since the commissioning of unit. Computers in the main control room consist of SCADA screens for all station sections for alarm handlings. Therefore, operators can check the parameters constantly.

However, sometimes the control system can be problematic because it is a PC based system which uses a Windows operation system that can freeze, so during the 2015 outage, the control unit was replaced with a safer alternative. The SCADA system is being replaced after 8 years of power plant operation.

Maintenance of instrumentation is carried out during the turbine operation, whereas during an outage of power plant, cleaning, scaling, and recalibrating is done. In the past, a differential pressure measuring device has been used to measure the water level in equipment such as the separator and condenser, but currently radar measurement equipment is used and appears to be more reliable. Besides the radar sensors in the condenser, there is an indicator of water level and Vegaswing instruments, which are vibrating level switches sensitive to liquid level, used for extra safety in case radar measurements fail as shown in Figure 27.

FIGURE 27: Radar and Vegaswing sensors for water level control

Radar sensors can also control pumps or pump valves. If high levels are measured then the pump starts if it is not running yet, and at low level the pump stops, pumping condensate, and the highest level trips the turbine.

The three level-controls of the separators are working independently, one is spare and can be taken out of service and repaired while two of them are operating (triple redundancy), checking the level of brine in the separator. Temperature sensors should be calibrated at least once a year during the annual overhaul and changed if necessary. By means of efficient safety and backup systems as well as periodic calibration of the instruments, wrong control signals, which are one of the most frequent risks in power plants, can be prevented.

Emergency alarms

The control system has a warning system classified into three categories:

Category 1: immediate attendance required, beeper of operator 1 is activated and if it is needed other operators are called to take care of the emergency incident. However, emergencies usually happen during day time.

Category 2: operators have to take care of this category, checking control room to see what caused the alarm, yet no need for immediate repair. Usually category 2 is a warning for upcoming category 1.
Category 3: it is only an alarm for an event. No failure has happened and operator only gets reports on screen.

Valve houses
Valves are closed during outage for maintenance of pipes but normally valves themselves do not need maintenance annually unless cleaning is necessary in case of blockage.

Reinjection systems
Reinjection systems include series of pipes that take condensate to be added to the brine from the separator before reinjection. They also include connection pipes used for mixing a little part of condensate to the main brine pipe, between the separator station and the mixing vessel at the power plant. This is done in order to use the pressure of the separator to pump the brine so that boiling due to pressure drop and elevation changes is killed in the pipe line. Brine temperature should be reduced by 5-10 degrees. During outage, inspection of the pipes and, if necessary cleaning, is done as well as calibration of the instruments as for example the temperature sensors. Figure 28 shows the repairing process of a brine pipeline.

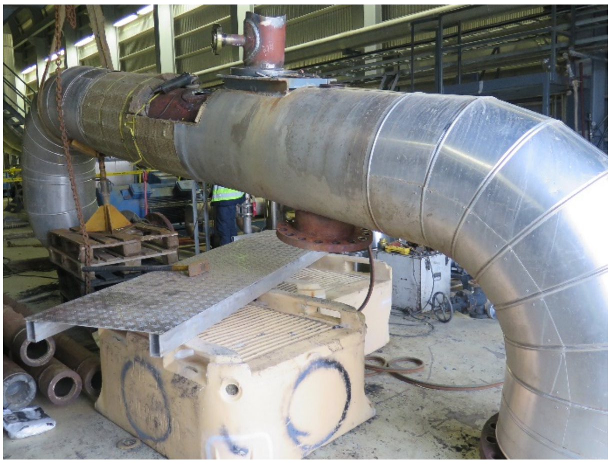


FIGURE 28: Repairing of pipes

4.5.4 Analysis of maintenance procedures

In Table 5, most common failures in Reykjanes power plant which require maintenance based on type of components, as well as required action in each type of maintenance method, have been classified. It explains what should be done to prevent or predict the problem, and if it failed, what action should be done to correct it.

TABLE 5: Summary of problems and solutions in Reykjanes power plant

Main system	Component	Most common problems in Reykjanes PP	Maintenance procedure: Preventive/predictive/proactive action	Maintenance procedure: Corrective action
Steam supply systems	Wellhead valves and control units	Scaling	Keeping fluid temperature high	Cleaning
	Separator	Scaling	Designing high separator working pressure	Cleaning
	Moisture eliminator	Cracks on carbon steel	Considering H_2S partial pressure and condensate pH during design	Repairing or Replacing in 5-year interval
			Efficient welding process and possibly post weld heat treatment to reduce hardness and internal stresses in the high-temp. pipe	
			Using drawn steel pipes with a manganese content less than 1%	
			Changing steel type from welded pipes to seamless,	
			Using higher alloy metals	

Main system	Component	Most common problems in Reykjanes PP	Maintenance procedure: Preventive/predictive/proactive action	Maintenance procedure: Corrective action
			Material crack test of mist eliminator pads	
	Reinjection systems	Minor scaling	Mixing condensate with brine	Cleaning
	Silencers	Scaling	Designed to be cleaned easily	Cleaning
Mechanical components	Turbine	Scaling on stator blades	Constant monitoring of steam pressure	Changing worn out parts, cleaning
			Visual inspection in outage	
			Suspecting cracks with magnetic particle testing, also referred to as MPI testing and Magnaflux Testing that identifies surface flaws in metal parts in turbine major overhaul period (every 5 years)	
	Condenser	Minor scaling	Choosing surface condenser avoiding scaling and corrosion	Cleaning
			Bringing cold water not directly to system from the sea but by wells and filtering	
	Gas extraction system	Cracks	Improving material (Using higher alloy metals)	Cleaning, or changing low-quality material, or grinding welds and re-welding or welding a patch over cracked parts
			Checking operating pressures of steam ejectors	
	Cooling system	Leakage of stuffing box in submersible pumps between pump and motor so seawater enters motor and destroys it	Redesigning of stuffing box with mechanical seal	Replacing or repairing faulty motors via rewinding the coils of motor in electrical shop
	Pumps and Motors	-Failure (seldom) -Leaking stuffing box -Erosion on pump impellers	Monitoring current and power of motor	Rewinding the coil or replacing the bearings
			Vibration monitoring	
			Improving quality of stuffing box like double mechanical shaft seals	
			Improving quality of impellers like duplex Stainless Steel	
	Lubrication system	Almost no problems	Using extra filters	-
			Using Centrifuge oil separators	
	Valves	Sticking by scaling (inevitable especially in brine lines)	Periodically operating valves (opening, closing)	Cleaning
	Ventilation system	-	Changing filters	-
	Air compressors	Failure in PLC controlling the unit	-	Repairing the PLC

Main system	Component	Most common problems in Reykjanes PP	Maintenance procedure: Preventive/predictive/proactive action	Maintenance procedure: Corrective action
Electrical components	Generator	Almost no problems	-	-
	Control system and instrumentation	-Wrong control signal, faulty trips -Failures in sensors and transducers	Redesigning control system	Replacing (renewing) defective components
			Checking the air by copper in electrical rooms	
			Using triple redundancy for critical sensors like separator level	
			Recalibrating equipment in outage	
	Transformer	Failure	Checking transformer oil for moisture or dirt	Replacing
	Protection systems	-Failure of relays -Faulty programming -Wrong connection between components -Wrong instrum.	Ensuring correct design	Redesigning protecttion system or reprogramming of system
			Checking instrument calibration in outage	

Analysis of maintenance procedures of the power plant regarding predictive technologies are shown in Table 6:

TABLE 6: Predictive maintenance technologies application in Reykjanes power plant

Technologies	Vibration Monitoring/Analysis	Lubricant, fuel Analysis	Wear Particle Analysis	Bearing, Temperature/Analysis	Performance Monitoring	Ultrasonic Noise Detection	Ultrasonic Flow	Infrared Thermography	Non-destructive Testing (Thickness)	Visual Inspection	Insulation Resistance	Motor Current Signature Analysis	Motor Circuit Analysis	Polarization Monitoring	Electrical Monitoring
Reykjanes Power Plant	✓	✓	-	✓	✓	-	-	✓	✓	✓	✓	-	-	-	✓
Application	Routine operation	Routine & outage	-	Is Monitored in SCADA	Routine operation & after overhauls	-	-	Routine operation & outage	(Only if necessary)	Routine operation& outage	Routine operation	-	-	-	Is Monitored in SCADA

In Table 7, a number of metrics that can be used to evaluate an O&M program have been presented. Not all of these metrics can be used in all situations. However, a maintenance program should make use of as many metrics as possible to better define deficiencies that can be used as a guide for tracking and trending metrics against industry benchmarks. Based on available data gathered from Reykjanes power plant in Table 4, some of these metrics have been calculated and results can be seen in Table 8 (Sullivan et al., 2010).

Understandably, based on available data only some of the metrics could be evaluated. Only the maintenance overtime factor of Reykjanes power plant is above expected range and other indicators are in an acceptable range.

TABLE 7: Industry O&M metrics and benchmarks (Sullivan et al., 2010)

Metric	Variables and Equation	Benchmark
Equipment Availability	$\% = \frac{\text{Hours each unit is avaialbe to run at capacity}}{\text{Total hours during the reporting time period}}$	> 95%
Schedule Compliance	$\% = \frac{\text{Total hours worked on scheduled jobs}}{\text{Total hours scheduled}}$	> 90%
Emergency Maintenance Percentage	$\% = \frac{\text{Total hours worked on emergency jobs}}{\text{Total hours worked}}$	< 10%
Maintenance Overtime Percentage	$\% = \frac{\text{Total maintenance overtime during period}}{\text{Total regular maintenance hour during period}}$	< 5%
Preventive Maintenance Completion Percentage	$\% = \frac{\text{Preventive maintenance actions completed}}{\text{Preventive maintenance actions scheduled}}$	> 90%
Preventive Maintenance Budget/Cost	$\% = \frac{\text{Preventive maintenance cost}}{\text{Total maintenance cost}}$	15% – 18%
Predictive Maintenance Budget/Cost	$\% = \frac{\text{Preventive maintenance cost}}{\text{Total maintenance cost}}$	10% – 12%

TABLE 8: Evaluation for Reykjanes power plant O&M program

Metric	Benchmark	Reykjanes Power Plant
Power plant availability	>95%	96.1%
Schedule compliance	>90%	~99%
Emergency maintenance percentage	<10%	N/A
Maintenance overtime	<5%	16%
Preventive Maintenance completion	>90%	~100%
Preventive maintenance Cost	15%-18%	NA
Predictive maintenance Cost	10%-12%	NA

4.5.5 Annual outage analysis (2015)

As mentioned before, to carry out this study, maintenance procedure of one of the Reykjanes power plant units in 2015 outage period has been observed during several days. All maintenance activities have been recorded and categorized based on the maintenance schedule of the 7 days' outage, based on the required maintenance of each component, on maintenance methods and on workforce needed to carry out the maintenance. A prepared schedule containing all maintenance actions in detail is presented in Appendix I. In the following sections, results achieved from collected data of the outage maintenance will be presented. A total of 81 actions have been completed during the 12-hour day 7 days' outage period.

In Figure 29, the share of components in activities during the outage period of the power plant is presented. Maintenance has been performed for all components. The turbine and its auxiliaries had the highest number of maintenance work processes while the generator and reinjection system have been the least effected with the lowest number of maintenance activities required. The maintenance activities carried out for each component have been classified based on the maintenance method applied. Both the highest corrective and preventive/predictive maintenance tasks have been connected to the turbine and its auxiliaries implying that these components are more sensitive and therefore need more attention during routine maintenance than others.

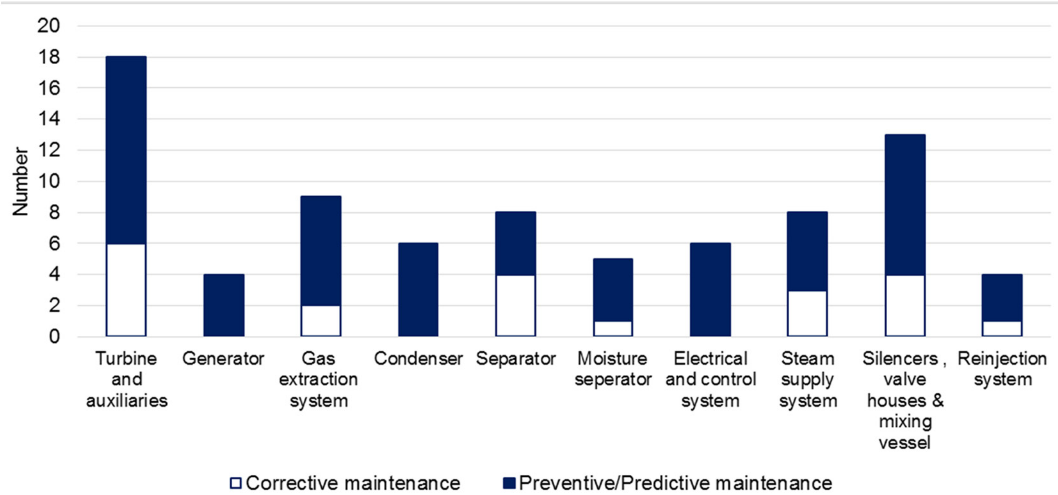


FIGURE 29: Shares and methods of maintenance used for components in the 2015 annual outage

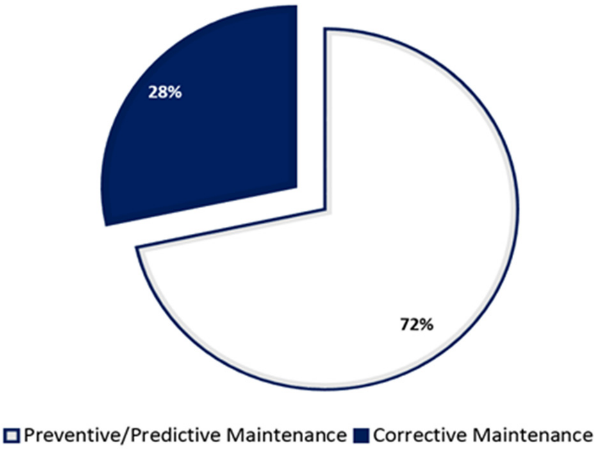


FIGURE 30: Maintenance methods used in the 2015 outage

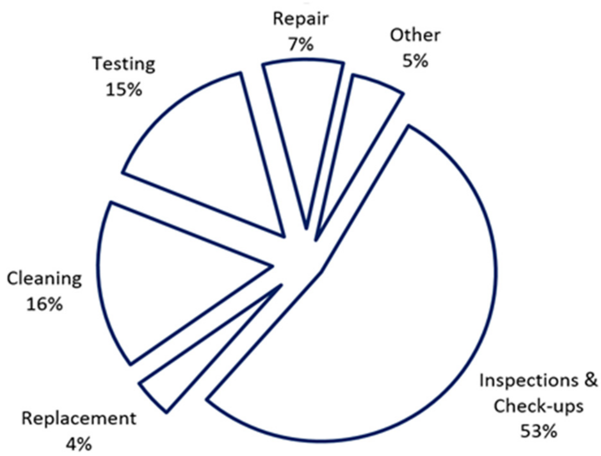


FIGURE 31: Maintenance activities share in annual outage cost 2014

Figure 30 presents a pie chart of the percentage of each maintenance method of the maintenance activities carried out during the outage maintenance period 2015. In addition, Figure 31 shows a pie chart of the percentage of cost categories in 2014 since cost data of the 2015 outage had not gathered completely yet.

Outage manpower:
Outage maintenance is organized and performed by the operation and maintenance team at Reykjanes and Svartsengi power plants. In addition, some activities are outsourced to local contractors and workshops, providing manpower to assist in performing outage maintenance actions. In Figure 32, the percentage of power plant staff and contractors in outage maintenance activities has been illustrated.

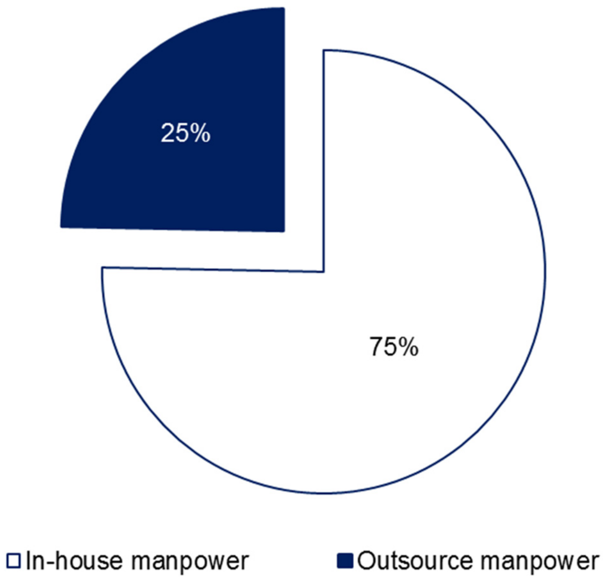


FIGURE 32: Manpower share in the 2015 outage

In Figure 33, an organizational chart of the outage period and number of personnel in each subcategory is been presented.

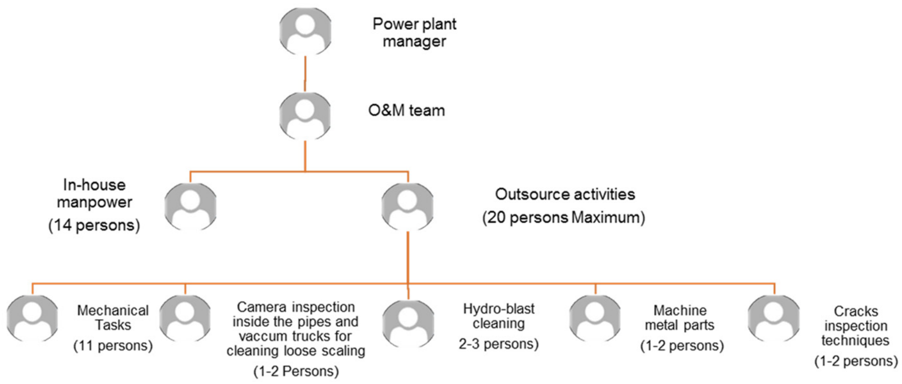


FIGURE 33: Annual outage manpower organizational chart of 2015

Outage cost

Performing effective maintenance has a great influence in reducing O&M costs as well as decreasing outage days and eventually lowering the costs for lost electricity. In Figure 34, electricity production during 2014, and the production drop due to stoppage time, has been illustrated. The total loss of electricity production for the 96 MW net power plant output was 820 MWh costing about 84 Million ISK. If days of outage period can be reduced by one day (24 hours), approximately 7 Million ISK cost due to lost production will be avoided, according to Table 3.

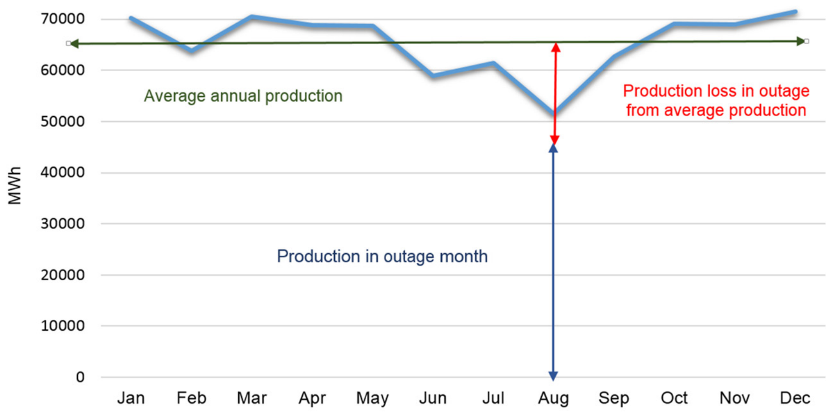


FIGURE 34: Electricity production loss during the annual 2014 outage

Finally, Figure 35 shows a cost breakdown of the outage maintenance carried out in 2014. Major costs of outage are allocated to manpower cost (77%), most of it power plant personnel.

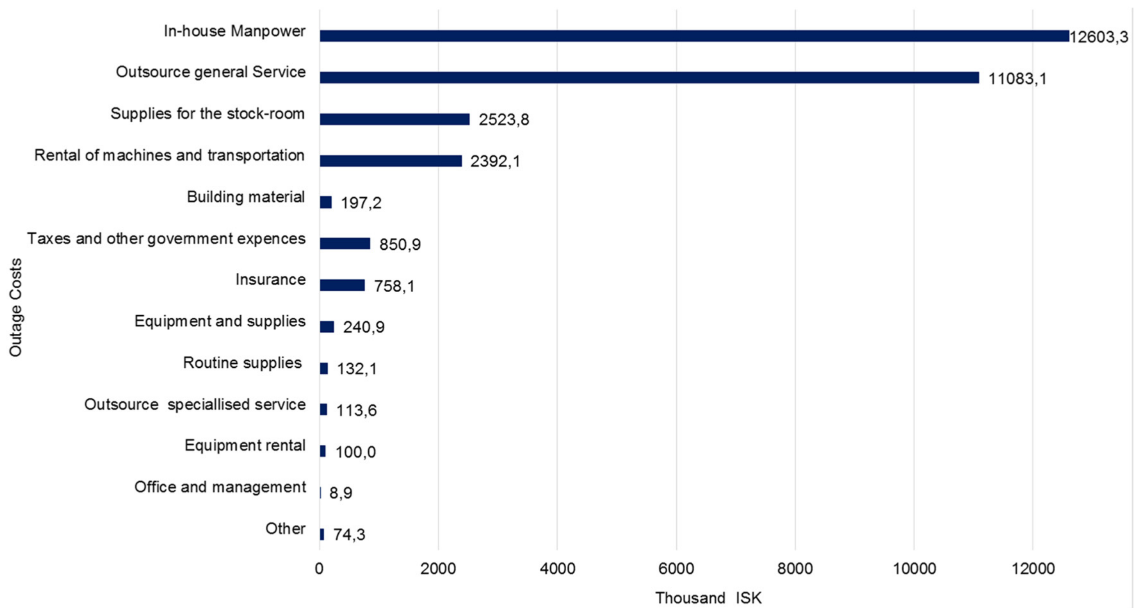


FIGURE 35: Breakdown of annual outage maintenance cost of 2014

5. CONCLUSIONS

From the preceding study the following can be concluded and recommended:

- Experienced operators of Reykjanes geothermal power plant have been able to run the power plant smoothly and have minimized the time and cost caused by outages by optimizing preventive and proactive maintenance, i.e. considering root-cause failures and efficient redundancies of components in a design phase, and constantly inspecting and testing equipment.
- As common in geothermal power plants, dealing with high temperature fluid and special chemical traits, the main source of problems in Reykjanes power plant is due to chemical compositions of geothermal fluids.
- The most common problem of the plant is scaling which basically has been prevented by maintaining high separation pressure of fluid and keeping the wells hot. Also cracks in steam pipes ought to be avoided since steam leaks in piping or components, leading to failures.
- Analysing metrics of IEEE 762 Standard, based on available data, indicates that the power plant performance is above the benchmark range. Nevertheless, there are many other performance indicators or benchmarking worth investigating to keep track of the power plant performance or developing a comprehensive set of indicators based on Reykjanes power plant requirements.
- To enhance the quality of O&M performance, inspecting procedures based on related available standards, such as API 571, are used and their requirements met. Thus, damage mechanisms affecting fixed equipment in the refining and petrochemical industries can be avoided. For specifying equipment, standards such as ANSI NACE MR0175/ISO 15156, can be used for equipment such as separators, to find corrosion cracking resistant material.
- By employing modern computerized systems, i.e. DMM system, comprehensive record of events and incidents for managers and operators are accumulated. The system is kept up to date and options such as expense tracking into the system are added, generating automated breakdown of costs of operating years in detail. Applying different categorizations would give great insight for power plant managers and operators.
- It would be beneficial to organize a database of work orders of DMM systems, and have a documentation of operation and critical maintenance data from operators, available when needed. Instructing contractors to prepare a documentation and reports for the O&M team to evaluate their performance regarding quality, time, cost, record of equipment and material contractor utilized etc. would be of great value. It provides the team with valuable data for comparing past and current conditions of the equipment and system performance.
- Utilizing tools and technologies of predictive maintenance that have not been applied before such as Wear Particle Analysis, Ultrasonic Noise Detection, and Ultrasonic Flow etc. presented in Table 6, can help detecting abnormalities of performance in early stages.
- Establishing an assessment system to investigate all steps and activities done according to the schedule (Gantt charts), especially during outage period when timing is critical.
- The turbine and auxiliaries had to have the most corrective, as well as preventive maintenance actions, while generators are the most reliable part of the power plant. Considering the fact that the steam turbine has its own major overhaul, it is understandable that the turbine and its auxiliary are the most critical components of the power plant and require more attention and maintenance care to decrease probability of failures.

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APPENDIX I: Schedule containing all maintenance actions in detail

Maintenance outage schedule of the power plant - August 2015	Type of maintenance: Corrective(C) preventive/ predictive (P)	Contractor
Turbine and auxiliaries		
Inspecting turbine through open manhole	P	In-House
Inspecting turbine steam strainer	P	In-House
Checking cooling water valves for lubrication oil cooler	P	In-House
Inspecting return oil filter in lubrication system	P	In-House
Turbine borescope inspection	P	In-House
Overhauling steam traps(Cleaning clogged traps from corrosion)	C	In-House
Overhauling steam traps on main steam pipe in basement of plant	C	In-House
Inspecting the "bypass valve": automatic drain valve on drain pipe from steam lines	P	In-House
Opening stuck valves and cleaning	C	In-House
Inspecting stuffing box inside the valves, changing old rings inside it made of carbon fibre and carbon that got hard when they wear out and lose their elasticity	P	In-House
Inspecting and replacing worn parts of gate valve in in front of the turbine steam traps	P	In-House
Testing all the control valves from the control centre , resetting	P	In-House
Reviewing and verifying the measurements of turbine instrumentation according to the list, recalibrating instruments	P	In-House
Inspecting and cleaning steam ejectors for turbine gland connected to the shaft	P	In-House
Cleaning main lubrication 2 filters (called Sister Filters one working one cleaned in outage in normal operation while in outage 2 of them cleaned)	C	In-House
Checking cleanness of oil filters	P	In-House

Maintenance outage schedule of the power plant - August 2015	Type of maintenance: Corrective(C) preventive/ predictive (P)	Contractor
Fixing leaks in the seawater piping system in seawater cooling system.	C	Out-Source (Mec.Contr.)
Repair the stainless steel piping from the vacuum drain tank and inspect the tank	C	OS (MC)
Generator:		
Inspecting of generator according to manual	P	In-House
Testing pressure of the generator cooling components	P	In-House
Inspecting the cooling water pipes toward air-coolers	P	In-House
Maintaining the generator heating on during the down time/outage	P	In-House
Gas extraction system		
Removing and inspecting the second stage ejector nozzle for inspection (crack inspection)	P	In-House
Cleaning filters in the drains of condensate from coolers that condense steam in NCG after ejectors	C	In-House
Inspecting of steam input valve of ejectors and checking stuffing box	P	In-House
Inspecting the steam traps on the steam lines to ejectors	P	In-House
Checking Interlocks of ejectors and verifying their functionality in control system	P	In-House
Cleaning Vegaswing sensors (level detection sensor) in the 2 drain systems (vacuum and atmospheric tank)	C	In-House
Testing and confirming of all warnings systems/messages	P	In-House
Checking main stop valve, adjusting operation limit of the valve	P	In-House
Inspecting control valves, changing if necessary	P	In-House
Condenser		
Testing vacuum pressure switch (bad vacuuming result in high pressure in outlet of turbine)	P	In-House
Examining and evaluating of rubber coating in the water compartments.	P	In-House
Inspecting all the measuring equipment, pipe connections and pressure and temperature sensors (If time permits)	P	In-House
Inspecting leakage of nipples and measurement equipment in the seawater system around the condenser.	P	In-House
Inspecting leaks and packaging of manholes	P	In-House
Inspecting expansions compensators in the pipe connected to the condensate pump	P	In-House
Moisture separator		
Opening and examining the moisture filters	P	OS (MC)
Removing and cleaning Vegaswing sensors	C	In-House
Examining gate valve around nuts/bolts of the moisture separator.	P	In-House
Checking for leaks on manholes moisture separator	P	In-House
Checking for leakage in the steam pipes connected to this station	P	In-House
General-, electrical-, control-, and machinery.		
Testing all control valves	P	In-House
Testing all remotely controlled stop-valves	P	In-House
Testing all alarms, parameters, confirming the messages in SCADA	P	In-House
Testing batteries and recharging units , also capacity test of battery system	P	In-House
Testing all remote controls from SCADA	P	In-House
Testing all status indicators , switches, valves and etc.	P	In-House
Steam Supply		
Examining the "well flow control valve" , replacing if necessary	P	In-House
Lubricating all the valves in the well basements	P	In-House
Examining all the measuring nozzles on the wells.	P	In-House
Examining all the drain valves	C	In-House
Replacing measuring valves on 12 , 25, 26 , 28 wells	C	In-House
Cleaning the drain pots and valves	C	OS (MC)

Maintenance outage schedule of the power plant - August 2015	**Type of maintenance: Corrective(C) preventive/ predictive (P)**	**Contractor**
Camera inspection of the pipelines(decide which pipelines should be inspected)	P	OS (Camera & Vacuum)
Changing the surface material (gravel) under the pipes outside separator station	C	OS
Separator station		
Cleaning main Separators	C	OS (C & V)
Examining all the measuring equipment and the water level controls of separator	P	In-House
Testing all the stop valves from the control room.	P	In-House
Cleaning steam trap in steam pressure control valves (in normal operation closed)	C	In-House
Cleaning diffuser in inlet of steam chimney next to separator station (downstream to pressure c.v.)	C	OS (MC)
Checking the condition of optical glasses and cleaning if necessary	P	OS (MC)
Checking and cleaning all check valves	P	OS (MC)
Repairing leak in steam pressure control	C	OS (MC)
Silencers – C valve house		
Empting water chamber from silencer, pump out the water with the diesel pump for cleaning	C	In-House
Inspecting valves in valve house	P	In-House
Checking butterfly valves ahead of the control valves in the valve house	P	In-House
Cleaning the nozzles on the silencer in the valve house	C	OS (Hydro-blasting)
Checking Thickness Measuring DN600 pipes in C valve house for corrosion from inside	P	OS (Crack Inspection)
Removing valve to the testing steam station and clean.	P	OS (MC)
Repair the end flange of the header from the base for the C valve house to the nozzles	C	OS (Metal Mac.)
Mixing vessel –D Valve house.		
Empty collection chamber with the diesel pump and well pump	P	In-House
Inspecting Valve house D	P	In-House
Examine butterfly valve in front of and behind the D - valve.	P	In-House
Cleaning the measuring pipe for connection pipes to pressure sensor	C	In-House
Inspecting outlet compartment D valve house	P	OS (MC)
Inspecting the reducer behind latter butterfly valve. (Cavitation)	P	OS (MC)
Reinjection		
Inspecting the check valve	P	OS (MC)
Removing butterfly valve for cleaning and examine pipelines from separator to mixing chambers	P	OS (MC)
Replacing ball valve for sampling	C	OS (MC)
Checking the control valve	P	OS (MC)