MAINTENANCE OF THE STEAM TURBINES AT HELLISHEIÐI POWER PLANT

Almar Gunnarsson

Faculty of Industrial Engineering,
Mechanical Engineering and
Computer science
University of Iceland
2013

Maintenance of the steam turbines at Hellisheiði power plant

Almar Gunnarsson

30 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Mechanical engineering

Advisors
Magnús Þór Jónsson
Rúnar Unnþórsson

Faculty Representative
Sigrún Nanna Karlsdóttir

Faculty of Industrial Engineering,
Mechanical Engineering and Computer science
School of Engineering and Natural Sciences
University of Iceland
Reykjavik, May 2013

Maintenance of the steam turbines at Hellisheiði power plant
Maintenance of steam turbines
30 ECTS thesis submitted in partial fulfillment of a *Magister Scientiarum* degree in Mechanical engineering

Faculty of Industrial Engineering, Mechanical Engineering and Computer science
School of Engineering and Natural Sciences
University of Iceland
Hjardarhagi 2-6
107, Reykjavik
Iceland

Telephone: 525 4700

Bibliographic information:
Almar Gunnarsson, 2013, *Maintenance of the steam turbines at Hellisheiði power plant*, Master’s thesis, Faculty of Industrial Engineering, Mechanical Engineering and Computer science, University of Iceland.

Printing: Háskólaprent, Fálkagata 2, 107 Reykjavík
Reykjavik, Iceland, May 2013

Abstract

In a geothermal power plant the working fluid used to produce electricity is often wet steam from geothermal wells, which is composed of corrosive chemicals. In this situation, more frequent maintenance of the equipment is required. By constructing an overview for the maintenance in geothermal power plants and how it can be done with minimum power outages and cost, the geothermal energy can be made more competitive in comparison with other energy resources. The focus of this thesis is to examine the maintenance needed for the steam turbines in the geothermal power plant at Hellisheiði. The local ability of the staff there to repair or construct turbine parts on-site is explored. It is also explored how the maintenance and condition monitoring is carried out today and what can be improved in order to reduce cost. Failure Mode and Effect Analysis (FMEA) is used to analyze the data, which were collected but that can help organizing maintenance and condition monitoring of Hellisheiði power plant in the future. Furthermore, the thesis presents an overview of currently employed maintenance methods at Hellisheiði power plant, the ability of domestic workshops to maintain and repair the steam turbines there and the power plant's need for repairs. The results show that the need for maintenance of the geothermal steam turbines at Hellisheiði power plant is high and that on-site maintenance and repairs can decrease operation cost.

Keywords: Geothermal Power Plant, Steam Turbine Maintenance, Failure Mode and Effects Analysis (FMEA)

Útdráttur

Gufa úr borholum er almennt notuð sem vinnuvökvi til að framleiða rafmagn í jarðvarmaverum. Gufan er bæði rök og inniheldur töluvert magn af tærandi efnasamböndum. Þetta leiðir af sér aukið viðhald á búnaði. Með því að búa til yfirlit yfir viðhald í jarðvarmaverum og hvernig má framkvæma það með sem minnstum tilkostnaði þá er hægt að gera jarðvarma samkeppnishæfari í samanburði við aðra orkugjafa. Í þessari ritgerð verður viðhaldsþörfin fyrir gufutúrbínurnar í jarðvarmaverinu upp á Hellisheiði greind. Geta til að gera við eða smíða hluti í jarðvarmatúrbínur á Íslandi er skoðuð. Einnig er skoðað hvernig viðhald og ástandsmat er framkvæmt þar í dag. Möguleikar til að draga úr kostnaði og bæta viðhald eru skoðaðir. Failure Mode and Effect Analysis (FMEA) er framkvæmd á þeim gögnum sem var safnað en það getur hjálpað til við að skipuleggja viðhald og ástandseftirlit í framtíðinni. Í þessari ritgerð er einnig yfirlit yfir þær viðhaldsaðferðir sem er beitt í dag, yfirlit yfir innlenda getu til að gera við og viðhalda gufutúrbínum í Hellisheiðarvirkjun og yfirlit yfir viðhaldsþörf þeirra. Niðustöðurnar sýna að viðhaldsþörfin fyrir gufutúrbínurnar í Hellisheiðarvirkjun er mikil og að viðhald á staðnum getur lækkað rekstrarkostnað.

Efnisorð: Jarðvarmaver, Viðhald á gufutúrbínum, Failure Mode and Effect Analysis (FMEA)

Contents

List of Figures

List of Tables

Nomenclatures

$\boldsymbol{a_u}$	Specific work
c	Absolute velocity
p	Pressure
u	Tangential velocity
w	Relative velocity
DMM	Dynamic Maintenance Management
FMEA	Failure Mode and Effect Analysis
RCM	Reliability Centered Maintenance

Acknowledgements

First of all I am thankful to GEORG for financing the work undertaken for this thesis. This thesis would also not have been possible unless for the help and support I received from my supervisors; Magnús Þór Jónsson and Rúnar Unnþórsson professor and associate professor, respectively, at the Faculty of Industrial engineering, mechanical engineering and computer science at the University of Iceland.

I am highly indebted and thankful to the maintenance staff at Hellisheiði power plant, in particular Sæmundur Guðlaugsson, Guðmundur H. Guðmundsson, Ragnar Gestson and Kristinn Rafnsson og for being helpful and providing valuable information towards this thesis.

I thank Þóra M. Þorgeirsdóttir from GEKON, Árni Pálsson from Framtak, Páll Pálsson from VHE, Tryggvi Hallvarðarson from Vélvík, Karl Geirsson from Klettur, Sigrún Nanna Karlsdóttir from NMÍ and Jens Þórðarson from ITS for showing interest in this thesis and providing valuable information towards it.

Furthermore I thank my colleagues Ari Elisson and Reynir S. Atlason for their support and contribute towards this thesis. I also thank Björn Finsen for providing help with this thesis.

1 Introduction

During the last decade the usage of renewable energy such as geothermal energy, has been growing worldwide and is becoming more important as a future energy resource. One of the main reasons for this is the disadvantages of fossil fuels.

At the end of 2010, the installed geothermal electrical capacity in the world was 10,898 MW and it had been growing approximately 400 MW/year from 2005. In 2015 it is estimated that the installed geothermal electricity capacity will be around 19,000 MW. Iceland has been one of the frontrunners in this development with an 185% increase in installed capacity, from 202 MW in 2005 to 575 MW in 2010 [1].

The supplies of geothermal energy in the earth's crust are enormous. It is considered that the heat supply in the earth's crust could meet with current estimated energy needs of mankind for the coming 14-15 million years. However, harnessing this energy is not an easy task, which reflects in the fact that today it is only considered possible to produce around 8.3% of the world total electricity production with geothermal energy [2]. Nevertheless the potential is huge.

Geothermal systems are mainly of four types: hydrothermal, hot dry rock (or enhanced geothermal systems), geopressure and magma energy. The utilization of geothermal energy has so far been limited to hydrothermal systems. A hydrothermal system is a system where water in a liquid or a vapor phase acts as a carrier to transfer heat from deep in the earth's crust up to the surface [3].

Although geothermal heat can be found all over the world, it cannot be utilized everywhere for generating electricity as the ambient temperature of a geothermal system generally has to be 150°C or higher if it is to be feasible for generation of electricity. Colder geothermal systems can however, be used for generating electricity. Electricity is for example generated in the Chena Hot Springs Resort in Alaska by using a geothermal resource with an ambient temperature of 74°C [2]. Most high temperature geothermal fields are found on so-called plate boundaries. Volcanic activity is also common at plate boundaries. Magmatic intrusions, which are considered to be the heat source for geothermal fields, are often found in such areas. The crust at plate boundaries is also highly fractured and thus permeable. But permeability is of much importance for geothermal fields that are to be used for generating electricity [2].

There are mainly four types of geothermal power plants used to generate electricity from geothermal energy: single-flash, double flash, dry steam and binary cycle power plants. Single-flash power plants are the most common ones. At the end of 2007, 159 such plants in 18 countries around the world were in operation. Single-flash power plants "flash" hot water at high pressure so it becomes a mixture of steam and water. The steam is separated from the water and expanded through a steam turbine, which drives a generator. Double flash power plants are an improvement of the single flash design. They produce 15-20% more power but are more expensive, more complex and require more maintenance than single flash power plants. At the end of 2007, 69 such units were in operation [3].

Iceland is located at the plate boundaries between the North American and the Eurasian tectonic plates and is one of the most tectonically active places on earth. There are for example over 200 volcanoes located on the volcanic zone running through the island. There are at least 26 high temperature areas within this volcanic zone, where the temperature at a depth of 1000 meters reaches 250°C. Iceland is thus highly feasible for generating electricity with geothermal energy [4]. Geothermal heat has been utilized for decades in Iceland, both for district heating and generating electricity. Generation of electricity started at Bjarnarflag power plant in 1969 with one 3 MW steam turbine [4]. The development since then until 2009 along with the location of the geothermal power plants in Iceland can be seen in Figure 1.1. Today there are six geothermal power plants operating in Iceland. Húsavík power plant, which used a Kalina working-cycle, stopped production in 2008 because of severe corrosion problems [5]. Hellisheiði power plant has been enlarged and its installed electrical capacity in 2012 was 303 MW, which makes it the largest geothermal power plant in Iceland and one of the largest geothermal power plants in the world. In 2011 4701 GWh of electricity were generated with geothermal energy in Iceland and the total installed electrical capacity was 665 MW. This was 25% of the total installed electrical capacity in 2011 [1, 6].

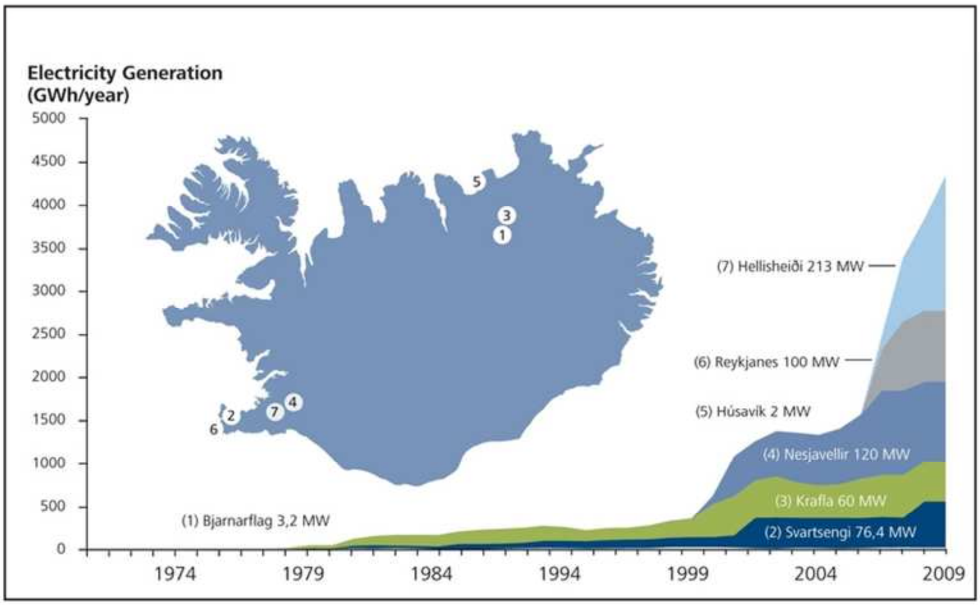


Figure 1.1 *Generation of electricity using geothermal energy 1969-2009. Note, the capacity of Hellisheiði is 303 MW today and Húsavík is no longer operating.[7].*

Operating and maintaining a geothermal power plant can be problematic. The working fluid used to produce electricity is often wet steam, which is composed of corrosive chemicals and is sometimes acid. Common problems due to the usage of such a working fluid are scaling, erosion and corrosion [8]. This means that frequent maintenance of the equipment in geothermal power plants is required which causes downtime and can be expensive.

One maintenance procedure that has to be carried out in geothermal power plants is overhauling of steam turbines. Overhauling of a steam turbine is one of the most expensive procedures when maintaining a power plant. Furthermore, overhauling introduces the threat of creating problems like vibration and leakage [9]. The risk of damaging the turbine parts is also at hand. Overhauling is therefore an undesirable procedure and should be done as rarely as possible. Today no overhauling service, which can carry out complete repairs of steam turbines, is located in Iceland. The knowledge and equipment, which is required for complete maintenance, is also not present. It means that for maintenance, steam turbines or their components sometimes have to be transported to a foreign overhauling service. This can be expensive, because of a low exchange rate, high transport costs and lost operation time.

Today 19 steam turbines are in operation in Iceland [4], [10]. Orkuveita Reykjavikur owns 11 of them and operates 2 geothermal power plants, Hellisheiði power plant where 7 steam turbines are located and Nesjavellir power plant where 4 steam turbines are located. The cost of maintaining these steam turbines for the next 15-20 years is estimated to be around 34.000.000 USD [11]. Very much foreign currency could thus be saved by carrying out these repairs domestically. It could also create many jobs. This can also result in substantial savings for Orkuveita Reykjavíkur if the current exchange rate does not improve greatly.

It will therefore be of a value to identify the maintenance needed for steam turbines in geothermal power plants as well as examining what can be repaired domestically and which instruments and knowledge are needed for a complete overhaul of steam turbines in Iceland. There is a lot of “know-how” knowledge at the power plants, which has been acquired through years of operation. In some cases turbine components have been improved or maintenance methods have been developed or invented. Documenting this knowledge will thus be of a value to the Icelandic geothermal industry.

1.1 Research focus

Maintenance of geothermal power plants is frequently required as already mentioned and one of the most costly procedures is the overhauling of steam turbines. It is thus important to identify the maintenance needed for steam turbines in geothermal power plants, explore how it is carried out and construct an overview for it. Doing so could help organize the maintenance and make it more efficient. Such an overview can also help deciding things like:

- Intervals between overhauls.
- Which turbine components are required in stock.
- Which type of labor force is needed and which skill they must possess.
- What kind of equipment and tools are needed on-site.

In order to complete the overview, a case study of the maintenance of the steam turbines at Hellisheiði power plant was conducted. The ability and the knowledge of how to repair the steam turbines also required a study. This is because then it will be clear what the local workshops are capable of. This also helps determining, which knowledge and instruments are needed to perform complete maintenance of steam turbines domestically. In order to do this the workshops servicing Hellisheiði power plant, were visited. It was also examined which repairs were made on-site at Hellisheiði power plant.

Documenting the knowledge regarding maintenance of geothermal steam turbines will be of a value to the Icelandic geothermal industry. It gives other geothermal power plants in Iceland the opportunity to use this already existing information. When all this knowledge has been collected, it opens up the possibility of exporting and selling it to the growing geothermal industry in the world.

Delivery reliability is an important aspect in the electricity production industry. Reliability is therefore an important factor when running a geothermal power plant. One way of improving reliability is through Reliability Centered Maintenance (RCM), which application has been chosen to be evaluated for Hellisheiði power plant. In this thesis Failure Mode and Effects Analysis (FMEA) is carried out for the steam turbines at Hellisheiði power plant with the aim of providing an input for the RCM.

1.2 Aim, objectives and scope of work

There are three aims with this thesis and they are to:

1. Analyze the maintenance that is required for the steam turbines at Hellisheiði power plant and how it is carried out.
2. Analyze the current ability to repair the steam turbines at Hellisheiði power plant either on-site or locally.
3. Provide an input for the evaluation of RCM for Hellisheiði power plant.

As regards the first aim, the main objectives which are studied were:

- Which failures and problems have occurred since the startup of the turbines, which actions were taken to repair failures in the turbines, and what are probable causes for the failures and the problems in the turbines.
- How surveillance of the turbines and their condition monitoring is carried out today.

The emphasis was on documenting both the actions and the methods that have been developed by the engineers at Hellisheidi power plant for maintaining the steam turbines, repairing them and overhaul. As regards the second aim, the main objectives which are studied were:

- The current experience and ability of both local workshops and the staff at Hellisheiði power plant to repair the steam turbine components domestically and to participate in the overhauling of the steam turbines.
- What equipment is available and what equipment is lacking for complete maintenance of steam turbines to be carried out.

As regards the third aim, the main objective was to carry out an FMEA for the turbines at Hellisheiði power plant.

This thesis is arranged in the following way: Literature review is in Chapter 1. Chapter 2 provides background information about steam turbines. The methodology, which was applied for the case study of Hellisheiði power plant, is described in Chapter 3. A case study of Hellisheiði power plant is presented in Chapter 4. Conclusions are revealed in Chapter 5.

1.3 Literature review

An overview and discussions in connection with previously made researches regarding maintenance of steam turbines is dealt with in this chapter.

Many papers have considered the maintenance and the management of it for steam turbines generating electricity with fossil fuels, some recent ones are [9, 12, 13, 14]. One paper has analyzed the maintenance of a steam turbine in the MakBan geothermal power plant in the Philippines and how its reliability can be increased [15].

Some papers about maintenance in geothermal power plants in Iceland have been written. One discusses common problems in geothermal power plants like scaling along with actions to deal with them and shows that the most persistent problems have to do with the chemistry of the geothermal fluid [8]. Another one reviews the maintenance history of

Svartsengi geothermal power plant with emphasis on the most intensive issues. It shows that constant monitoring and condition based maintenance along with skilled operators and maintenance staff are the key to reliable operation [16].

A few studies focusing on maintenance in geothermal power plants have been carried out by the students of the Geothermal Training Programme of the United Nations University (UNU-GTP). One of them is a case study of the failures in the turbines, condensers, cooling towers, gas extraction system and the separators at the Olkaria II geothermal power plant in Kenya. It shows that the turbines there suffers from scaling and erosion and turbine washing can create erosion problems [17]. Another one analysis how the maintenance in the Olkaria I and Olkaria II geothermal power plants can be optimized along with an FMEA of the power production systems there. The study shows that maintenance cost is a significant part of the operation cost of geothermal power plant and RCM is a preferable maintenance method [18]. Another one studied maintenance problems and solutions to them in the Aluto Langano geothermal power plant in Ethiopia [19]

Manufacturers of geothermal steam turbines like Fuji and Toshiba have conducted researches and on-site experiments in order to lengthen the lifetime of their steam turbines and they have published the results. Fuji has for example developed methods like coating and shot peening to reduce corrosion and improve erosion resistance of turbine components. They have also made experiments to recognize the effect of geothermal steam on different materials for rotors and turbine blades and built a test rig at the geothermal field at Reykjanes, which gave vital results which were very important as regards the development of the steam turbines both for Svartsengi power plant and Reykjanes power plant [20, 21]. Toshiba has also done researches and experiments in order to lengthen the lifetime of their geothermal steam turbines. They have, for example, done on-site experiments at several geothermal power plants and studied the chemical composition of geothermal steam and made assumption according to it on the lifetime of steam turbine components [22].

Some studies, which focus on specific failures in steam turbines in geothermal power plants and solutions to them, have been carried out. There is for example, a study on the development of a method to estimate the amount of scaling at the first stage of a steam turbine by monitoring steam pressure, which shows that the scale deposition can be monitored by measuring the pressure before and after the stage [23]. Another article publishes a case study of the cause for erosion of rotor labyrinth seals and procedures to reduce it. The case study shows that the erosion process is strongly dependant on particle velocity and it can be greatly reduced by installing a flow deflector [24]. Another one studied possible causes for failures at the last stage rotor blades of a geothermal steam turbine and discovered that possible causes are high cycle fatigue, erosion and corrosion [25]. A study, which researches erosion damages that were caused by water droplets at the last stage rotor blades in condensing steam turbines, has also been carried out [26].

Some studies, which conduct an FMEA on system in operation, have been carried out. One article publishes an FMEA for wind turbines and it shows which components need improvement and helps identifying weak points in the wind turbines design [27]. Another study evaluates the application of RCM for hydraulic turbines by applying FMEA on its oil circulation system. It shows that FMEA has great importance for evaluation of potential failures in a system [28].

2 Steam turbines

This chapter provides background information about steam turbines. It includes a general description of steam turbines, of their function, of their components and of their main design factors. Forces that act on steam turbines are also dealt with.

2.1 Definition of a steam turbine and various designs

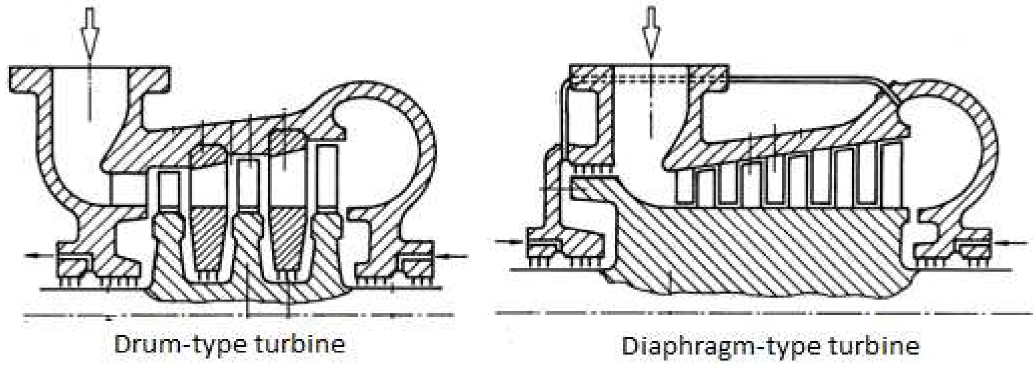
Steam turbines belong to a category of machines called turbo-machines. The two main characteristics of turbo-machines are the following: Firstly, the energy conversion takes place on/in a rotating wheel from a compressible or incompressible fluid. Secondly, the housing is equipped with diaphragms to obtain higher efficiency [29].

The basic function of a steam turbine is to transform the thermal energy of steam into mechanical energy. This is generally done in the following way: Thermal energy of the steam is converted into kinetic energy by acceleration, and momentum exchange is used to change the kinetic energy into mechanical energy [30].

Steam turbines have some advantages. They have high rotational speed and a parallel connection of many steps on the same shaft is possible. This means that high output can be achieved with a relatively small machine compared with reciprocating machines. Units with, for instance, a capacity of 1.6 GW are possible. They can expand the steam towards low pressure and high specific volume is thus possible. This means that high pressure ratio is possible, which results in high efficiency. They have no oscillating masses so operation is smooth and there is no contact between the fluid and lubricant. Steam turbines have high reliability and a relatively long lifetime and they are most often readily available. Steam turbines can also make use of various fluids, which means that they can be used in variable working environments and for different applications. Today steam turbines are able to expand steam from around 280 bar down to 0.03 bar, produce up to 1500 kJ per kg of working fluid and withstand water steam with a temperature of around 850°C [29].

There are two different designs available for steam turbines, which are impulse turbines and reaction turbines. These two designs difference in the way how they convert the inner energy of a fluid into mechanical energy.

The pressure drop in an impulse turbine occurs only across the stator blades but no pressure drop occurs across the rotor blades. This means high acceleration of the steam across the stator blades but also relatively high energy losses compared with a reaction turbine. Furthermore, the high pressure drop across the stator blades means that good seals between the stator blades carrier and the turbine shaft are required to reduce gap leakages. The rotor in an impulse turbine is therefore generally of a drum-type, that is the rotor has a relatively small diameter compared with a rotor in a reaction turbine and rotor drums are used to support the rotor blades. A small diameter rotor means less gap leakage as the flow area is smaller. This is possible because there is no pressure difference across the rotor blades and thus no pressure force that has to be dealt with. The only axial thrust on the rotor in an impulse turbine is due to the thrust on the rotor labyrinth seals and different hub heights between the inlet and the outlet. A Rotor of a drum-type can be seen in Figure 2.1. Due to the high velocity of the steam in impulse turbines they deliver higher peripheral work than reaction turbines. The construction of impulse turbines is, however, costly in comparison with the construction of reaction turbines. [31, 32]. An example of pressure diagram and an absolute velocity diagram of an impulse turbine along with general blade arrangement can be seen in Figure 2.2.


Drum-type turbine

Diaphragm-type turbine

Figure 2.1 *Two different rotor types for a steam turbine [31].*

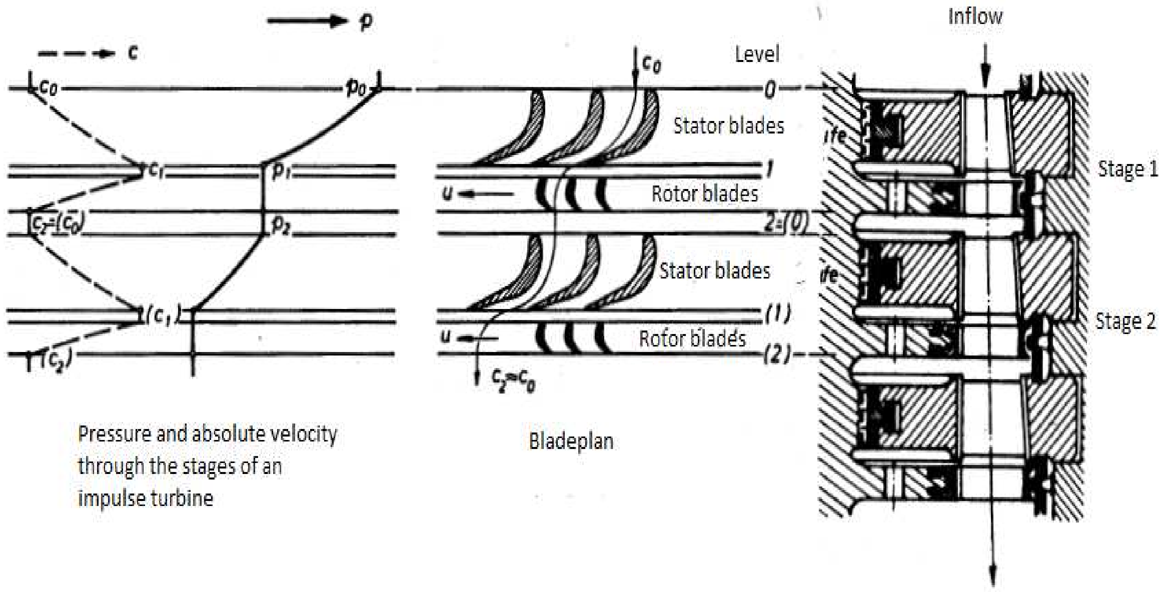


Figure 2.2 *A pressure diagram, an absolute velocity diagram and a blade plan for an impulse turbine, p represents pressure and c represents absolute velocity [29].*

The pressure drop across each step in a reaction turbine is divided between the stator blades and the rotor blades. The rotor blades function similar to the wings of an airplane in a take-off position. A pressure force acts on the rotor blades of a reaction turbine because of the pressure difference in front of and behind the blades. The rotor in a reaction turbine is thus generally of a diaphragm-type, which has a large diameter compared with a drum-type rotor to support the rotor blades. A rotor of a diaphragm-type can be seen in Figure 2.1. A reaction turbine requires a balancing piston to deal with the axial thrust that is created due to the pressure difference across the rotor blades. The reason why a reaction turbine delivers less peripheral work than an impulse turbine is due to less acceleration of the steam through its stator blades. The steam therefore conceives less kinetic energy that can be converted into mechanical energy at the rotor blades. A reaction turbine also suffers from more gap leakage than an impulse turbine. This is due to pressure difference both across the stator and the rotor blades [30, 32]. An example of pressure diagram, an absolute velocity diagram and the blade arrangement of a reaction turbine can be seen in Figure 2.3.

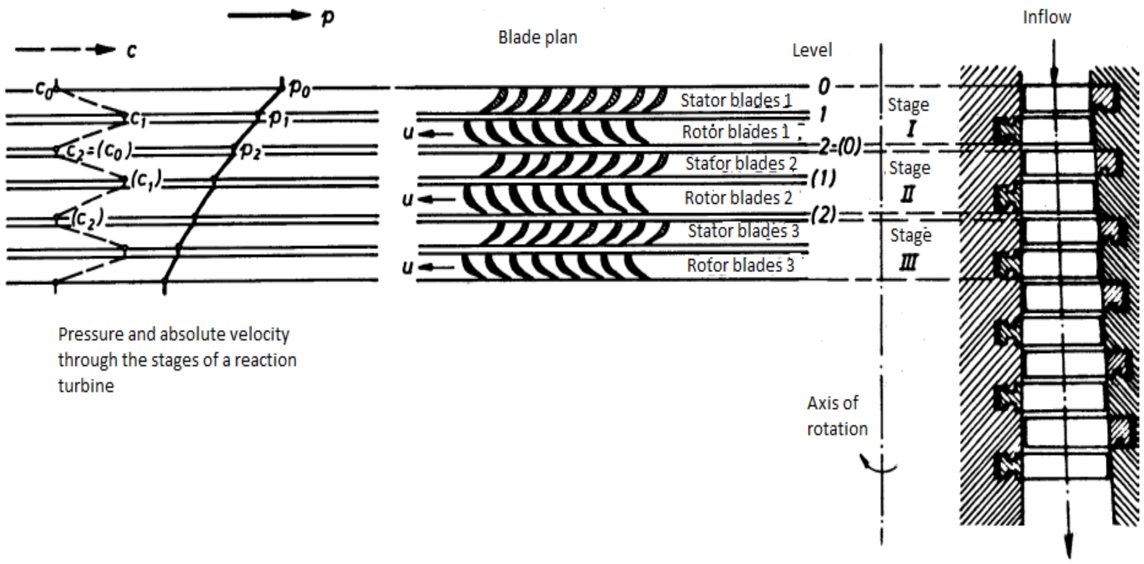


Figure 2.3 *A pressure and an absolute velocity diagram and a blade plan for a reaction turbine. p represents pressure and c represents absolute velocity [29].*

Comparison of velocity diagrams and blade arrangement for both reaction and impulse turbines can be seen in Figure 2.4. The specific work a_u of an axial turbine can be described with Euler's turbine equation

$$a_u = u\Delta c_u \tag{2.1}$$

where c_u is the tangential part of the absolute velocity and u is the tangential velocity [29]. It can thus be seen from Figure 2.4 that the peripheral work of an impulse turbine is higher than in a reaction turbine if their tangential velocity is the same. The difference between the rotor and stator blades and the steam flow angles can also be seen. The rotor blades of an impulse turbine have the same inlet and outlet steam flow angles but this is not the case as regards the rotor blades of a reaction turbine.

Steam turbines can be divided into condensing and back-pressure turbines. A condensing turbine expands the steam to a pressure lower than the atmospheric pressure. A condenser is therefore required at the outlet to create vacuum behind the turbine. A back-pressure turbine however, expands the steam down to atmospheric pressure or a higher pressure. The turbine can therefore release the steam directly out to the environment [32].

Steam turbines can also be constructed differently with regard to flow, pressure and exhaust. Turbines can be double or single flow. A double flow design can be used to balance the axial thrust in reaction turbines instead of a balancing piston. Furthermore, high pressure seals are not needed. Double flow turbines are, however, longer and more expensive than single flow turbines. Turbines can be single, double or triple pressure turbines. A single pressure turbine has one inlet and one outlet. Double pressure turbine, however, has two inlets at different pressures and one outlet. This is preferable in a double flash power plant as the steam used is at different pressure levels. Thus one double pressure turbine and one condenser can be used instead of buying two single pressure turbines and two condensers. This is also convenient if the wells in the geothermal system used have various pressures. Steam turbines can have various exhaust designs, which are upward, downward and axial. The axial exhaust design has no pressure loss in the exhaust pipe. Furthermore, large pressure recovery can be achieved by installing a diffuser shaped duct at the outlet of the turbine. The axial exhaust design also means shortened time for assembly work and low turbine building height in comparison to the other axial exhaust designs. Shortened time for assembly work and low turbine building height can reduce the construction cost of a power plant. However, axial exhaust design means that there is a short distance between the turbine and the condenser and they are at the same height. This introduces the risk of flooding the turbine and thus possibly damaging it. A downward exhaust design has almost no exhaust pipe losses but there is less pressure recovery than with an axial exhaust design. The condenser is, however, under the turbine, which means that this design requires the highest power plant house. The upward exhaust design has up to 10% losses in the exhaust pipes but this design is both compact and does not include the risk of flooding the turbine. The axial exhaust design can thus achieve the highest performance for the single flow turbine design. This is of importance for geothermal steam turbines as both their adiabatic heat drop along with the mass flow through them is relatively low [31, 33]. The three different exhaust types can be seen in Figure 2.5.

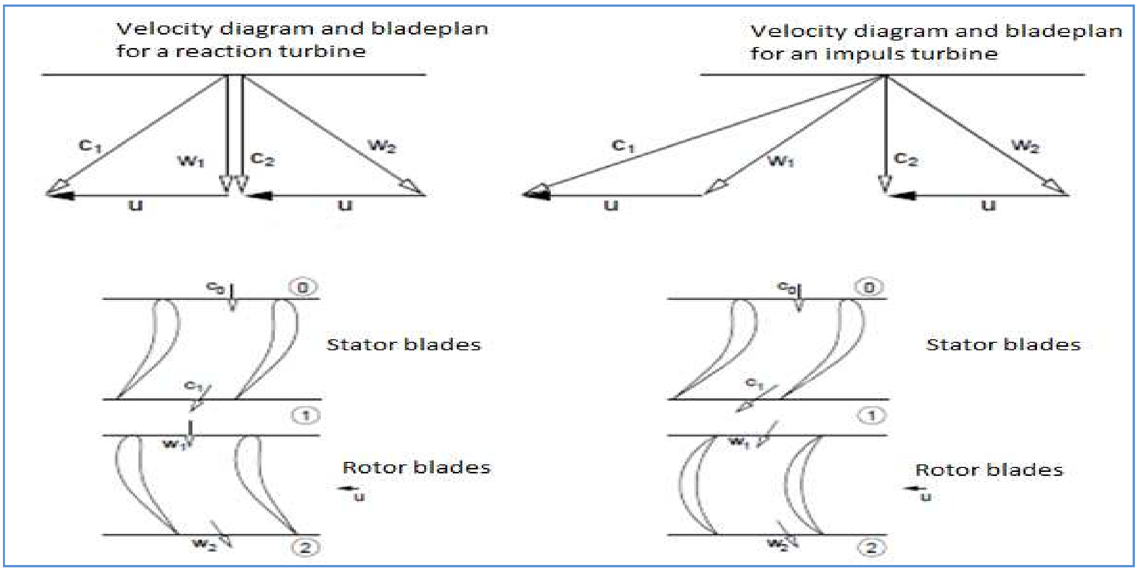


Figure 2.4 *A velocity diagram and a blade plan for both an impulse and a reaction turbine. c represent absolute velocity, w represent relative velocity and u represent tangential velocity [29].*

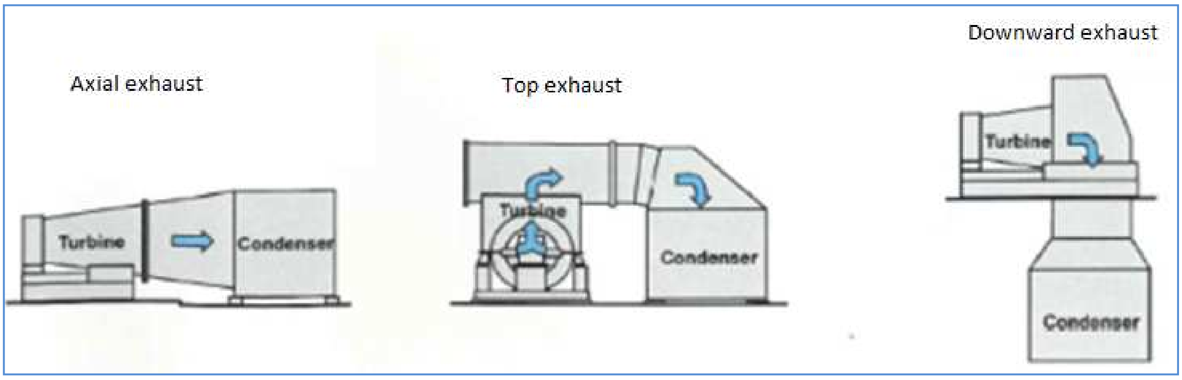


Figure 2.5 *Different types of exhaust for a steam turbine [33].*

2.2 Steam turbine components

The main components of a steam turbine are seals, bearings, rotor, rotor blades, diaphragms and casing. A description of these components is provided in this chapter.

The object of the bearings is to support the turbine rotor and it is normally supported by two such bearings, one at each end. Hydrodynamic journal bearings are typically used because of their damping properties. Multi-pad hydrodynamic journal bearings are popular because they are very stable and have good damping properties. The bearings are cooled with oil during operation [29, 30].

The purpose of the seals is to minimize leakage into a turbine, out of a turbine and between the stages in a turbine. The seals in a steam turbine are normally labyrinth seals, which are mechanical seals. They are generally found at each end of a turbine, on the diaphragms, on the rotor and on the rotor blades. The number of fins and the clearance controls the mass flow through a labyrinth seal. The main advantage of labyrinth seals is that they are contactless and thus no cooling is needed and wear is little [29, 31]. Different designs of labyrinth seals and the characteristic of the flow through them can be seen in Figure 2.6. It can also be seen that the steam undergoes high acceleration as it flows over the fins.

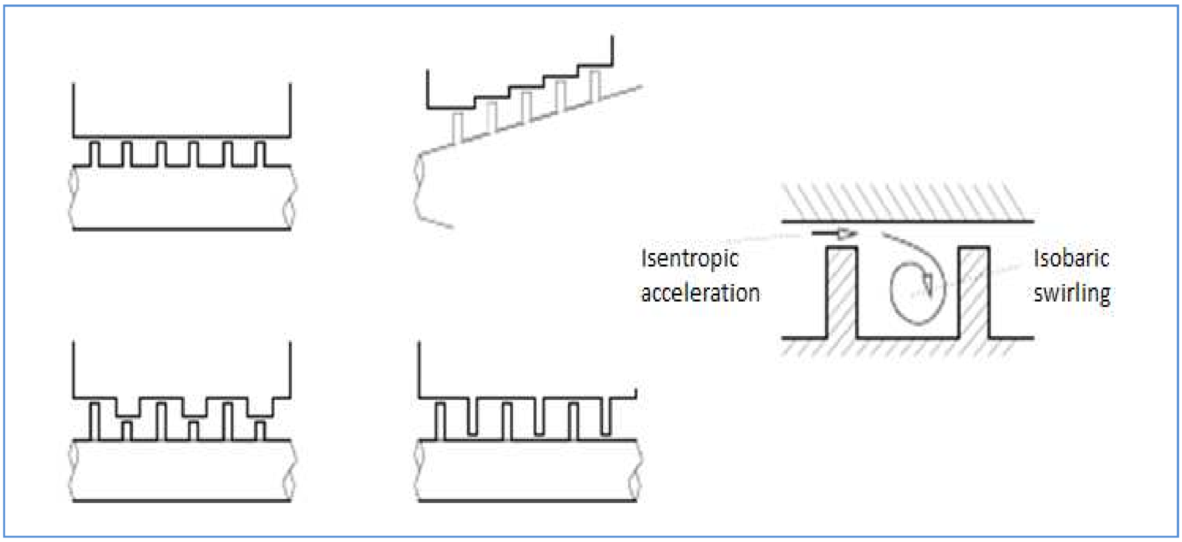


Figure 2.6 *Left, different designs of labyrinth seals in steam turbines. Right, flow in a labyrinth seal [29]*

The purpose of the diaphragms is to transform thermal energy of the steam into kinetic energy. This is achieved with the stator blades on the diaphragms. As the steam flows through the stator blades its pressure drops, its absolute velocity increases and thus its kinetic energy [29, 32]. This can be seen graphically in Figures 2.2, 2.3 and 2.4.

The purpose of the rotor blades is to convert kinetic energy of the steam into mechanical energy. This is done with momentum exchange between the steam and the rotor blades as the stem flows through them [29, 30]. The velocity and pressure changes across the rotor blades can be seen in Figures 2.2, 2.3 and 2.4.

The purpose of the rotor is to support the rotor blades and transfer the mechanical energy that they deliver. The rotor can for example be used to drive a generator or a compressor.

The purpose of the casing is to support the diaphragms and seal of the rotor. It also insulates the turbine from the environment.

2.3 Highly stressed components

Highly stressed components in steam turbines are listed in this chapter along with a description of the forces acting on them.

Both the stator and the rotor blades in a steam turbine are generally highly stressed. The main forces that affect the rotor blades are centrifugal forces and bending forces. The centrifugal forces are due to the rotation of the blades and they cause tensile stresses. These tensile stresses are highest at the root of the rotor blades and at their feet and increase with the length of the blades. Bending forces act on both stator and rotor blades and cause bending moment and torsion. This can be seen in Figure 2.7. Thus the static load on the blades is composed stress caused by tension, bending and torsion [29].

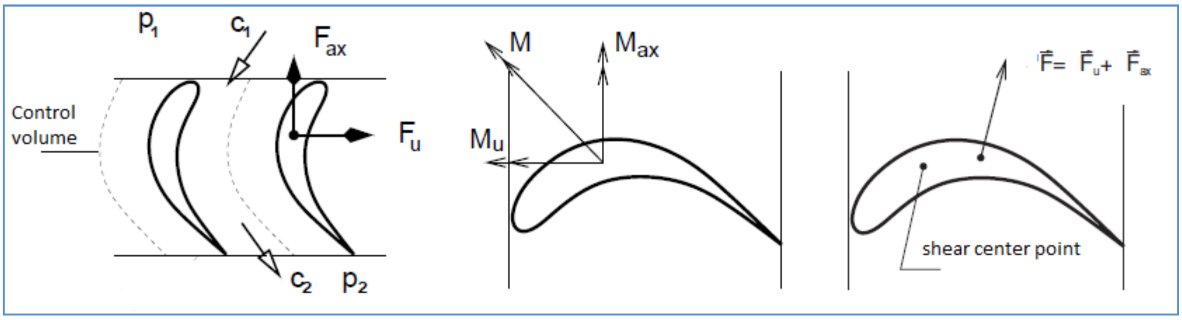


Figure 2.7 *Left, the bending forces F_{ax} and F_{u}, which act on a blade. Middle, the resulting bending moment M that acts on a blade. Right, the resulting torsion caused by F that acts on a blade [29].*

The highest tensile forces in a turbine are in the feet of the rotor blades. This means that the blade attachments on a rotor have to withstand high tensile forces. The design and the construction of the blade attachments are therefore complicated both because of limited space available and requirements of simple montage. As the last stages rotor blades are the longest, their blade attachments experiences the highest tensile forces [29]. Different types of rotor blade feet and their attachments can be seen in Figure 2.8. Figure 2.9 shows the force distribution in two different blade attachments.

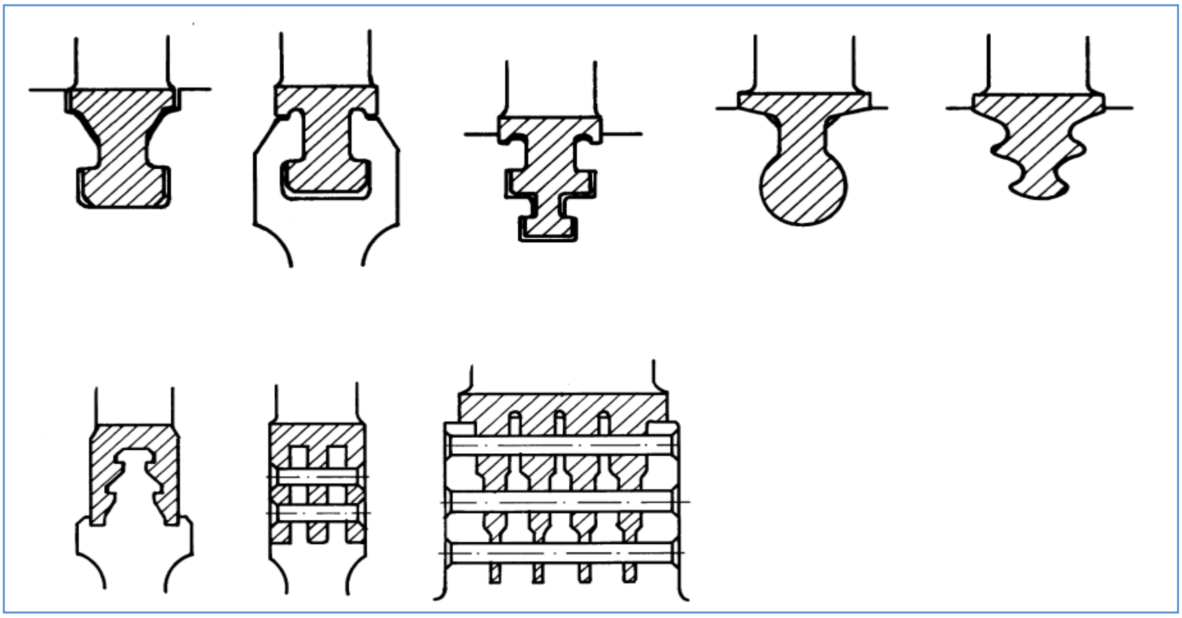


Figure 2.8 *Common types of rotor blade feet and their attachments.[29].*

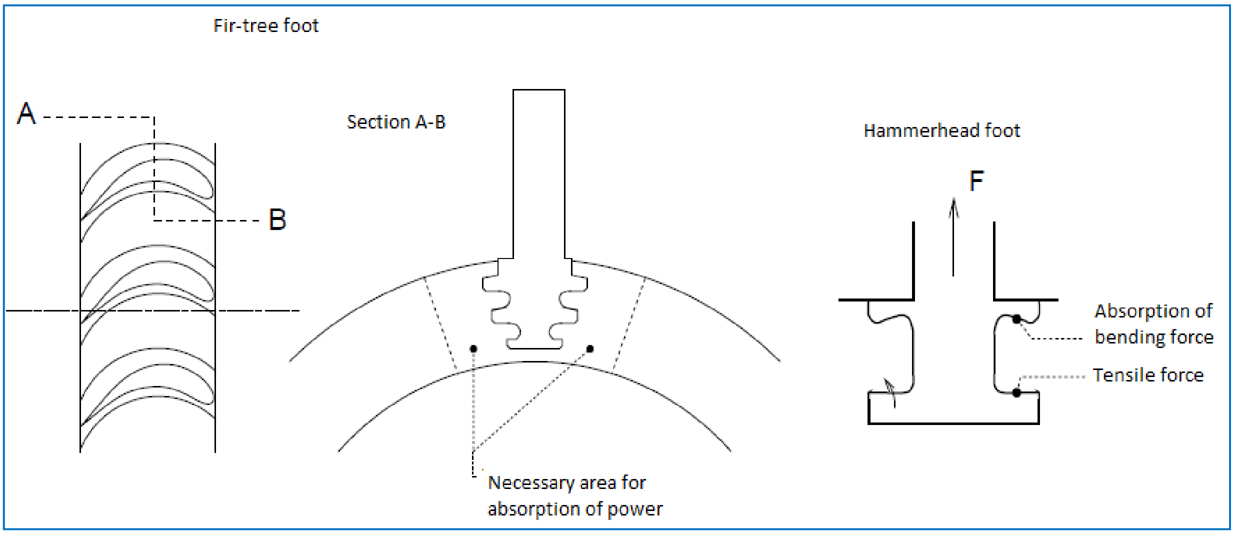


Figure 2.9 *Left and middle, arrangement of an axial inserted fir-tree foot in a turbine. Right, illustration of how forces are distributed from a hammerhead foot into a blade attachment on a rotor [29].*

A generator, which has to generate electricity with the frequency of 50 Hz, has to operate at a rotational speed of 3000 rpm. A steam turbine that drives a generator in a power plant is normally at least several megawatts. A direct connection between the generator and the turbine is therefore needed, a clutch is normally used. This is to avoid using a cooling system with high power consumption. This means that a steam turbine has to operate at the same speed as the generator it drives. A special care has to be taken regarding the vibration of steam turbines because of this high rotational speed. Vibration can for example have severe effects on the stator and the rotor blades of a turbine. The bending oscillations of the blades are generally the most important ones to control as they have the lowest intrinsic frequencies and the largest amplitudes. Excitation of turbine components can for example be caused by uneven pressure and velocity distribution over the circumference in a turbine, an unbalanced rotor, hydrodynamic forces and instabilities in the bearings and a thermal distortion of a rotor. Friction is commonly used to control and to damp the vibration of the blades in a turbine. Common ways to employ friction are for example to install lacing wire or snubbers between the blades. Damping can also be achieved through the blade attachment. The rotor in a turbine also has critical speeds, which have to be avoided [34].

A Campbell-diagram is used to identify a favorable operating range for a turbine. It represents the natural frequencies and the excitation frequencies as a function of the rotating speed for particular turbine components, for example the last stage rotating blades. It can thus locate the speed at which various components are excited by the rotational speed of a turbine [29].

Temperature gradients in turbine components cause thermal stresses. Conditions that cause high thermal stresses are for example the startup, the shutdown and a load shedding of a turbine. Thermal stresses of a turbine component can result in low cycle fatigue. Important factors regarding thermal stresses are the specific heat capacity and thermal conductivity of component materials along with its size and form [29].

3 Methodology

In this chapter the reaserch methods, which were used in this thesis, are represented. The methods that were used to accumulate information are described and it is illustrated how an FMEA is carried out.

3.1 Identification of maintenance needed

The first aim was to identify the maintenance needed for steam turbines in geothermal power plants. To do that a case study of how the maintenance for the steam turbines at Hellisheiði power plant is carried out was conducted.

The following methods were used to obtain information about the maintenance of the steam turbines at Hellisheiði power plant. Secondary data, in the form of maintenance reports and documents from the Dynamic Maintenance Management (DMM) system at Hellisheiði power plant, were collected and analyzed. DMM system is a computerized maintenance management system (CMMS). It allows maintenance managers and supervisors to access information regarding manpower, equipment and maintenance polices. These information can assists in improving maintenance effectiveness and control [35]. Employees in the power plant were also interviewed. The interviewing was made with semi structured questions, that is before every interview a list of questions was prepared. However, every interview was allowed to ebb and flow, following associated leads and new issues as they arose. All the data obtained were analyzed both qualitatively and quantitatively.

The secondary data, coupled with the interview data, will assist in the building up of an overview of how the maintenance for the steam turbines at Hellisheiði power plant is carried out.

3.2 Identification of domestic ability

The second aim was to identify the ability of local workshops to overhaul and repair the steam turbines at Hellisheiði power plant. To do that local workshops and other companies involved in the geothermal industry in Iceland were visited, their facilities inspected and some of their employees interviewed. It was decided to focus only on companies, which were already involved in the maintenance of the steam turbines at Hellisheiði power plant and are likely to participating in the maintenance of the steam turbines there in the future.

It was decided to visit the workshops Framtak, Vélvík and Vélsmiðja Hjalta Einarssonar (VHE) along with the companies Nýsköpunarmiðstöð Íslands (NMÍ), Icelandic Technical Service (ITS) and Klettur.

Interviews with the employees of these companies and workshops were carried out and the same method was used for the interviews as is described in Chapter 3.1. Their facilities were also visited to see which equipment is available and which potential they possess. All the data obtained were analyzed both qualitatively and quantitatively.

The interview data, along with the inspection of the facilities, will help to make an overview over both the potential and the current ability of Icelandic companies to carry out overhaul and repairs of the steam turbines at Hellisheiði power plant.

3.3 FMEA

The third aim was to provide an input for the evaluation of Reliability Centered Maintenance (RCM) for Hellisheiði power plant. To do that an FMEA was used to construct an overview over studied failures and their possible causes in a systematic way for the steam turbines at Hellisheiði power plant. Failure Mode and Effect Analysis (FMEA) is often used as an input when RCM is to be established for a system. RCM is a tool, which uses systematic approach to evaluate system's equipment and available resources, to organize maintenance. The aim with RCM is thus to identify the importance and the likelihood of failures of different components of a system and so minimizes overhauls, increase reliability and makes maintenance more focused on critical components [36]. FMEA is a logical, structured analysis of a system or subsystem. It is used to identify possible failure modes before they occur, along with their causes and possible effects. The main focus of an FMEA is to prevent failures and in turn enhancing safety [37]. The method is normally intended for use during the development phase of either a product or a process. An FMEA conducted on a process already in operation can though, however, provide useful insights regarding its maintenance, which is the main intention of the FMEA carried out here [38].

When an FMEA is conducted on a system, its possible failures are identfied. These possible failures are called failure modes and each failure mode has a potential effect and each effect has some relative risk. To estimate this relative risk, a criticality analysis, which is based on three factors, severity, occurence and detection is used. Severity accounts for the consequence of a failure if it happens, occurence accounts for the frequency or probability of a failure to occur, and detection accounts for the likelihood of detecting a failure before its impact affects the system. By multiplying these factors together a risk priority number (RPN) is found. The failure modes, which have high RPN or high severity ranking should be investigated further in order to enhance the safety of the system studied [37].

4 Case study of Hellisheiði power plant

The case study of the maintenance of the steam turbines at Hellisheiði power plant is represented in this chapter. The most common fault types in the steam turbines are discussed. The failures that have occurred in the steam turbines from startup are analyzed along with the ability of local workshops to repair them. The results from the FMEA are also presented.

4.1 Introduction

Orkuveita Reykjavíkur (OR) owns Hellisheiði power plant where 7 steam turbines are in operation. The generation of electricity started in 2006 with two 45 MW_e steam turbines. In 2007 a 33 MW_e low pressure steam turbine was added and in 2008 two further 45 MW_e steam turbines were commissioned. At last two 45 MW_e steam turbines were added in 2011. Hellisheiði power plant is also a heating plant with an output of 133 MW_{th}. All the 45 MW_e steam turbines are high pressure steam turbines manufactured by Mitsubishi but the 33 MW_e low pressure steam turbine is manufactured by Toshiba. The turbines are operated with a control system manufactured by Siemens [39].

The six high pressure steam turbines from Mitsubishi are of a similar design and are single-cylinder, single flow, impulse-reaction, axial exhaust, condensing turbines. The steam at the inlet is around 167°C and at c.a. 7.5 bar(a). The steam at the outlet is around 45°C and at c.a. 0.1 bar(a). The rated output of each turbine is 40 MW_e but the maximum output is 45 MW_e. All the turbines have 6 stages and the height of their last stage rotor blades is 762 mm. The first two turbines, which were installed at Hellisheiði power plant, were the first geothermal steam turbines in the world with an axial exhaust design [33] [10]. A general assembly picture of a high pressure steam turbine at Hellisheiði power plant can be seen in Figure 4.1.

Some actions were taken during the design of the high pressure steam turbines in order to increase their reliability. The rotating blades at every stage are integral shroud blades. Tenon riveting and welding at the stubs on the last stage rotor blades are thus not needed but such mechanisms are susceptible to both stress corrosion cracking and corrosion fatigue. The advantage of integral shroud blades is thus improved reliability against corrosion fatigue Usage of integral shroud blades for the last stages rotor blades also results in contact between adjacent blades during operation, which causes friction. This friction creates much damping effect against vibration of the rotor blades. It is considered that this can reduce the vibration of the last stages rotor blades up to 20% in comparison with conventional grouped blades [33]. An example of integral shroud blades can be seen in Figure 4.2.

The 762 mm last stage rotor blades, which are used in the high pressure steam turbines, are relatively long for geothermal steam turbines. In order to avoid stress corrosion cracking in the blade grooves due to high centrifugal forces, as are described in Chapter 2.3, a low strength material was used to construct the rotor. The number of blades at the last stage was also reduced and larger roots for the rotor blades were designed [33].

The 33 MW low pressure steam turbine from Toshiba is a single cylinder, single flow, axial exhaust, impulse, condensing turbine. The steam at the inlet is around 1 bar(a) and the outlet pressure is around 0.09 bar(a). The turbine has 4 stages and is fitted with integral shroud rotor blades at every stage [40].

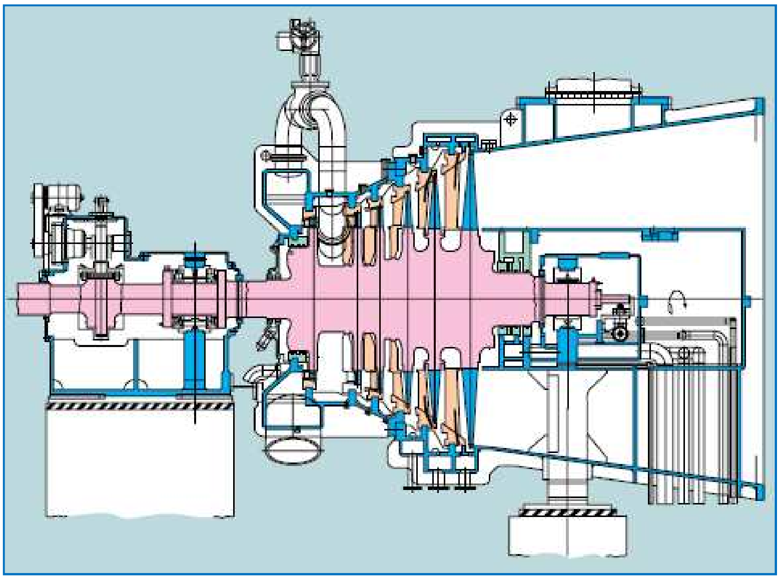


Figure 4.1 *General schematic figure of the assembly of the six Mitsubishi steam turbines at Hellisheiði power plant [33].*

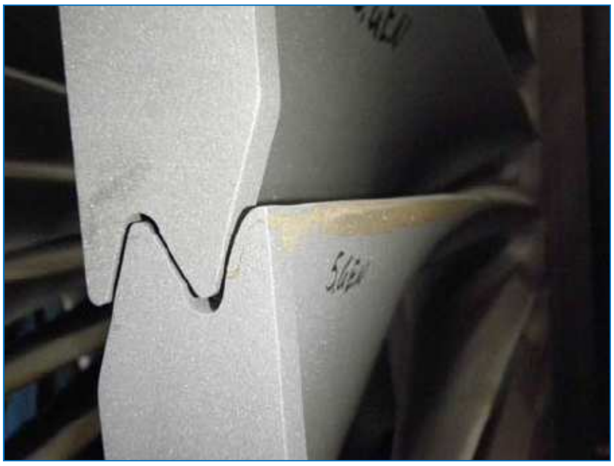


Figure 4.2 *The tip of the integral shroud blades at stage five in steam turbine 2 at Hellisheiði power plant [41].*

4.2 Fault types

Analysis of the maintenance reports for the steam turbines at Hellisheiði power plant indicates that the most common failures are scaling, erosion, corrosion and crack formation. The mechanism behind these failures and their effects is therefore studied in the following sections. Measurements to recognize and prevent those failures are also presented. Later on this helps identifying the root causes of failures that have occurred in the steam turbines at Hellisheiði power plant and provides a valuable input to the FMEA.

Scaling

The working fluid, which is used in a geothermal power plant, usually contains dissolved minerals. If these minerals become supersaturated in the working fluid they may precipitate and form scaling in some of the power plant equipment like the steam turbines. Common scales are for example silica (SiO_2) and calcite ($CaCO_3$) [8]. Normally most scaling accumulation can be found on the back side of the first stage stator blades. This is because the largest pressure drop in a steam turbine is generally across the first stage stator blades [29]. Typical silica scaling on a first stage diaphragm can be seen in Figure 4.3.

Figure 4.3 *Silica scaling on the first stage diaphragm in turbine 3 at Hellisheiði power plant [41].*

Silica can precipitate either as amorphous silica, which is the non crystalline form of silica, or as quartz, which is the crystalline form of silica. The solubility of silica in water is dependent on both the phase and the temperature of the water and the pH level. The solubility of silica decreases fast with decreasing temperature. Combination of boiling and cooling of geothermal fluid thus eventually leads to supersaturating of silica in the fluid. Amorphous silica is more common as scale than quartz although it has higher solubility in a mixture of water and steam than quartz. This is because quartz rarely precipitates due to slow formation of quartz crystals. [42]. Generally only 25% of the working fluid can be converted into steam and it can only be cooled by ca 100°C if precipitation of silica is to be avoided [8].

Calcite scales are common in wells with reservoir temperature of 140-240°C. Degassing of CO_2 and the resulting raise of pH level causes formation of calcite scales. Calcite scales are commonly found over a 200-300 m long part in a geothermal well above where flashing occurs [8]. Calcite is also more soluble in cooled working fluid than hot. This means that there is low risk of scale formation when the working fluid is cooled [42].

Scaling on stator blades reduces the throat area between them. This causes changes in the steam flow velocities, the steam flow angles, the axial force and decrease in the pressure after the stage where the scaling occurs. The results of these changes are decreased efficiency and output capacity of a steam turbine. Scaling also reduces the useful life of the blading system of a geothermal turbine [23] and increases the surface roughness of its blades [9]. Scaling can be detected by monitoring the pressure after the stage where it occurs along with the turbine efficiency, output capacity and axial force. The pressure after the stage where scaling has occurred is, however, generally the most indicative parameter to detect scale deposition [23].

X-ray diffraction (XRD) and a Scanning Electron Microscope (SEM) can be used to analyze the chemical composition of scaling. XRD is used for identification of crystalline substances and SEM is used for distributive and qualitative analysis [8].

To clean scaling in a steam turbine during operation, “turbine washing” can be used. This is done in the following way: The moisture of the steam entering the turbine is increased up to around 5% with water injection and the turbine is operated at that condition for a few hours. This procedure can clean scaling and recover much of the turbine output. However, this should be practised with care as increased moisture of the steam causes high erosion rate [8].

Erosion

Erosion is mainly caused by small solid particles or water droplets that continuously impinge on the surface of some component. The steam, which is used in geothermal power plants, often contains hard solid particles like silicon, sulphur and phosphor along with other elements. Furthermore, steam turbines in geothermal power plants are often condensing turbines. A condensing steam turbine expands steam into the wet region, sometimes down to a steam quality of 0.85, which causes formation of droplets in the steam. Geothermal steam turbines are therefore highly susceptible to erosion [24]. Formation of droplets is also undesirable in a steam turbine because it decreases the efficiency. The Baumann’s empirical rule states that 1% moisture equals 1% loss of efficiency. This can mainly be explained by two things. The formation of droplets in steam causes thermodynamic losses and droplets cause mechanical losses as they hit the rotor blades [29].

The most affected parts by erosion are normally the diaphragms, the labyrinth seals, the drain holes, the turbine casing, the cover band and rivets formed on the tenon head of the rotor blades, the rotor blades and the rotor discs [24]. Erosion can also affect all the steam path seals. That is the over-shroud seals, the end seals, the root and the diaphragms seals of an impulse turbine and the under-shroud seals of a reaction turbine. Erosion of seals commonly results in reduced internal efficiency of a turbine due to leakage. Erosion of rotor labyrinth seals can for example decrease the efficiency by 2-4% or more. Erosion also leads to decreased time between overhauls [24].

The rate of wear due to erosion generally depends on the surface material affected, the properties, the relative velocity and the impact angle of the particles/droplets in the steam. The amount and size of the particles/droplets is also a factor [24, 43]. An example of erosion damage in a steam turbine can be seen in Figure 4.4.

The last stage rotor blades in condensing turbines often suffer from high wear rate because of erosion. The cause for that can be explained in the following way. As steam is expanded through a turbine its wetness increases this leads to droplets formation on the pressure side at the last stages stator blades. These droplets are carried with the steam towards the rotor blades but do not follow the steam path because they are heavier than the steam. This leads to impingement of the water droplets at the leading edge and the back face of the leading edge on the rotor blades [26]. This can be seen graphically in Figure 4.5. The most important parameters when it comes to erosion of rotor blades are droplet size, droplet velocity and peripheral speed of the blades [43]. The amount and the size of the water droplets reduce from the tip of the rotor blades towards their roots. This can partly be explained with the centrifugal force acting on the droplets. The tips of the rotor blades also have the highest rotational speed, up to 600 m/s. The rotor blades are therefore normally most eroded at the tip. Erosion damage to the back face of rotor blades does not have great effect on the reliability and the service time of the blades. Erosion damage to the leading edge of rotor blades is, however, one of the most important things when it comes to reliability and service time of the blades [26]. Erosion of rotor blades can also increase the swallowing capacity of a steam turbine [9].

Figure 4.4 *Both pictures are from turbine 3 at Hellisheiði power plant. Left, wear due to erosion on the horizontal joint on the fourth stage diaphragm. Right, wear due to erosion on the leading edge and the back face of the leading edge at the tip of a rotor blade at stage six [41].*

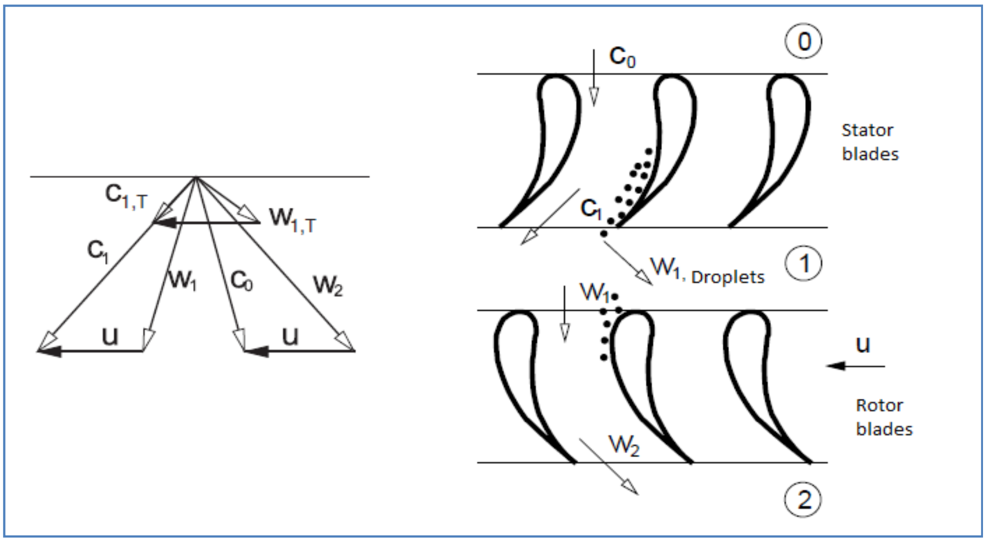


Figure 4.5 *Left, velocity diagram for steam and droplets. Right, cross section of stator and rotor blades. c is absolute velocity, w is relative velocity and T represents droplets [29].*

It is hard to detect erosion without visual inspection. However, there are some procedures available to reduce or prevent erosion in steam turbines. Efficient and well designed draining system can reduce the amount of droplets in the steam. By increasing the distance between the stator blades and the rotor blades at the last stages the erosion of the rotor blades can be decreased. By having the last stage stator blades hollow, they can both be heated with steam or prepared with draining slots at the end to remove moisture from the blade surface. The blade tip speed can be restricted. The leading edge of the rotor blades can be laser or flame hardened. A strong material with high degree of hardness like stellite can also be used to reinforce the blades [21, 44].

Corrosion

Geothermal fluid often contains large quantities of corrosive chemicals, which occur both as particles and non-condensable gases. These corrosive chemicals are for example chloride, sulfate, hydrogen sulfate and carbon dioxide. Majority of the corrosive chemicals that are dissolved as solid particles in the steam are removed from with equipment like separators and moisture separators upstream from a steam turbine. The amount of corrosive substances in the steam that enters the steam turbines in a geothermal power plant is nevertheless 100 to 1000 times more than in the steam, which is used in fossil fuels power plant. Geothermal steam can also be acid and when it condenses it produces acid water. This can cause severe corrosion at the last stages of a steam turbine. Geothermal steam turbines are therefore susceptible to corrosion. Common types of corrosion are for example uniform corrosion, corrosion fatigue, stress corrosion cracking (SCC) and erosion corrosion [20], [22].

Corrosion can affect every component of a steam turbine but especially parts, which are not made of stainless materials. Corrosion can damage or cause cracking in parts, which can lead to catastrophic failures. It is also hard to detect corrosion in steam turbines without visual inspection or non-destructive testing.

To reduce or prevent corrosion some action can be taken during the manufacturing of a steam turbine. Spray coating can be used to coat critical parts like rotors and stationary blade holders. Flame spray coating experiment with WC-CrCo have shown good results but WC-CrCo can improve the corrosion resistance of a component. Shoot peening enhances the capability of a surface to withstand corrosion fatigue and SCC. Selection of materials is also important. The lifetime of steam turbine components can be increased by selecting materials that are corrosive resistant, SCC resistant and suitable for their working environment. This is, however, not an easy task as every geothermal system has a unique chemical composition, pressure and temperature and these factors have very much affect on corrosion rate and corrosion cracking [20, 21, 22]. Table 4.1 shows the chemical composition of the non-condensable gases in the geothermal steam from 9 different geothermal systems. The variation is great as can be seen, even between geothermal fields that are located relatively close to each other like Reykjanes and Hellisheiði.

Table 4.1 *Chemical composition of non-condensable gases in geothermal steam at different geothermal systems. Note the row marked "Gas" shows how much percent of the total volume of the steam at each geothermal system is non-condensable gases. Rows 3-7 show in which amount which substances are found in the non-condensable gases at each geothermal system. [22, 45, 46].*

Power plant	Krafla	Reykjanes	Hellisheidi	Nesjavellir	Geysers	Tiwi	Matsukawi	Mori	Cerroprietor
Gas (%)	1.2	0.4	0.51	0.4	0.5-1.9	1.7-1.2	0.2-0.6	3.5-5.4	~0.4
CO_2 (%)	96.5	95.2	73.2	39.3	63.5-69.3	97.0-97.5	79.3-85.2	97.9-98.2	~24.0
H_2 (%)	1.5	1.5	0.79	33.1	12.7-14.7	0.26-0.28	~0.28	0.02-0.07	~76.0
N_2 (%)	-	0.9	2.0	2.1	-	0.26-0.28	-	0.47-0.58	-
H_2S (%)	1.5	2.3	23.5	25.3	1.69-2.99	2.22-2.74	12.9-17.7	0.5-1.0	-
CH_4 (%)	-	-	0.06	-	11.9-15.3	0.26-0.28	~1.15	0.52-0.62	-

Cracking

Cracks tend to form on diaphragms, rotors and rotor blades. Cracks in rotors and stator blades can eventually lead to a failure, which can have sever effects. Cracks can be caused by fatigue, vibration and a combination of erosion and corrosion. The last stages rotor blades, especially their roots, are, however, the components that are most susceptible to the crack formation. The reason for this is mainly the length of the last stages rotor blades. They are both susceptible to vibration and experience high centrifugal force as mentioned in Chapter 2.3. Condensing steam turbines can also experience flow recirculation, pressure fluctuation and counter-flows at the last stages. This causes excitation of the blades, which causes high vibratory stresses [25].

Vibration of a turbine component can lead to crack formation. If the vibration frequency of some component matches the resonance of any other component a severe failure may occur. Vibration can for example be caused by mass unbalance, misalignment between the generator rotor and the turbine rotor and operation with reduced mass flow. Mass unbalance can be caused by scaling, erosion and corrosion. Misalignment between the generator rotor and turbine rotor can be caused by failure in supports or installation. Reduced mass flow changes the blade entry flow incidence angle. This results in the steam striking the suction side of the rotor blades and exiting them [25]. Vibration of a steam turbine has therefore to be monitored carefully. Vibration monitoring can also be used to detect failures or potential failures.

Right selection of materials can reduce crack formation. Materials with low crack propagation rate should be used where there is a danger of crack formation.

Some methods are available to detect cracks. One commonly applied method is dye penetrant testing as it is both simple and inexpensive. It is a method which has its limitation because it only detects surface fractures. Other common methods are for example ultrasonic testing and radiographic testing.

4.3 Maintenance and condition monitoring of the steam turbines at Hellisheiði power plant

The surveillance of the steam turbines at Hellisheiði power plant is carried out in the following way. Every turbine at the power plant is powered down once a year and explored with a borescope to find and identify any failures. Problems that can be observed with a borescope are for example scaling and wear of rotor and stator blades. The time between major overhauls is, however, four years assuming that no problems occur in the meantime. The startup and the shutdown of a turbine are undesirable processes, which should be practised as rarely as possible, because they cause high thermal stresses as is described in Chapter 2.3.

The deciding factor for the time between major overhauls is wear of the turbines components. This is because wear can be hard to detect without visual inspection, especially on places like the horizontal joints and the casing seat at the diaphragms. Experience indicates that after four years of operation there is an increased risk that the turbines have suffered severe wear, which could be hard or impossible to repair. Another factor, which also has effect on the interval between overhauls is scaling. It is, however, considered possible to operate the steam turbines at Hellisheiði power plant for up to six years if scaling is the predominating factor.

A turbine overhaul comprises several activities, which fall under three major phases i.e. dismantling/inspection/cleaning, replacement/repair and reassembling/testing. The overhauling process normally takes about 4 weeks. Reassembling is one of the most complex phases in the overhauling process, especially the alignment of the diaphragms and the alignment between the turbine rotor and the generator rotor. The maintenance staff at Hellisheiði power plant has been developing the overhauling process of their steam turbines with help from experts in the Icelandic geothermal industry. The overhauling process is now organized and carried out by the maintenance staff at Hellisheiði power plant without any supervision or help from the turbines manufacturer. Local contractors and workshops have, though, provided manpower to help with the overhauling process. This allows the staff at Hellisheiði power plant to organize and optimize the overhauling processes in the future with regard to spare parts, time and expenses.

Condition monitoring is used to detect failures in the steam turbines at Hellisheiði power plant. Quantities that are monitored are vibrations, efficiency and thermodynamic data like temperature and pressure. Vibration is an especially good indicator to both detect failures and predict potential failures for a rotating machine like a steam turbine. By monitoring vibration, problems like unbalanced rotor, failure in bearings and failure in supports can be detected before they cause severe malfunctions. The amount of dissolved minerals in the steam is also measured both at the inlet and the outlet of the turbines. This way the amount of minerals that accumulates in the turbines can be estimated [10].

4.4 Failures in the steam turbines at Hellisheiði power plant

Four of the seven steam turbines at Hellisheiði power plant have been overhauled since startup of the power plant, that is to say three high pressure steam turbines manufactured by Mitsubishi and the low pressure steam turbine manufactured by Toshiba. The turbines had been operating from 2.5 up to 4 years before they were overhauled. Here are the failures, which were observed during the overhaul of these four steam turbines, discussed and possible causes identified. Each component of the steam turbines is looked at individually. All the information in this chapter is either conceived from maintenance reports, DMM data or interviews with the employees at Hellisheiði power plant.

Diaphragms

Here are the failures and the problems for the diaphragms in the steam turbines at Hellisheiði power plant along with their possible causes discussed.

Scaling is not a serious problem at Hellisheiði power plant and is generally found in a small amount on the stator blades, mainly, though, on the first stage diaphragms. Turbine 3 has, however, suffered from considerable scaling problems that caused performance drop and hastened the overhaul of the turbine. Scaling was found on the stator blades through the whole turbine, the greatest amount being found on the stator blades in the first stage diaphragms. An example of scaling can be seen in Figure 4.6. XRD and SEM analyses of the scaling in turbine 3 measured mainly quartz, metal sulfide, sodium chloride and zeolithe. The maintenance staff at Hellisheiði power plant believes that well 45, which is a relatively dry well, is responsible for this scaling. In order to prevent further scaling problems in the future, water injection has been started at the wellhead on well 45. The result from that process is promising.

Figure 4.6 *Left, scaling on the first stage stator blades in turbine 2 at Hellisheiði power plant. Right, scaling on the first stage stator blades in turbine 3 at Hellisheiði power plant [41].*

A common problem on the diaphragms is wear at the horizontal joints and it is mainly found on the first four stages. An example of this can be seen in Figure 4.7. No such wear is, however, found in the low pressure turbine. This can be explained with different design of the horizontal joints there. They are bolted together and made of stainless steel instead of carbon steel, which is used in the high pressure turbines. The wear at the horizontal joints is most likely caused by solid particle erosion rather than water droplet erosion. There are two reasons, which support this. This damage is not found at the last stages diaphragms were the moisture in the steam is highest. This damage is, however, found at the first stages where it seems that more solid particle are present as can be seen from the scaling problems. Another reason that can partly explain why this damage is less at the last stages, is the pressure difference across the first stages in a steam turbine, which is generally higher than across the last stages. The steam, which flows between the horizontal joints on the diaphragms in the turbines, therefore accelerates more at the first stages than the last. Velocity has high influence on erosion rate as is stated in the Erosion section in Chapter 4.2. Corrosion is, however, unlikely to be the predominant mechanism for this wear although it could have some effect. The following reasons support that. The wear is localized as can be seen in Figure 4.7, which indicates that certain flow conditions cause it rather than corrosion. The short operation time of the turbines also indicates that corrosion is not the predominant mechanism for this damage.

No cracks were found with visual inspection on the diaphragms except at the first stage stator blades in turbine 3. Therefore a dye penetrant inspection according to the EN571-1 standard was carried out to locate all surface cracks and damages on them. The first stage diaphragms have 122 stator blades. The inspection revealed 70 surface cracks in the stator blades on the upper diaphragm and 39 surface cracks in the stator blades on the lower diaphragm, which did not fulfill the EN1289 standard. All the cracks discovered were on the backside of the stator blades. Figure 4.8 illustrates cracks in four of the stator blades. There are mainly two possible causes for this formation of cracks. Wear could have changed the vibration properties of the stator blades, which along with vibration could be the cause. The high level of scaling might also be responsible. During the inspection it was also noticed that 22 stator blades in the upper diaphragm and 29 stator blades in the lower diaphragm were damaged in such a way that a part of the stator blade had broken or worn off. This could be caused by either erosion or corrosion or a combination of them. An interesting fact is that the stator blades in the upper diaphragm had suffered from more damage than the ones in the lower diaphragm. The reason for that is unknown. The first stage diaphragm in turbine 3 is the only one, which has been examined especially for cracks. It is thus possible that diaphragms in other turbines could have small cracks, which cannot be found with visual inspection.

Figure 4.7 *Left, erosion damage on the horizontal joint on the second stage diaphragm in turbine 2 at Hellisheiði power plant. Right, erosion damage on the horizontal joint on the third stage diaphragm in turbine 3 at Hellisheiði power plant [41].*

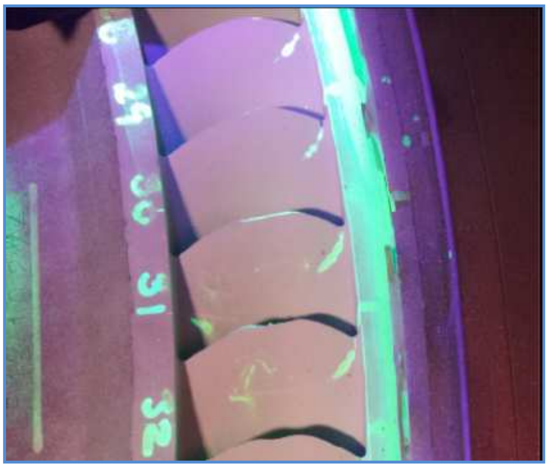


Figure 4.8 *Cracks at the backsides of the stator blades on the first stage diaphragm in turbine 3 at Hellisheiði power plant [41].*

The outer labyrinth seals on the diaphragms experience a small wear, mainly the ones on the first two stage diaphragms. The labyrinth seals on the first stage diaphragms in turbine 3 were, though, especially worn. This wear is probably because of solid particle erosion because of the same reasons as the wear of the horizontal joints. Solid particle erosion could also explain the high wear rate of the labyrinth seals in turbine 3 as there is high amount of solid particle present there due to scaling. Furthermore the labyrinth seals have feasible conditions for erosion as the steam flows through them with high velocity as is described in Chapter 2.2. But velocity has high influence on erosion rate as is stated in the Erosion section in Chapter 4.2. Higher pressure difference over the first stages diaphragm than the last ones only add to this problem.

The stator blades experience wear at their roots both the inner and the outer ones. This damage is most severe at the inner roots of the stator blades at the fourth stage diaphragms. It is though also found both at the inner and at the outer roots at the stator blades at stages five and six, though mainly at the outer ones. An example of this damage can be seen in

Figure 4.9. This wear is most likely caused by a combination of solid particle and water droplet erosion and possible erosion corrosion. Solid particle erosion is, though, probably the dominating mechanism because there is less damage at stages 5 and 6 where there is more moisture in the steam. Different design of the stator blades roots at the first three stages can explain why they do not suffer from this wear. The roots at the first three stages along with the outer one at stage four are also made of stainless steel, while carbon steel is used at the other stages. This difference can be seen in Figure 4.10. This damage did, however, not occur in the low pressure turbine. This can be explained with the construction of the hoops where the stator blades are attached to the diaphragms there as they are made of stainless steel.

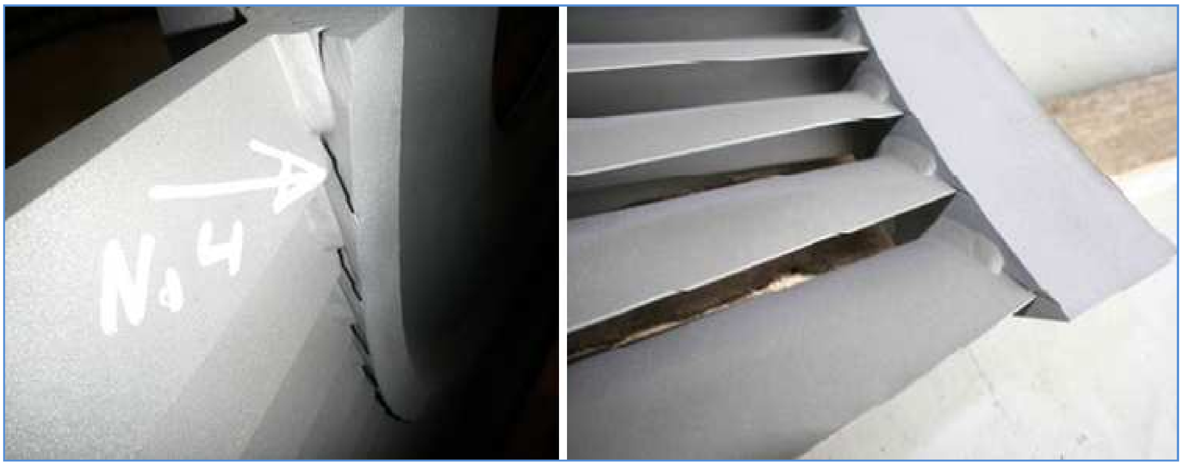


Figure 4.9 *Left, wear at the inner roots of the stator blades at stage four in turbine 3 at Hellisheiði power plant. Right, wear at the inner roots of the stator blades at stage five in turbine 2 at Hellisheiði power plant [41].*

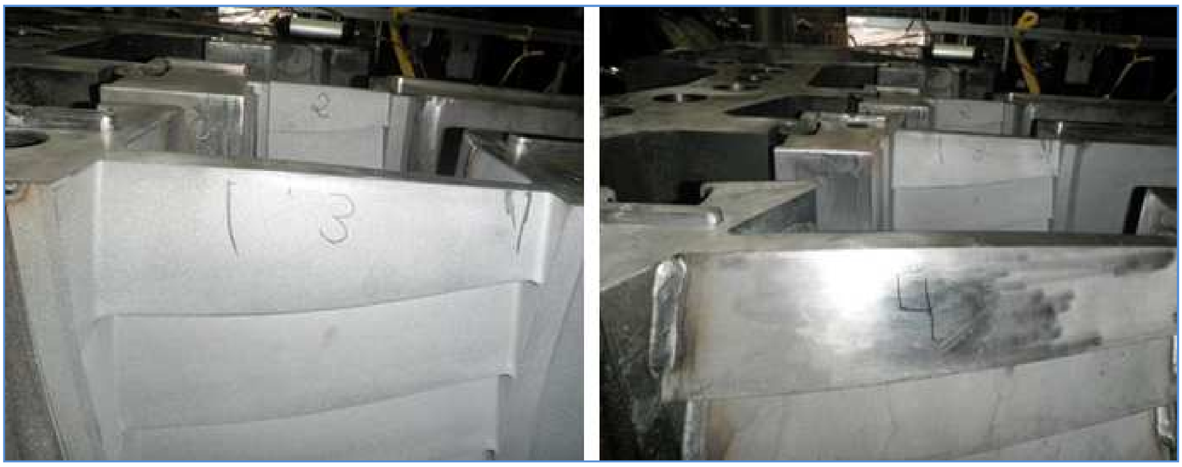


Figure 4.10 *Both pictures are from turbine 3 at Hellisheiði power plant. Left, an example of the design of the inner and outer roots at the stator blades at stages 1-3 can be seen. Right, an example of the design of the inner and outer roots of the stator blades at stages 4-6 [41].*

The casing seats on the diaphragms have experienced some problems. Impurities tend to accumulate in the seats, especially at the first stages. Some wear problems have also occurred. They occur mainly on the diaphragms at the first stages. The most likely cause is thus solid particle erosion for the same reason as for the wear of the horizontal joints. However, corrosion is also likely to be partly responsible.

Wear at the side of the diaphragms is also a problem. This wear is only found on the sides of the diaphragms above and behind the drains holes in the casing. It is therefore most likely caused by water droplet erosion. An example of this can be seen in Figure 4.11. This damage is not found in the low pressure turbine. Different design of the drain system there could explain that.

Figure 4.11 *Both pictures are from turbine 2 at Hellisheiði power plant. Left, wear on the side and on the bottom of the third stage diaphragm. Right, wear at the side of the fourth stage diaphragm [41].*

The severity of some of the damages after only 2.5-4 years of operation is interesting. Many problems are also sectional, which is very interesting, for example the wear at the inner root of the stator blades at the fourth stage diaphragms and the wear of the horizontal joints at the first stages diaphragms. It is also interesting that the diaphragms in the low pressure turbine manufactured by Toshiba have suffered from fewer damages than the high pressure turbines manufactured by Mitsubishi. Application of stainless materials in areas susceptible to wear like the horizontal joints and the stator blade roots in the turbine manufactured by Toshiba could explain this. In general, stainless steel seems to have good resistance against erosion.

The draining system in the turbine manufactured by Toshiba is different from the one in the turbines manufactured by Mitsubishi. In the high pressure turbines from Mitsubishi there are draining holes in the bottom of the casing in front of the diaphragms. In the low pressure turbine from Toshiba there are drain catchers, which accumulate the droplets in a cell, between the stator and rotor blades. There are also grooves on the backside of the leading edge on the rotor blades, which lead to those cells, that are supposed to catch the droplets in the steam. These two different drain systems can be seen in Figure 4.12. Both systems only transport the moisture in the steam over to the next stage but not out of the turbine. The experience from Hellisheiði power plant is that the draining system designed by Toshiba appears to work better than the one designed by Mitsubishi.

In Table 4.2 a summary of failures, which occur on the diaphragms in the steam turbine at Hellisheiði power plant, can be seen. However, Table 4.2 only represents failures that are common or predominating when it comes to maintenance. It is thus possible that other failures occur at the diaphragms although they are not listed in the Table 4.2. It can be seen that the most common problem is erosion. Scaling is a problem for some components but corrosion and cracking do not seem to be a problem. Short operation time of the turbines can explain that. The main indicator that was considered for the estimation of the “Time until repair is needed” factor is the time until the damage, caused by a particular failure, starts to have effect on the safe operation of the turbine. It is based on the subjective assessment of the author after interviewing the maintenance staff at Hellisheiði power plant and analyzing secondary data.

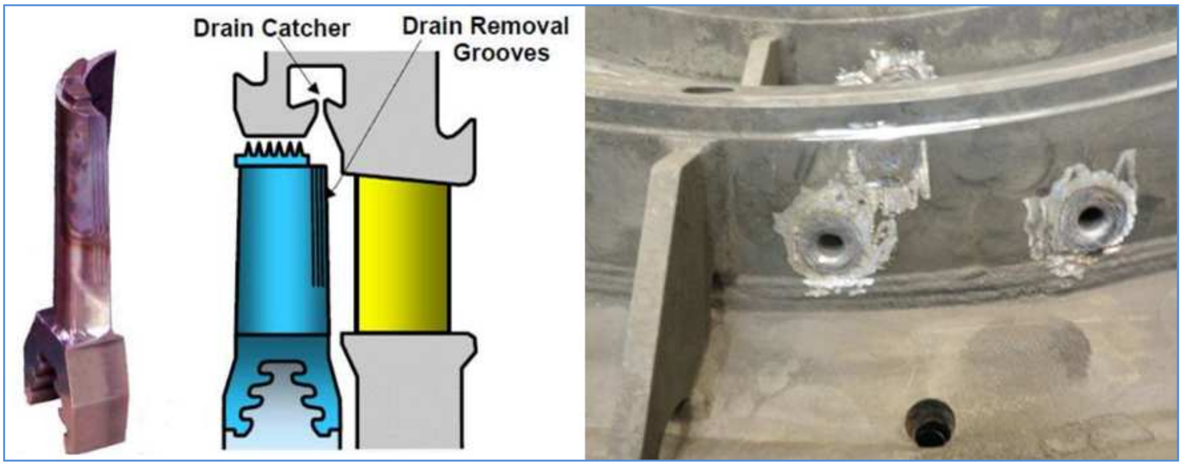


Figure 4.12 *Left, illustration of how the draining system in the low pressure turbine manufactured by Toshiba works. Right, example of drain holes in the casing in the high pressure steam turbine manufactured by Mitsubishi [41, 47].*

Table 4.2 *Summary of failures for all the components of diaphragms in the steam turbines at Hellisheiði power plant.*

Diaphragms					
	Corrosion	Erosion	Cracking	Scaling	Time until repair is needed [years]
Stator blades		X	X	X	4-8
Casing seats	X	X		X	4-8
Roots at stator blades		X		X	4
Inner labyrinth seals		X			4-8
Outer labyrinth seals		X			4-8
Sides	X	X			4
Horizontal joints		X			4

Rotors

The failures and the problems of rotors in the steam turbines at Hellisheiði power plant along with their possible causes are discussed below.

The seal surface on the high pressure side wears but at a very slow rate. It is most likely caused by solid particle erosion because the steam there is relatively dry. The low pressure side also experience wear but at a higher rate or around 0-0.2 mm/year. The wear on the low pressure side is probably caused by a combination of corrosion, solid particle erosion and water droplet erosion. The corrosion can be caused by inflow of air from the environment but moisture and solid particles in the steam can cause the erosion. An example of wear on seal surfaces can be seen in Figure 4.13.

Wear occurs in rotor labyrinth seals and it is mainly found in the first two stages rotor labyrinth seals and the rate can be up to 0.4 mm/year. The most likely cause for this wear is solid particle erosion. There are mainly two reasons, which support this. The wear is at the rotor but water droplets are normally found outwards in turbines as is described in the Erosion section in Chapter 4.2. The steam is also relatively dry at the first stages. Furthermore, labyrinth seals have feasible conditions for erosion as already explained in the Diaphragms section in Chapter 4.4. An example of this wear can be seen in Figure 4.14. The wear in the rotor labyrinth seals has to be monitored carefully because there is nothing that slows down the steam before it hits the rotor drums when the labyrinth fins have been worn down. This would result in a high erosion rate at the rotor drums, which would be both difficult and expensive to repair and could have severe effects.

Figure 4.13 *Both pictures are from turbine 3 at Hellisheiði power plant. Left, wear of the low pressure seal surface. Right, the high pressure seal surface, which has almost no wear [41].*

Figure 4.14 *Left, 1.5mm wear of the rotor labyrinth seal for diaphragm two in turbine 3 at Hellisheiði power plant. Right, about 1mm wear of the rotor labyrinth seal for diaphragm two in turbine 2 at Hellisheiði power plant [41].*

Some problems are associated with the rotor drums. The steam balance holes often show signs of wear. This can be seen Figure 4.15. The cause is not known but a probable cause is erosion. This wear is undesirable both because the steam balance holes experience high stress and it can lead to crack formation in the future. Another problem at the rotor drums is wear, which takes place beside the blade roots on the top of the rotor drums. The wear is mainly found on the backside of the rotor drums above the steam balance holes at the first stages. An example of this can be seen in Figure 4.15. This wear is most likely associated with the wear at the steam balance holes, and the steam that flows through them.

One hypothesis from Mitsubishi is that some turbulence flow or condensation happens around the steam balance holes and these may cause this wear. The blade attachment on the rotor drums also has to be monitored carefully as regards crack formation because of this wear.

It is worrying how worn the rotors in the steam turbines are after only 2.5 to 4 years of operation. It means that both costly and complex repairs are required in a few years. Furthermore, damages like the ones on the rotor drum will cause crack formation in the future with potential severe effects.

In Table 4.3 a summary of the failures, which occur on the rotors in the steam turbines at Hellisheiði power plant, can be seen. Table 4.3 only represents failures that are common or predominating when it comes to maintenance. It is thus possible that other failures occur at the rotors although they are not listed in Table 4.3. The same method is used to estimate the "Time until repair is needed" factor as in table Table 4.2. Erosion is the most common failure for the rotors. Corrosion and fractures are also present but the rotors do not suffer from scaling problems. It can, however, be practical to perform some repairs on a rotor although it is not needed with regard to safe operation but it can be seen that the rotors can be operated for at least 8 years before repairs are necessary. That way more expensive and complex repairs in the future can be avoided.

Figure 4.15 *Left, wear of a steam balance hole at stage 3 in turbine 1 at Hellisheiði power plant. Right, wear at the backside of the rotor drum, beside the rotor blades roots at stage 2 in turbine 2 at Hellisheiði power plant [41].*

Table 4.3 *Summary of failures for all the components of the rotors in the steam turbines at Hellisheiði power plant*

Rotors					
	Corrosion	Erosion	Fractures	Scaling	Time until repair is needed [years]
Seal surfaces	X	X			>8
Labyrinth seals		X			>8
Rotor drums		X	X		>8

Rotor blades

The failures and the problems of rotor blades in the steam turbines at Hellisheiði power plant along with their possible causes are discussed below.

There are labyrinth seals on the top of the rotor blades at stages 1-3 in the high pressure steam turbines and at all four stages in the low pressure steam turbine. The labyrinth seals in the high pressure steam turbines wear but the ones in the low pressure turbine do not wear. The wear is most likely caused by a combination of water droplet erosion and solid particle erosion. It can be explained in the following way. Droplets tend to form in steam, which flows through a diaphragm, and they accumulate outwards in a turbine as is described in the Erosion section in Chapter 4.2. A part of the droplets therefore flows with the steam over the rotor blades. As the steam flows over the rotor blades it accelerates and vortex flow occurs as can be seen in Figure 2.6 in Chapter 2.2. In this way the solid particles along with the water droplets in the steam erode the labyrinth seals. An example of this can be seen in Figure 4.16. This wear does not occur in the low pressure steam turbine as already mentioned. This can be explained with the draining system there, which is demonstrated in Figure 4.12 but it seems to prevent this wear. It can thus be concluded that the dominating mechanism for this type of wear is water droplet erosion.

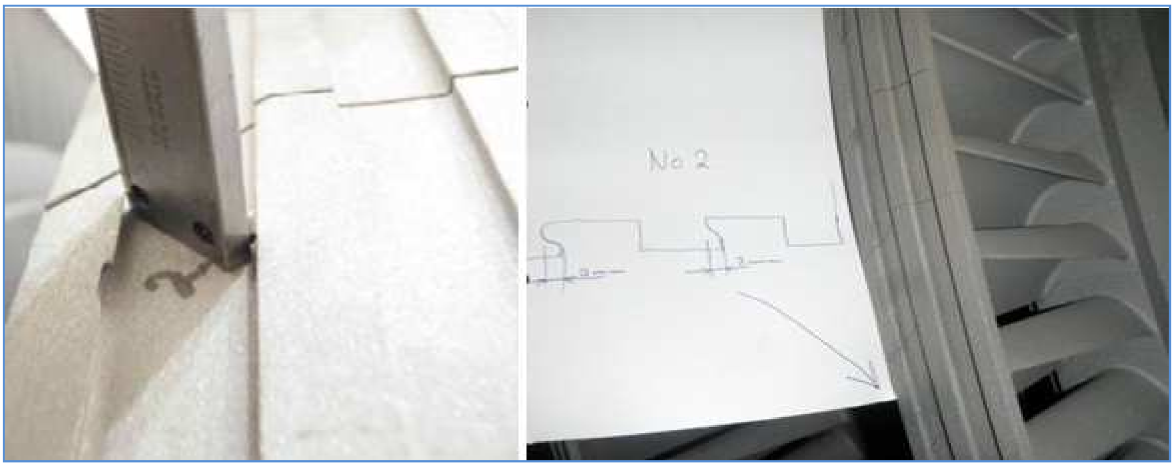


Figure 4.16 *Both pictures show wear of labyrinth seals on the top of the rotor blades in the turbines at Hellisheiði power plant. Left, the second stage in turbine 2. Right, the second stage in turbine 3 [41].*

The leading edge and the backside of the leading edge on the rotor blades wear, often at a high rate. The wear is mainly found at the tip of the last stages rotor blades. An example of this can be seen in Figure 4.17. This wear is consistent with the one that is described for rotor blades in the Erosion section in Chapter 4.2 and is thus most likely caused by water droplet erosion. The wear starts at the fourth stage rotor blades in the high pressure steam turbines but at a low rate. The rate increases at the fifth stage but the material loss at the leading edge on the rotor blades there is around 0.1-0.15 mm/year [40]. The highest rate is on the leading edge of the sixth stage rotor blades but the material deterioration there is around 0.5-1.5 mm/year [40]. The wear starts at the third stage rotor blades in the low pressure steam turbine at a slow rate. The rate increases at the fourth stage but the material deterioration at the leading edge on the rotor blades there is around 0.1-0.15 mm/year [40]. The last stages rotor blades in the steam turbines at Hellisheiði power plant have a stellite shield strip at their leading edge. It is possible to replace or repair the stellite shield strip if the material deterioration has not propagated to the blade base material beneath the strip but in that case it could be necessary to replace the blade. Therefore this wear needs to be monitored carefully.

Both the last stages rotor blades in the low pressure turbine and in the high pressure turbines have stellite coating on the leading edge. It is interesting that the last stages rotor blades in the low pressure turbine experience less wear rate than the ones in the high pressure turbines. This indicates that the draining system in the low pressure turbine manufactured by Toshiba, which is described in the Diaphragms section in Chapter 4.4, is more effective than the one in the turbines manufactured by Mitsubishi. However, there could be other explanations. For example, different length of rotor blades or different working environment, with regard to pressure and temperature, could have effect. Information from the manufactures about other design features that could reduce erosion is also not available.

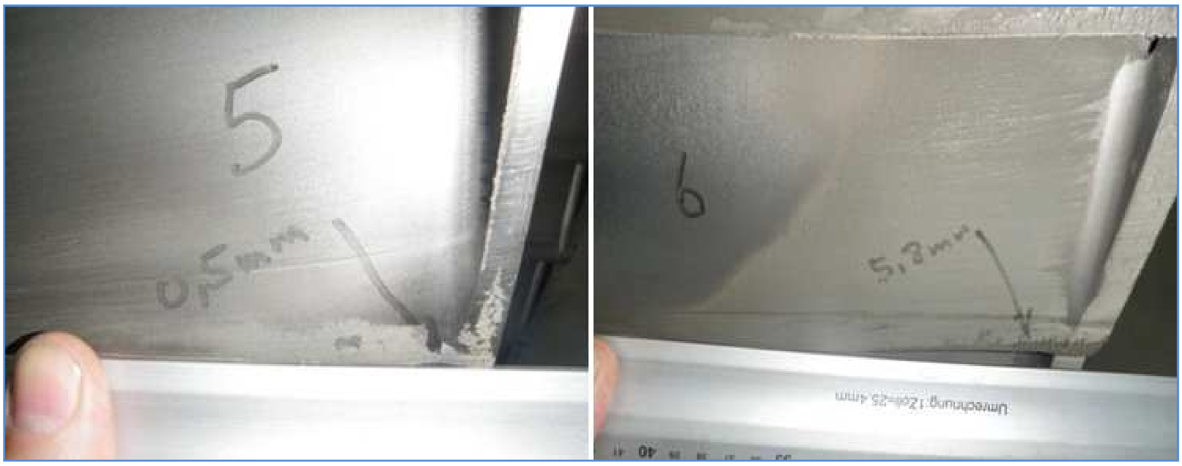


Figure 4.17 *Both pictures are from turbine 1 at Hellisheiði power plant. Left, material deterioration at a fifth stage rotor blade. Right, material deterioration at a sixth stage rotor blade [41].*

The rate of the wear on the last stages rotor blades and the labyrinth seals at the first stages is worrying. If the turbines continue to operate under unchanged conditions either a costly repair or replacement of the rotor blades and the labyrinth seals is foreseeable after few years. The failures, which have occurred on the rotor blades in the steam turbines at Hellisheiði power plant, are summarized in Table 4.4. Table 4.4 only represents failures that are common or predominating when it comes to maintenance. It is thus possible that other failures occur at the rotor blades although they are not listed in the Table 4.4. The same method is used to estimate the “Time until repair is needed” factor as in Table 4.2. Erosion is the most common problem but cracks and scaling are also found at the rotor blades. The rotor blades can operate safely for more than 8 years [40] but it would, however, be well worth considering to repair them sooner. That way more expensive and complex repairs in the future could be avoided. No corrosion on the rotor blades can be explained with short operation time of the turbines.

Table 4.4 *Summary of failures for the rotor blades in the steam turbines at Hellisheiði power plant*

Rotor blades					
	Corrosion	Erosion	Cracking	Scaling	Time until repair is needed [years]
Labyrinth seals		X			>8
Rotor blades		X	X	X	>8

Gland seal systems

The failures and the problems in the gland seal systems in the steam turbines at Hellisheiði power plant along with their possible causes are discussed below.

A gland seal system is generally fitted with sets of labyrinth packing to reduce leakage of steam through it. These sets of labyrinth packing both wear and accumulate dirt. The wear is probably caused by solid particle erosion at the high pressure side because the steam there is relatively dry. However, this wear is probably a combination of solid particle erosion, water droplet erosion and corrosion at the low pressure side. Both solid particles and water droplets are in the steam at the turbine outlet, which along with an acceleration of the steam that flows through the labyrinth packing as can be seen in Figure 2.6 in Chapter 2.2, support this. The corrosion can be caused by air which flows in the gland seal system at the low pressure side or it may be caused by condensation of corrosive gases.

The casings around the labyrinth packing both accumulate dirt and wear. The wear is mainly found around the labyrinth packing. This is probably due to the same causes as are responsible for the wear of the labyrinth packing. The casings in the low pressure turbine, however, wear less than the ones in the high pressure turbines. This can be explained with different construction materials. The casings in the low pressure turbine are made of stainless steel but the ones in the high pressure turbines are made of carbon steel.

There are scaling and wear problems in the pipes, which either transport steam from the gland seals to the condenser or transport steam into the gland seals. It seems that the slant of the pipes has effect on the scaling problems and the pipes accumulate more scaling if their incline is not sufficient [40]. An example of scaling in such a pipe can be seen in Figure 4.18.

Figure 4.18 *Scaling in the pipe, which transports the steam from the high pressure gland seal to a condenser, for the low pressure turbine manufactured by Toshiba at Hellisheiði power plant [41].*

The failures, which have occurred in the gland seal systems in the steam turbines at Hellisheiði power plant, are summarized in Table 4.5. Table 4.5 only represents failures that are common or predominating when it comes to maintenance. It is thus possible that other failures occur in the gland seal systems although they are not listed in Table 4.5. The same method is used to estimate the “Time until repair is needed” factor as in Table 4.2. It can be seen that a turbine cannot be operated for more than 8 years without repairing the gland seal systems for it. Scaling is the most common problem. The labyrinth packing and the casing also corrode and erode. No cracks were found in the gland seal systems which was not surprising as they are not highly stressed.

Table 4.5 *Summary of failures for all the components in the gland seal systems for the steam turbines at Hellisheiði power plant*

Gland seal systems					
	Corrosion	Erosion	Cracking	Scaling	Time until repair is needed [years]
Labyrinth packing	X	X		X	4-8
Casings	X	X		X	4-8
Pipe system	X			X	4-8

Casings and bearings

The failures and the problems in the casings and the bearings in the steam turbines at Hellisheiði power plant along with their possible causes are discussed below.

The attachments for the diaphragms both accumulate dirt and wear. Most of the dirt is found at the attachment for the first stages diaphragms. The dirt is probably associated with scaling, which seems to accumulate forwards in the turbines. The wear is most likely caused by solid particle erosion or water droplet erosion or a combination of these two. Most dirt accumulation is found in the low pressure steam turbine. One likely explanation is that the low pressure steam turbine is operated in another working environment than the high pressure turbines. Thermodynamic quantities like temperature and pressure are for example different. Another likely explanation is that the low pressure turbine uses steam, which is produced with “flashing”. This can cause precipitation of minerals in the steam and scaling in the turbine as is described in the Scaling section in Chapter 4.2.

The drain holes in the high pressure turbines, which are located at the diaphragm attachments in the bottom of the casing, experience wear. An example of this can be seen in Figure 4.19. The wear is most likely caused by water droplet erosion as there is relatively high amount of moisture in the steam that flows through the drain holes.

Figure 4.19 *Left, wear of a drain hole at the third stage in turbine 2 at Hellisheiði power plant. Right, wear of drain holes in turbine 3 at Hellisheiði power plant [41].*

The only problems with the pressure bearings are dirt accumulation and scratches. The main bearings had no visible damages at all. The main bearings had only been in operation for 2.5-4 years before they were inspected during overhauling of the turbines. It was thus to be expected that no wear or damages had occurred yet as this operation time is relatively short for such bearings. A pressure bearing and a main bearing can be seen in Figure 4.20.

Figure 4.20 *Left, pressure bearing from turbine 1 at Hellisheiði power plant. Right, one half of a main bearing for turbine 3 at Hellisheiði power plant [41].*

In Table 4.6 a summary of failures, which occur on the casings in the steam turbines at Hellisheiði power plant, can be seen. The bearings are not represented in Table 4.6 because they only suffered from couple of problems. Table 4.6 only represents failures that are common or predominating when it comes to maintenance. It is thus possible that other failures occur in the casings although they are not listed in the Table 4.6. The same method is used to estimate the "Time until repair is needed" factor as in Table 4.2. Scaling and erosion are the most common problems. No fractures were found on the casings, which was not surprising as they are not highly stressed.

Table 4.6 *Summary of failures in the casings for the steam turbines at Hellisheiði power plant*

Casings					
	Corrosion	Erosion	Fractures	Scaling	Time until repair is needed [years]
Diaphragm attachments	X	X		X	4
Drain holes		X			4
Casings	X			X	4-8

Discussions

Scaling is mainly found at the first stages in the turbines at Hellisheiði power plant. This indicates that more solid particles are present in the steam there than at the last stages. Droplets accumulate outwards in turbines because of centrifugal forces, their formation takes time and takes place on locations with rapid pressure drop like at the pressure side on the stator blades, as is described in the Erosion section in Chapter 4.2. The steam at the first stages in the turbines is also relatively dry. It is therefore unlikely to contain a high amount of droplets. It can thus be concluded that the wear at surfaces like the horizontal joints and the labyrinth seals, which are exposed to direct contact with steam at the first stages in the turbines, is mainly caused by solid particle erosion. It can also be concluded that the predominating cause of the wear at the last stages in the turbines is water droplet erosion. Another reason, which indicates that solid particle erosion takes place in the turbines at Hellisheiði power plant, is quartz scaling in the turbines as is already described in the Diaphragms section in Chapter 4.4. As quartz particles are considered to be hard particles, they are likely to cause solid particle erosion. It is also likely that erosion corrosion is partly responsible the wear in the steam turbines.

Table 4.7 shows the chemical composition of the brine water leaving the separators at Hellisheiði power plant but SiO_2 and Cl are the most common dissolved minerals in the brine [48]. This indicates that both SiO_2 and Cl are found dissolved in the steam that enters the turbines. The SiO_2 and Cl are thus partly responsible for the erosion and the corrosion of the steam turbines.

Table 4.7 *The chemical composition of the brine water leaving the separators at Hellisheiði power plant [48]*

Material	SiO_2	Cl
mg/kg	822	170

The low pressure steam turbine manufactured by Toshiba generally experiences less wear at the rotor blades than the high pressure steam turbines manufactured by Mitsubishi. As was already explained in the Erosion section in Chapter 4.2, droplets tend to form on the last stages stator blades. This indicates that it is more effective to drain a turbine between the stator and the rotor blades like Toshiba does than before the diaphragms like Mitsubishi does. It is, however, difficult to tell if a different draining system is the predominating factor for less wear in the steam turbine manufactured by Toshiba because other design factors, which are discussed in the Diaphragms section in Chapter 4.4, could also be responsible.

The diaphragms in the low pressure steam turbine manufactured by Toshiba also wear less than the ones in the high pressure steam turbines manufactured by Mitsubishi. Usage of stainless steel at surfaces, which are exposed to direct contact with steam, can explain this. The experience of the employees at Hellisheiði power plant is that stainless materials seem to have good resistance against wear.

It is known that solid particles can be partly "washed" from steam by increasing its moisture and removing the droplets from the steam for example with a moisture separator. It is possible that this mechanism occurs in a steam turbine. This could be explained in the following way: The wetness of steam increases through a steam turbine and water droplets form, the solid particles in the steam are carried with these droplets beside the stages of the turbine through its draining system. This could explain why there are less scaling problems at the last stages in the steam turbines at Hellisheiði power plant.

4.5 Repairs of the steam turbines at Hellisheiði power plant

The actions that were taken to repair the failures and problems in the steam turbines at Hellisheiði power plant will be discussed in this chapter. Each component of the steam turbines was looked at individually. All the information in this chapter was obtained from visiting and interviewing the employees of the following companies: Hellisheiði power plant, VHE, Vélvík, Framtak, Klettur and NMÍ.

General information

In order to repair or obtain a steam turbine component at Hellisheiði power plant one has two options and the first one is to construct or repair the component either on-site or at nearby workshop. The second option is either to let a company specialized in the maintenance of steam turbines like Turbocare or Sulzer carry out this work or the original component manufacturer.

Both specialized companies and the original manufacturer possess decades of experience and knowledge along with specialized equipment and machines, which are not available in Iceland today, to maintain and repair steam turbines. Some problems are, however, associated with those parties. The waiting time for repairs or new components can be long, especially by the original manufacturer. The waiting time for spare parts from Mitsubishi can for example be from 2-3 months up to 1.5 years [49]. This is common as turbine manufacturers rarely have parts in stock because of the variety of turbines that they produce. Mitsubishi has recently established a workshop in Belgium for the maintenance of steam turbines in order to improve their aftermarket service. High price is another problem. Price of repairs or components from foreign companies follows both the energy price in the world and the demand. This means that those prices are high for Icelandic power companies as the energy price in Iceland is relatively low in comparison to the world [50]. Transport costs and a high exchange rate only add more expenses.

Icelandic companies possess a lot of equipment and machines, which can be utilized for the maintenance of steam turbines. However, more experience and knowledge along with some machines are required to perform complete maintenance of steam turbines domestically. One of the main advantages of Icelandic workshops is a short waiting time. Vélvík was for example able to produce a set of labyrinth packing for the gland seal system at the low pressure side in one of the steam turbines at Nesjavellir power plant in five days.

A common problem when it comes to the maintenance of steam turbines is lack of information from the original manufacturer. Generally no manuals or instructions regarding maintenance of steam turbines are provided. This means that no or little information about things like time intervals between overhauls, execution of dismantling and repairs of components are available. This makes maintenance without help from the original manufacturer or a specialized company difficult.

The components in the steam turbines at Hellisheiði power plant often accumulate scaling, dirt and rust as was already described in Chapter 4.4. This has to be cleaned during the overhaul of the steam turbines. Previously high-pressure washing was used but today sandblasting with garnet sand is applied. This method has shown good results but as far as the author knows, no studies have been made to explore the effects of sandblasting on the surface of the components.

Diaphragms

The actions and the methods that are available in Iceland to repair the diaphragms in the steam turbines at Hellisheiði power plant are discussed in this section.

Mainly two methods are available to repair wear on horizontal joints. One method is to weld the damaged area with tungsten inert gas (TIG) welding. The filler rod, which is generally used, is ER309Mo. ER309Mo is stainless steel with 12% C, 23-35% Cr and 12-14% Ni [51]. The second method is to cover the horizontal joints with filler material. It is considered that this will make them more robust and resistant against wear and thus lengthen their lifetime. This is done in the following way: they are milled down, welded with TIG welding where ER309Mo is used as filler and at last milled down to the original height and shape. Figure 4.21 illustrates a diaphragm during such a repair and Figure 4.22 shows a diaphragm before and after such a repair. Welding repairs of the horizontal joints in the steam turbines at Hellisheiði power plant are generally carried out on-site by the power plant's maintenance staff. The above mentioned methods have already been applied on the steam turbines at Nesjavellir power plant and they have reduced the wear rate of the horizontal joints.

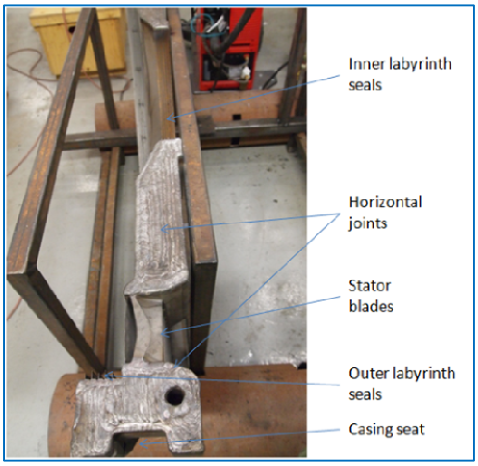


Figure 4.21 *The first stage diaphragm from turbine 3 at Hellisheiði power plant after welding. The horizontal joint still has to be milled down to the original height and shape.*

Figure 4.22 *Both pictures are of the horizontal joint on the second stage diaphragm in turbine two at Hellisheiði power plant. Left, the horizontal joint before repair. Right, the horizontal joint after repair [41].*

Welding repairs can cause problems because welding introduces the threat of high residual stresses and distortion of the welded object [52]. Extensive welding increases the risk. This has been the case with the diaphragms in the steam turbines at Hellisheiði power plant but they have sometimes become distorted during welding repairs. This can lead to them not fitting in the steam turbine casing during assembly. Some actions are available to decrease the adverse effects of welding. The diaphragms can be heated before welding, the welding can be made piecewise and the diaphragms can be cooled down slowly after the welding process is finished. Framtak has also been experimenting with a new method to repair horizontal joints on diaphragms and then Wencon repair materials are used to repair damaged areas. Wencon materials are epoxy based repair compounds to rebuild and protect surfaces exposed to wear, corrosion or cavitation. Wencon materials have excellent adhesion to all materials, except soft plastic [53]. This method does not include welding and the problems associated with it can thus be avoided. This method was applied to one of the steam turbines in Reykjanesvirkjun during its last overhaul but the result will not be available until the turbine is overhauled again.

Mainly two methods are available when repairing wear in casing seats. One method is to use TIG welding with ER309Mo filling material to repair the damaged areas but this method is not preferable if the damages are extensive because of the already mentioned problems associated with welding. The second method is to reconstruct the damaged area with some stronger material to prevent further problems in the future. To do that the damaged area is milled down and a piece made of stainless steel is constructed to weld over it. The welding that is required is minimized with this method and so is the risk of distortion and residual stresses in the object that is being welded. This way the casing seat is also covered with stainless steel, which is considered to be more robust and resistant against wear than the original carbon steel in the diaphragms. It is believed that this will lengthen the lifetime of the casing seat. An example of this can be seen in Figure 4.23. VHE carries out the milling work of the diaphragms in the steam turbines at Hellisheiði power plant but the welding is done on-site by the maintenance staff at the power plant.

Figure 4.23 *Both pictures are of a diaphragm from a steam turbine at Nesjavellir power plant. Left, wear in a casing seat, the side of the seat has been milled down. Right, here a piece of stainless steel is being welded over the side of the casing seat.*

The wear on the sides can be repaired in two different ways. One way is to use TIG welding with ER309Mo filling material to repair the wear but welding is not a preferable method as already described. The second way is to weld a shield made of stainless steel over the damaged area. An example of such a repair can be seen in Figure 4.24. The second method has been used to repair the sides on the diaphragms in the steam turbines at Nesjavellir power plant and has reduced the wear rate of the sides greatly [10]. The repairs of the sides on the diaphragms in the steam turbines at Hellisheiði power plant are carried out on-site by the maintenance staff at the power plant.

Figure 4.24 *Left, the fourth stage diaphragm from turbine 2 at Hellisheiði power plant. Right, new diaphragm for the fourth stage in turbine 2 at Hellisheiði power plant with a shield to prevent erosion damage [41].*

Fractures in stator blades can be repaired with TIG welding with ER309Mo as a filling material. Welding a stator blade on a diaphragm is, however, a demanding work. As described earlier, welding induces stresses because of the high temperature changes involved. Later on, those stresses can cause new fractures to form with possible severe effects. The maintenance staff at Hellisheiði power plant has designed and built a cooling element to cool the stator blades during welding to solve this problem but one method to decrease residual stresses in a welded object is to cool it during welding. The cooling element is made of two units cooled with water. By doing this, both sides of the stator blades can be cooled during welding. This equipment can be seen in Figure 4.25. The wear at the inner and the outer roots at the stator blades can also be repaired with TIG welding with ER309Mo as a filling material. At Hellisheiði power plant this repair is conducted by the maintenance staff at the power plant as well. Orkuveita Reykjavíkur has also designed and built equipment, which can be seen in Figure 4.26, to support and rotate the diaphragms during welding repairs. It is considered that welding the diaphragms with this equipment will cause less distortion. Diaphragms where the stator blades or the roots at the stator blades have been repaired with welding are yet to be installed in a turbine so it is not yet known if those repairs are compatible with original components.

There is an ongoing project regarding the stator blades in the steam turbines at Hellisheiði power plant. The aim is to evaluate whether it would possible and profitable to construct them in Iceland or not, but a new stator blade from Mitsubishi costs around 24,000 USD [10]. This project is being conducted by Orkuveita Reykjavíkur, Vélvík and NMÍ and is sponsored by Rannís. The stator blade, which is under consideration, can be seen in Figure 4.26. Orkuveita Reykjavíkur is studying the market for this in Iceland and the profitability. They believe that the demand for stator blades for steam turbines in Iceland is sufficient and the production of them would be profitable. NMÍ is doing research on how such a stator blade is manufactured, for example, which surface treatments are used, which materials and which machines. Vélvík is assessing whether they are able to construct a stator blade or not. This includes the making of a 3D CAD model of a stator blade and the construction of it. They believe that they can construct stator blades and that the manufacturing time would be around 5-6 hours.

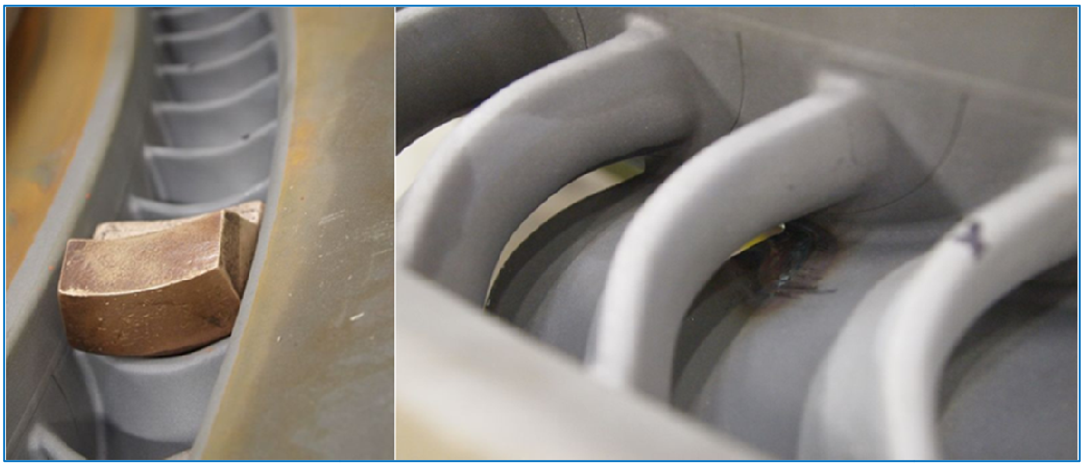


Figure 4.25 *Left, cooling element to cool stator blades on a diaphragm during welding. Right, the stator blades on the first stage diaphragm in turbine 3 at Hellisheiði power plant after welding.*

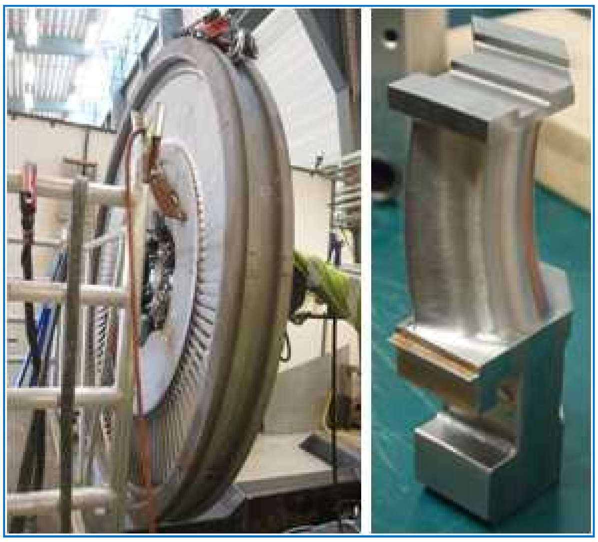


Figure 4.26 *Left, diaphragm from a turbine at Hellisheiði power plant during welding repairs in specially designed equipment. Right, a stator blade for one high pressure steam turbine at Hellisheiði power plant.*

The fins in a labyrinth seal wear during operation. They are very thin as can be seen in Figure 4.27 and are thus hard to weld but it is relatively easy to replace them. They are therefore generally replaced for new ones. Previously at Hellisheiði power plant, original fins were purchased from Mitsubishi for around 4200 USD/piece [10]. However, in 2012 it was decided to start producing them on-site because of this high price. The workshop 3X was hired to design and build a machine to construct the fins. This project was successful and the machine was completed in February 2013.The fins can now be constructed on-site for only around 430 USD/piece [10]. The fins are made of duplex steel. Although the fins can be made on-site they still need to be mounted in a turbine and tested to see if they function as well as fins purchased from Mitsubishi.

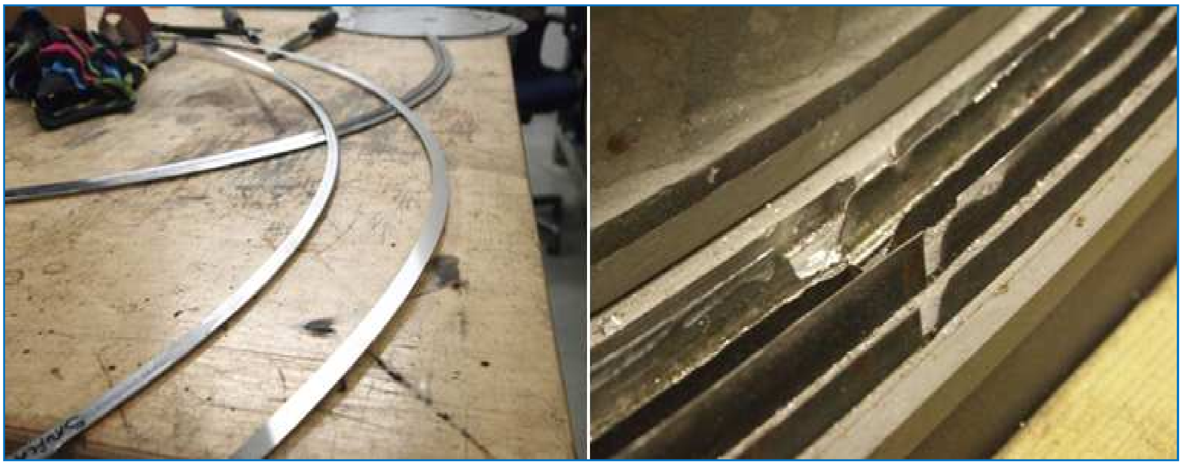


Figure 4.27 *Left, labyrinth fins made on-site at Hellisheiði power plant. Right, worn outer labyrinth fins on a diaphragm from a steam turbine at Hellisheiði power plant.*

The price of rebuilding a diaphragm in Iceland is around 30,000 USD but outsourcing it to a foreign company costs around 60,000-70,000 USD [10]. Sending a diaphragm to a specialized foreign company for repair is also not a guarantee for quality. Diaphragms have for example come back distorted after such repairs. It is though profitable to rebuild diaphragms as the price of a new diaphragm is around 240,000 USD [10].

A summary of the local and the on-site ability to repair the diaphragms in the steam turbine at Hellisheiði power plant can be seen in Table 4.8. "N/A" means that the included action is not applicable for that component. The "Can be fully repaired" column states whether the repair for the included component is compatible with the original component or not. The "Is being developed" column states that the included component can be repaired but the applied repair method or other repair methods are being developed and it is not yet known if the repairs either will be or are compatible with an original component. It can be seen that all the components of the diaphragms can be either repaired or replaced locally or on-site. However, not every part can be fully repaired. For example only minor repairs can be performed on the stator blades and their roots but more complex repairs are still being developed.

Table 4.8 *Summary of the on-site and the local ability to repair the diaphragms in the steam turbines at Hellisheiði power plant.*

Diaphragms							
	On-site and local ability				Status of repair		
	Can be repaired	Can be replaced	Can be constructed	Cannot be repaired	Only minor repairs	Can be fully repaired	Is being developed
Stator blades	X				X		X
Casing seats	X	N/A	N/A			X	
Roots for stator blades	X	N/A	N/A		X		X
Inner labyrinth seals		X	X	X	N/A	N/A	N/A
Outer labyrinth seals		X	X	X	N/A	N/A	N/A
Sides	X	N/A	N/A			X	
Horizontal joints	X	N/A	N/A			X	

Rotors and rotor blades

The actions and the methods that are available in Iceland to repair the rotors and the rotor blades in the steam turbines at Hellisheiði power plant are discussed in this section.

Almost no repairs on rotors or rotor blades are carried out in Iceland today. The reason is that a sufficiently large lathe and a balancing machine are not available. Any repairs made on a rotor or a rotor blade can cause a mass unbalance of the rotor, which can make it inapplicable. Thus a rotor generally has to be balanced with a balancing machine after each repair. Repairs of rotors and rotor blades have until now only been carried out by companies like Turbocare and Sulzer or the original manufacturer, which are specialized in such repairs. Rebuilding or repairing rotors is also expensive, both the transport and the repair itself. The cost today can be around 1,600,000 USD [10].

Transporting a rotor from Iceland to a foreign county for repair is time consuming, expensive and introduces the risk of damaging the rotor. This means that damage on a rotor blade like wear on the backside of the leading edge is not repaired during each overhaul. It would both take longer time than the 4 weeks that the overhauling takes and be too expensive. Operators prefer to wait until the wear on a rotor and its blades is considered sufficient enough for the rebuilding of the rotor to be inevitable. This way more repairs can be made on a rotor in one trip to a service company. However, this increases the risk that components like rotor blades either require a considerable repair or can be too worn to repair and need to be replaced for new ones with associated cost. It would thus be more practical to carry out repairs of a rotor and rotor blades on-site or at nearby workshops during the overhauling of a turbine. In this way, small damages like wear in rotor labyrinth seals and rotor blades could be repaired at early stages. This would increase the lifetime of the rotor and its components. Figure 4.28 shows the rotor from steam turbine 2 at Hellisheiði power plant.

Figure 4.28 *The rotor from turbine 2 at Hellisheiði power plant during overhauling of the turbine [41].*

Even if a rotor is repaired by a specialized company, this does not guarantee quality. This was the case with the rotor from turbine 2 at Nesjavellir power plant. When it was overhauled after around 4 years of operation after being rebuilt by Sulzer, a severe wear of the seal surface on the low pressure side was discovered with the material loss then being around 3 mm. It is believed that a material with insufficient corrosion resistance was selected to rebuild the surface.

The summary of repairs for the rotors and the rotor blades in the steam turbines at Hellisheiði power plant can be seen in Table 4.9. “N/A” means that the included action is not applicable for that component. It can be seen that no part of a rotor can be repaired or replaced on-site or locally today. Table 4.9, however, only takes into consideration the ability of local companies or the maintenance staff at Hellisheiði power plant.

Table 4.9 *Summary of the on-site and the local ability to repair both the rotors and the rotor blades in the steam turbines at Hellisheiði power plant*

Rotor and rotor blades				
	On-site and local ability			
	Can be repaired	Can be replaced	Can be constructed	Cannot be repaired
Labyrinth seals (on rotor)		N/A	N/A	X
Rotor blades				X
Seal surfaces		N/A	N/A	X
Labyrinth seals (on blades)		N/A	N/A	X
Rotor drums		N/A	N/A	X

Gland seal systems

The actions and the methods that are available in Iceland to repair the gland seal systems in the steam turbines at Hellisheiði power plant are discussed in this section.

Mainly two methods are available when repairing wear in a casing for a gland seal system. One method is to weld the damaged areas with MIG or TIG welding and the maintenance staff at Hellisheiði power plant can perform this work. The evidence from Nesjavellir power plant indicates that the casings repaired with this method are as good as the original ones. This method has, however, been problematic as it causes distortion of the casings being repaired, which is hard to repair. The second method is to repair the wear with Wencon repair materials. Framtak has been developing that method. It is promising and has shown good results but it is not yet known if the casings, which are repaired with this method, are compatible with original casings.

There is an ongoing project, which aims at improving the casings for the gland seal systems in the steam turbines at Hellisheiði power plant. The idea is to cover the inner side of the casing with more robust material as it suffers the highest wear rate. This is done in the following way: The inner side of the casing is milled a few millimeters down. Then an attachment for a new replaceable inner casing is constructed in the old casing and a new replaceable casing, which is made of robust steel with seats for the labyrinth packing, is installed in the old casing. In this way, a component susceptible to wear may be changed in a simple and quick way like sacrificial anodes on boats and is constructed of more robust material than the original one. A casing that has been rebuilt with this method can be seen in Figure 4.29. This work is being conducted by Framtak and the result so far is promising. However, a casing that has been improved with this method is yet to be fitted in a turbine at Hellisheiði power plant. It is thus not known if a casing that has been improved in that way is compatible with an original one.

It is hard to repair labyrinth fins as was already explained in the Diaphragms section in Chapter 4.5. Furthermore, the labyrinth fins on the labyrinth packing are not exchangeable like the ones on the diaphragms. The labyrinth packing is made of 6 segments, which can be seen in Figure 4.30 and they can be changed. The segments in the labyrinth packing for the gland seal systems in the steam turbines at Hellisheiði power plant were previously purchased from Mitsubishi but today they can also be manufactured by Vélvík. One set of such labyrinth packing has already been constructed and installed in a steam turbine at Nesjavellir power plant. It will, however, not be known if the labyrinth packings, which are manufactured by Vélvík, are compatible with the original ones until the next overhaul of that turbine is carried out. The final cost of producing those labyrinths packings domestically is not yet known, as Vélvík has just started producing them. The first cost estimate, however, indicates that the cost of a labyrinth packing manufactured by Vélvík will be a lot less than of a one manufactured by Mitsubishi [10].

Figure 4.29 *Left, repaired casing with new labyrinth packing made by Vélvík and a new replaceable inner casing made by Framtak. Right, an enlarged view of the new inner casing.*

Figure 4.30 *Left, repaired casing with labyrinth packing manufactured by Vélvík ready for installation. Right, new labyrinth seals for a labyrinth packing made by Vélvík ready for installation [41].*

Summary of repairs for the gland seal systems in the steam turbines at Hellisheiði power plant can be seen in Table 4.10. “N/A” means that the included action is not applicable for that component. The “Can be fully repaired” and the “Is being developed” columns represent the same as in Table 4.2. It can be seen that all components of the gland seal systems can either be repaired or replaced on-site or locally. Although the labyrinth packings can be constructed locally it is not yet known whether they are completely comparable to original ones. Their construction is therefore still in development.

Table 4.10 *Summary of the on-site and the local ability to repair the gland seal systems in the steam turbines at Hellisheiði power plant*

Gland seal systems							
	On-site and local ability				Status of repair		
	Can be repaired	Can be replaced	Can be constructed	Cannot be repaired	Only minor repairs	Can be fully repaired	Is being developed
Labyrinth packings	N/A	X	X				X
Casings	X	X				X	X
Pipe systems	X	X	X			X	

Casings and bearings

The actions and the methods that are available in Iceland to repair the casings and the bearings in the steam turbines at Hellisheiði power plant are discussed in this section.

It is mainly one method, which is available for repairing the wear at the drain holes in the casings for the steam turbines at Hellisheiði power plant. Either drill them in oversize or drill new holes beside the old ones and weld cylinders made of stainless steel in the holes. This can be seen in Figure 4.31. This will make it easier to repair the drain holes in the future because the cylinders can simply be replaced by new ones. This method has already been applied to the steam turbines at Nesjavellir power plant and it has reduced the wear rate of the drain holes in them [10].

Figure 4.31 *Left, drain holes in a diaphragm attachment in turbine two at Hellisheiði power plant with stainless steel cylinders fitted in. Right, drain holes in a diaphragm attachment in turbine one at Hellisheiði power plant after being repaired with stainless steel cylinders [41].*

It is mainly one method, which is available for repairing the wear on the attachments for the diaphragms in the steam turbines at Hellisheiði power plant. Weld them with MIG or TIG welding and polish them down to the original shape. This can be made by the maintenance staff at Hellisheiði power plant. In Figure 4.32 a diaphragm attachment before and after such a repair is shown. It is important that a surface on the side of an attachment is flat, else leakage between the diaphragm and the casing is likely to occur, which can cause erosion damage. Previously this work was done by hand but the results were not satisfying because the repaired attachment often eroded. A special polishing machine was thus designed and built by Héðinn to polish the sides of the attachments in the steam turbines at the power plants at Hellisheiði and Nesjavellir. This machine can be seen in

Figure 4.33. Diaphragm attachments in the steam turbines at Nesjavellir power plant that have been polished with this machine have not eroded [10]. Wear at other locations in a casing can either be welded and polished by the maintenance staff at Hellisheiði power plant or repaired with Wencon repair materials by Framtak.

Figure 4.32 *Left, wear at the diaphragm attachment in turbine two at Nesjavellir power plant. Right, diaphragm attachment in turbine two at Nesjavellir power plant after welding and polishing [41].*

Figure 4.33 *Polishing machine to polish diaphragm attachments in a casing of a steam turbine [41].*

The pads in the journal bearings can be replaced with new ones when they are too worn for further usage. This can be carried out by the maintenance staff at Hellisheiði power plant. However, the mechanism that supports the pads in the bearings is complicated, which means that it can be problematic to replace them.

Summary of repairs for the casing and the bearings in the steam turbines at Hellisheiði power plant can be seen in Table 4.11. “N/A” means that the included action is not applicable for that component. The “Can be fully repaired” and the “Is being developed” columns represent the same as in Table 4.2. It can be seen that every part of the casings or the bearings can be fully repaired or replaced either on-site or locally.

Table 4.11 *Summary of the on-site and the local ability to repair the casings and the bearings in the steam turbines at Hellisheiði power plant.*

Casings and bearings							
	On-site and local ability				Status of repair		
	Can be repaired	Can be replaced	Can be constructed	Cannot be repaired	Only minor repairs	Can be fully repaired	Is being developed
Diaphragm attachments	X	N/A	N/A			X	
Drain holes	X	X	X			X	
Casings	X					X	
Bearing pads		X		X			

Discussions

Repairs of all stationary parts in the steam turbines at Hellisheiði power plant can be made in Iceland, either by local workshops or the maintenance staff at Hellisheiði power plant. However, no repairs on moving components like rotor and rotor blades can be made and only few components can be manufactured. However, many of the repaired or manufactured components are either being tested in operation or are yet to be tested in operation. It is therefore not yet known in many cases if a component either repaired or manufactured locally or on-site, is compatible with an original component.

Outsourcing repairs to foreign companies specialized in repairs of steam turbines has often given good results. It is, however, no guarantee of quality as mentioned in the Diaphragms and Rotors and rotor blades sections in Chapter 4.5. The experience also shows that it is less expensive to repair or construct components in Iceland than by foreign companies or the original manufacturer.

As mentioned in the Rotors and rotor blades section in Chapter 4.5, both a lathe and a balancing machine are required if repairs of rotors and rotor blades are to be carried out in Iceland. With a lathe and a low speed balancing machine simple repairs of rotors could be carried out. Simple repairs of a rotor are for example welding and polishing of fractures and small wear at rotor blades, replacing of rotor blades, welding of rotor labyrinths and welding or coating of seal surfaces on a rotor. However, sufficient knowledge of how to maintain and repair steam turbine rotors is still not available in Iceland. Orkuveita Reykjavíkur is interested in both building up this knowledge and purchasing the required equipment, either in cooperation with local workshops and power companies or on their own. Orkuveita Reykjavíkur has been exploring if it is economical to purchase such machines. They estimate that a large enough lathe and a low speed balancing machine for rotor repairs along with training to use them would cost around 2.000.000 USD. This is a high startup cost. Nevertheless, Orkuveita Reykjavíkur estimates that the payback time would only be some years.

Some experiments are being made in order to improve stationary parts in the steam turbines at Hellisheiði power plant. The aims of these experiments are to lengthen the lifetime of stationary turbines parts, make them easier to repair and solve problems associated with them. Surfaces like the horizontal joints and the casing seats on the diaphragms, which suffer from high wear rate and are in direct contact with steam, are for example being rebuilt with stainless steel. However, in many cases it is not yet known if the experiments are successful although early results are promising.

TIG welding is a commonly used method to repair steam turbine components at Hellisheiði power plant. Welding with TIG is, however, not a preferable method to weld steam turbine components as already described in the Diaphragms section in Chapter 4.5. Orkuveita Reykjavíkur has recently purchased equipment to anneal parts and Cold Metal Transfer (CMT) welding equipment. Annealing is a method that reduces residual stresses in a welded object. CMT is a relatively cold welding method compared with conventional arc welding methods like MIG and TIG. This means decreased risk of residual stresses and distortion of the welded object. Other welding techniques, which are used to repair turbine components and cause less residual stresses and distortion than MIG and TIG, like submerged arc welding and narrow groove welding, are also something that could be worth exploring [54, 55].

Repairs with wencon repair materials are new in Iceland and it will be exciting to see if these repairs are successful. It will also be interesting to see how they turn out in comparison with welding repairs.

Both the surveillance and the condition evaluation of steam turbine components at Hellisheiði power plant, especially with regard to cracks, have to be improved. Today, the most applied inspection method either to identify fractures in components or fractures after welding is dye penetrant inspection. However, this method only detects surface fractures and can therefore be unreliable, especially when welding repairs are inspected. The surveillance at Hellisheiði power plant has been improving and cooperation with companies, which conduct condition evaluation and non-destructive testing, like NMÍ, has been increasing. The feasibility of applying more developed Non Destructive Testing (NDT) methods than dye penetrant inspection to identify defects like fractures is something that is worth considering, especially for highly stressed components. Such methods are, for example, eddy current testing, ultrasonic testing and phase contrast imaging. The establishment of those methods is, however, costly and time consuming. Detailed data and information regarding the inspected components have to be present if NDT is to give accurate results. It is often difficult to get that information from either the original manufacturer or specialized workshops. NDT also requires experienced staff. One possible way to establish NDT for the steam turbines at Hellisheiði power plant would be to perform them in cooperation with Icelandair Technical Service (ITS). ITS employees have decades of experience and knowledge when it comes to NDT and the equipment required. Data and information concerning the objects, which require inspection, still would have to be acquired. Another option is to hire a foreign company specializing in NDT to carry out this work.

The choice of materials to repair steam turbine components is of great importance. This is often a difficult task because information about the exact chemical composition of components is hard to obtain. This is of great importance in steam turbines, which are working in a temperature range from 100-300°C. Clearances in a steam turbine can also be down to some parts of millimeters. Material composition of components in a steam turbine is thus chosen so every part of the turbine expands in similar way when it is started up to avoid contact between parts or thermal stresses. The material that is used to repair or build a component therefore needs to have a similar coefficient of thermal expansion as the material in the original component. Problems can arise if this is not done correctly. The employees at Hellisheiði power plant have for example both been working with experts in material science in Icelandic companies like NMÍ and in foreign companies in this field when it comes to deciding, which materials should be used for repairs.

4.6 The ability of local workshops to repair the steam turbines at Hellisheiði power plant

In this chapter the ability to repair steam turbines in Iceland will be discussed. Ideas for the next steps in the maintenance of steam turbines are also represented. The information in this chapter is obtained from Vélvík, Framtak and VHE. These are three workshops, which have been participating in the maintenance of Hellisheiði power plant and are interested in further developing the maintenance of steam turbines in Iceland.

Framtak is a workshop that has been servicing the Icelandic geothermal industry since 2000 and has both experience in installing and overhauling steam turbines. They have much general knowledge when it comes to welding and annealing of objects. Furthermore, Framtak has been doing experiments to repair components in steam turbines with Wencon materials instead of welding. Framtak is also with considerable experience in repairing and balancing turbochargers and pumps.

Vélvík is a workshop that has been producing components like labyrinth packing and bolts for the steam turbines at Hellisheiði power plant. They have a high quality lathe and milling workshop and are very much experienced in producing complicated objects for companies like Marel and Össur. Vélvík also owns a simple 3D scanner.

VHE is a workshop, which is not much used to repairing steam turbines but they are a capable company and are interested in participating in steam turbine repairs. They have a lot of experience when it comes to welding. VHE also has an engineering department.

An overview over the ability of VHE, Framtak and Vélvík to machine objects with a lathe or a milling machine can be seen in Table 4.12 and in Table 4.13. It can be seen that VHE has the largest milling machine but Framtak has the largest lathe. Vélvík cannot manufacture or repair as large objects as VHE and Framtak. Vélvík can, however, manufacture objects with more accuracy.

Table 4.12 *Overview over the ability of VHE, Framtak and Vélvík to machine objects with a lathe*

		Company		
Ability	**Lathe**	VHE	Framtak	Vélvík
	Length [m]	4	6	2
	Diameter [m]	0.71	1.2	0.4
	Precise [mm]	0.01	0.01	0.001

Table 4.13 *Overview over the ability of VHE, Framtak and Vélvík to machine objects with a milling machine*

Company				
Ability	**Milling**	VHE	Framtak	Vélvík
	Table Length [m]	5	0.5	2.5
	Table width [m]	2.2	0.7	0.82
	Height [m]	3	1.2	0.72
	Precise [mm]	0.01	0.01	0.001

As already stated in the Rotors and rotor blades section in Chapter 4.5, almost no repairs can be made on rotors and rotor blades in Iceland although the need is present and will only grow as was described in Chapter 1. Two things are required, if maintenance of rotors is to be carried out in Iceland. The first thing is a sufficiently large lathe and a balancing machine. The second thing is the knowledge and the experience of how to perform such repairs. It is estimated that a lathe, which could also serve as a low speed balancing machine, would cost around 1,200,000 USD [10]. The cost of building such a lathe in Iceland is estimated to be around 167.000 USD [56] but the possibility of it has not been evaluated. Building a lathe that would fit into a container and could be transported on-site is also an idea that has come up. That way transportation of rotors, which is risky, could be ceased.

There are mainly two ideas of how to establish a lathe and a balancing machine for rotors in Iceland. The first is that the power companies in cooperation with the workshops interested in the maintenance of rotors would found a company together and set up and operate the necessary equipment. The second is that one power company or workshop would purchase the equipment necessary.

In order to acquire the knowledge needed to maintain rotors and rotor blades, cooperation either with a company specialized in the maintenance of these components or with the original components manufacturer has to be established. This is, however, a difficult task as those parties are often not willing to share their knowledge. VHE has already started this development by making contact with IMPH, which is a Spanish company specialized in the maintenance of steam turbine rotors among other things. IMPH is interested in sending both staff and equipment to Iceland to teach how maintenance of rotors is carried out.

In Table 4.14 is a summary of the ability and the knowledge present in Iceland as regards repairing or constructing steam turbine components. “Equip” represents whether or not sufficient machines and tools are available in Iceland to perform the included action. “Know” represents whether or not sufficient knowledge is available in Iceland to perform the included action. “N/A” means that the included action is not applicable for that component. Table 4.14 is based on the subjective assessment of the author after interviewing employees at VHE, Framtak, Vélvík and Hellisheiði power plant. It can be seen that the equipment, which is required to construct relatively small spare parts for steam turbines like stator blades, rotor blades and labyrinth packing is available in Iceland today. Knowledge of the construction of such small spare parts is, however, in most cases only available for stationary components. The equipment required to machine steam turbine components except for a rotor is in most cases available in Iceland. However, the knowledge that is needed to machine steam turbine components is in most cases only available for stationary components. Equipment is present in Iceland to weld all steam turbine components but the required knowledge is only available for stationary components. It can, therefore, be concluded from Table 4.14 that the knowledge to repair or construct steam turbine components is in many cases not available in Iceland although the required equipment is present.

Table 4.14 *Overview over the domestic ability to repair or construct steam turbine components. Equip represents whether or not sufficient machines and tools are available in Iceland to perform the included action. Know represents whether or not sufficient knowledge is available in Iceland to perform the included action. N/A means that the included action is not applicable for that component.*

Equipment and knowledge available in Iceland							
	Components	Welding		Constructing		Machining	
		Equip.	Know.	Equip.	Know.	Equip.	Know.
Diaphragms	Stator blades	X		X		X	
	Casing seat	X	X	N/A	N/A	X	X
	Roots for stator blades	X	X	N/A	N/A		
	Inner labyrinth seals	N/A	N/A	X	X	X	X
	Outer labyrinth seals	N/A	N/A	X	X	X	X
	Sides	X	X	N/A	N/A	X	X
	Horizontal joints	X	X	N/A	N/A	X	X
Rotor and rotor blades	Labyrinth seals (on rotor)	X		N/A	N/A		
	Rotor blades	X		X		X	
	Seal surfaces	X		N/A	N/A		
	Labyrinth seals (on blades)	X		N/A	N/A	X	
	Rotor drums	X		N/A	N/A		
Gland seal system	Labyrinth packing	N/A	N/A	X	X	X	X
	Casing	X	X	X	X	X	X
	Pipe system	X	X	X	X	X	X
Casing and bearings	Diaphragm attachments	X	X	N/A	N/A	X	X
	Drain holes	X	X	X	X	X	X
	Casing	X	X			X	X
	Bearings	X				X	

4.7 Possible improvements

As a result from the case study of the maintenance of the steam turbine at Hellisheiði power plant, it is clear that some design concepts work better than other. In this chapter, an overview over possible improvements and practical designs for steam turbines in geothermal power plants is given.

An efficient draining system is important to reduce erosion due to water droplets. A draining system like the one that was described in the Diaphragms section in Chapter 4.5, where the steam is drained between the stator and rotor blades, has turned out to work well. Using hollow last stages stator blades is another thing that should be looked into to reduce moisture in the steam. Transporting the droplets that the draining system accumulates out of a turbine rather than between stages is also a possibility worth looking into. This would reduce the moisture in the steam and thus the wear that is caused by water droplet erosion. However, this would most likely reduce the efficiency of the turbine at the same time. Long last stage rotor blades generally suffer from more water droplet erosion than short ones as was described in the Erosion section in Chapter 4.2. It is therefore a question whether a double flow steam turbine is not more suitable in a geothermal power plant than a single flow steam turbine because it can be built with shorter rotor blades.

The wear of the rotor labyrinth seals can be reduced by installing a flow deflector on the diaphragms before their inlets. A flow deflector can reduce both the steam flow and steam velocity through the seals and thus the rate of solid particle erosion [24].

It is believed that by constructing all surface areas on turbine components, which are in direct contact with the steam, with a coat made of stainless steel, might lengthen their lifetime. This is already being done with surfaces on the diaphragms in the steam turbines at Hellisheiði power plant, like the horizontal joints and the inner and outer roots at the stator blades.

In order to solve the wear problem on a seal surface on a rotor, a replaceable sleeve can be built and placed over it. The sleeve can then be replaced with a new one instead of having to weld or coat the seal surface to repair the wear on it. This method would also not necessarily require a balancing of the rotor. The application of a replaceable casing, which is a similar solution, is for example already being developed for the gland seal systems in the steam turbines at Hellisheiði power plant as was described in the Gland seal system section in Chapter 4.5.

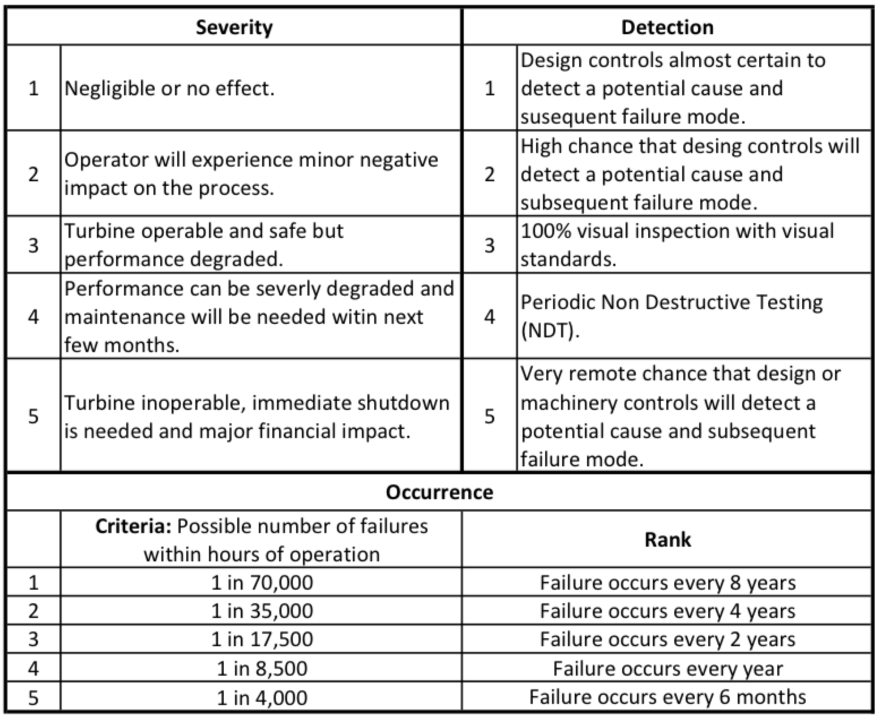
4.8 Results from an FMEA

The results from an FMEA, which was conducted for the steam turbines at Hellisheiði power plant, are represented in this chapter. The FMEA is based on maintenance reports and DMM data from Hellisheiði power plant. Interviews and meetings with the employees were also carried out in order to identify as many failure modes as possible. The resolution of the FMEA is at component level to see where further analysis is needed at part level. A criticality analysis is carried out and it is based on a ranking system adapted to the data analyzed. This FMEA is partly based on failures, which are related to the special condition at Hellisheiði power plant, and thus only applicable for the steam turbines there. It may, however, be used as a reference for similar work in other geothermal power plants.

Based on the data gathered about the steam turbines at Hellisheiði power plant, each of the criticality factors, which were described in Chapter 3.3, was given a ranking that can be seen in Table 4.15 ranging from 1 to 5. The ranking was custom-made to cover the range of the data present for the steam turbines at Hellisheiði power plant. It is based on the military standard technique (MIL-STD-882D) and adapted from the book The Basics of FMEA [37]. By multiplying the three criticality factors (severity x occurrence x detection) a Risk Priority Number (RPN) is obtained for each failure mode present. In this study the RPN number can range from 1 to 125 for each failure mode and its effects. A high number indicates that a special care needs to be taken regarding maintenance and surveillance of the component with regard to the failure mode. If a failure mode gets a high severity rating, then it has to be evaluated as well, even though a low RPN number is obtained [37].

Evaluation of parameters for each criticality factor was both qualitative and quantitative since it was based both on real data and the subjective evaluation of the author of this thesis. The complete table with evaluated parameters can be seen in Table 4.16.

T**able 4.15** *Definition of the ranking numbers for the three criticality factors (severity, detection and occurrence) in the FMEA*



Severity		**Detection**	
1	Negligible or no effect.	1	Design controls almost certain to detect a potential cause and susequent failure mode.
2	Operator will experience minor negative impact on the process.	2	High chance that desing controls will detect a potential cause and subsequent failure mode.
3	Turbine operable and safe but performance degraded.	3	100% visual inspection with visual standards.
4	Performance can be severly degraded and maintenance will be needed witin next few months.	4	Periodic Non Destructive Testing (NDT).
5	Turbine inoperable, immediate shutdown is needed and major financial impact.	5	Very remote chance that design or machinery controls will detect a potential cause and subsequent failure mode.

Occurrence		
	Criteria: Possible number of failures within hours of operation	**Rank**
1	1 in 70,000	Failure occurs every 8 years
2	1 in 35,000	Failure occurs every 4 years
3	1 in 17,500	Failure occurs every 2 years
4	1 in 8,500	Failure occurs every year
5	1 in 4,000	Failure occurs every 6 months

Erosion of diaphragms and rotor blades has the highest RPN number along with high severity number. Corrective actions to eliminate or reduce erosion of these components are therefore of worth and should be attended to first. A detailed analysis of the cause of erosion in these components would also be of value.

Erosion of rotor and casing along with scaling for casing and diaphragm and cracking in rotor blades has a medium high RPN number. Corrective actions that can eliminate or reduce those failure modes are thus not of priority. However, some actions to deal with these failure modes could be of worth considering.

Cracking in rotor blades and misalignment of rotor have high severity numbers. These failure modes should therefore be given special attention although their RPN number is not especially high. Other failure modes have a relatively low RPN number, which indicates that further analysis does not have to be made at this stage.

Table 4.16 *The results from the FMEA*

Component	Component Function	Potential Failure Mode	Potential Cause(s) of Failure	Occurrence (O)	Potential Effect(s) of Failure	Severity (S)	Detection (D)	RPN (O x S x D)
Labyrinth seals	Mechanical Sealing	Erosion	-Solid particles in the steam -Formation of droplets in the steam	3	-Performance drop -Leakage	2	2	**12**
		Corrosion	-Exposion to corrosive substances in the steam	1	-Performance drop -Leakage	1	3	**3**
		Rubbing	-Misalignment of rotor	1	-High wear rate -Damagae to labyrinth seals	2	2	**4**
Diaphragm	Convert thermal energy to kinetic energy by accelerating steam	Erosion	-Penetration of solid particles from the steam -Penetration of droplets from the steam	4	-High wear rate -Formation of fractures -Breaking of nozzles -Vibration	4	3	**48**
		Scaling	-Too dry steam -High amount of substances in steam	2	-Decreased pressure after turbine stage -Efficiency drop -Performance drop -Drop in mass flow -Vibration -Clogging of steam path	3	3	**18**
		Corrosion	-Exposure to corrosive substances in the steam	1	-Wear	2	3	**6**
Rotor Blades	Convert kinetic energy to mechanical energy	Erosion	-Penetration of solid particles from the steam -Penetration of droplets from the steam	3	-High wear rate -Formation of fractures -Breaking of blades -Vibration	5	3	**45**
		Cracking	-Fatigue -Vibration	1	-Breaking of blades	5	4	**20**
		Scaling	-Too dry steam -High amount of substances in steam	2	-Decreased pressure after turbine stage -Efficiency drop -Performance drop -Drop in mass flow -Vibration -Clogging of steam path	3	2	**12**
Bearings	Support the rotor	Wear	-Aging	1	-Vibration	2	1	**2**
		Fracture formation	-Fatigue -Vibration	1	-Damage to bearings	2	4	**8**
Rotor	Transfer mechanical energy to generator	Erosion	-Penetration of solid particles from the steam -Penetration of droplets from the steam	3	-High wear rate -Unbalanced rotor -Vibration	2	3	**18**
		Corrosion	-Exposion to corrosive substances in the steam	2	-Wear	2	3	**12**
		Misalignment of rotor	-Generator supports are skewed -Turbine supports are skewed	1	-Vibration	4	2	**8**
		Fatigue	-Ageing	1	-Fractures in blade attachments	2	4	**8**
Casing	Protects the rotor and forms the steam path	Erosion	-Penetration of solid particles from the steam -Penetration of droplets from the steam	4	-High wear rate of diaphragms attachments and drain holes	2	3	**24**
		Scaling	-Too dry steam -High amount of substances in the steam	3	-Clogging of drain holes	2	3	**18**
		Corrosion	-Exposure to corrosive substances in the steam	2	-Wear of casing	1	3	**6**

5 Conclusions

One interesting discovery in connection with the reaserch carried out for this thesis is the high wear rate of many components in the steam turbines at Hellisheiði power plant. This is especially interesting with regard to two things. Firstly, decades of experience are available in Iceland when it comes to the maintenance and the operation of steam turbines in geothermal power plants. Secondly, Orkuveita Reykjavíkur operates Nesjavellir power plant where 4 steam turbines manufactured by Mitsubishi are located. These are 30 MW, single cylinder, single flow, condensing turbines with 8 stages and top exhausts. The first two were commissioned in 1998, the third one in 2001 and the fourth in 2005 [57]. The steam turbines at Hellisheiði power plant were manufactured by Mitsubishi and were supposed to be an improved version of the steam turbines at Nesjavellir power plant. However, many of the failures, which occur in the steam turbines at Nesjavellir power plant, also occur in the steam turbines at Hellisheiði power plant. This applies, for instance, to the wear of the horizontal joints on the diaphragms, the wear at the holes in the rotor drums and the extensive wear at the last stages rotor blades. The question is therefore, why the experience from Nesjavellir power plant and the Icelandic geothermal industry was not better utilized for the design and the construction of the steam turbines for Hellisheiði power plant. Two possible explanations are that Mitsubishi did not improve the design of the steam turbines at Nesjavellir power plant enough or Orkuveita Reykjavíkur did not make enough demands for a better design.

The wear rate at the diaphragms in the steam turbines at Hellisheiði power plant is high. From the case study of Hellisheiði power plant, it can be concluded that the predominant failure mechanism is in most cases solid particle erosion. However, water droplet erosion also takes place. Thorough analysis of the chemical composition of the steam, which expands through the turbines, along with measures to reduce the amount of particles in the steam would thus be of value. It seems that the surface materials that are in to direct contact with the high velocity steam, i.e. at the horizontal joints and stator blade roots, are not suitable for the Hellisheiði power plant. The results from repairing or rebuilding these surfaces with special stainless steel alloys are promising.

The wear of the rotors in the steam turbines at Hellisheiði power plant after 2.5-4 years of operation is more than expected. Some actions are thus required if costly and time-consuming repairs of the rotors in coming years is to be avoided. From the case study of Hellisheiði power plant, it can be concluded that a combination of solid particle erosion and water droplet erosion is the cause for this wear. The wear due to water droplet erosion at the rotor blades at stages five and six is especially worrying. It indicates that the last stages rotor blades are too long, which would result in too high tip speed of the blades and thus high erosion rate. It is thus importance to consider carefully whether a double flow steam turbine or a single flow steam turbine is more appropriate when selecting a steam turbine for a geothermal power plant. Mainly two methods are available to reduce the erosion at the last stages rotor blades in a steam turbine. One is to decrease the wetness of the steam. The second is to reinforce the blades. The wetness of the steam can be decreased either by installing more efficient draining system or by expanding the steam to a higher pressure. Expanding the steam to a higher pressure would, however, reduce the power output of the turbine. Furthermore, it can be concluded that the design of the draining system in the low pressure turbine manufactured by Toshiba is more efficient than the one in the high pressure turbines manufactured by Mitsubishi. Comparison of the wear at the last stages rotor blades in the steam turbines from those two manufacturers supports this. A detailed analysis of the operation conditions of the turbines at each stage could also be worth carrying out.

Some parts of the gland seal systems and the casings in the steam turbines at Hellisheiði power plant experience high wear rate. From the case study of Hellisheiði power plant, it can be concluded that the wear of these parts is probably caused by erosion or corrosion or a combination of these two. It also seems that materials for some parts like the draining holes in the casing have not been chosen carefully enough.

It can be concluded that the right selection of materials and an efficient draining system for a steam turbine, which is to be used in a geothermal power plant, can reduce the maintenance required and thus the operation cost.

One way to build a steam turbine for a new geothermal power plant that would be adapted to the local geological conditions is to develop the turbine on-site. This can be done in the following way. If, for example a geothermal power plant is to be built with four steam turbines, only one should be commissioned in the beginning. This turbine could be monitored by both the manufacturer and the power plant staff and any defects or problems could be documented. The three remaining turbines could then be improved with regard to these defects or problems and installed 2-4 years later. This method is preferred by geologists as it gives them an opportunity to monitor the effect of utilization on the geothermal system. That way the capacity of the system can be better estimated before more turbines are commissioned and overexploitation can be prevented. Furthermore, on-site experiments with materials during construction of the power plant or development of the well field would be of a value. It can thus be concluded that the maintenance cost of steam turbines in geothermal power plant can be reduced with a good cooperation between the power company and the steam turbine manufacturer. Such cooperation could, however, increase the startup cost of the turbines. Fewer turbines in operation at the beginning also mean less electricity production and thus less income for the first years.

The maintenance staff at Hellisheiði power plant has developed the overhauling process for their steam turbines with help from experts in the Icelandic geothermal industry. This has allowed the staff at Hellisheiði power plant to organize and optimize future overhauling processes with regard to spare parts, time and expenses. Today, the overhauling of the steam turbines at Hellisheiði power plant is carried out by the staff on-site without any supervision or help from the manufacturers of the turbines. This shows that it is possible for a geothermal power plant to build up knowledge to overhaul steam turbines with their own staff.

The case study of the maintenance of the steam turbines at Hellisheiði power plant revealed that the equipment and the knowledge, which are required for simple repairs of stationary components, are available in Iceland today. It is still not yet known if many of the repaired components are compatible with original ones although early results are promising. Stationary steam turbine components are generally not highly stressed as was stated in Chapter 2.3. This means that although a repaired component is not compatible with an original one, it is unlikely that it will fail and cause severe damages in the steam turbine. Knowledge from experienced parties like the original manufacturer is thus not necessarily required to carry out simple repairs on stationary steam turbine components. Simple repairs for stationary turbine components are for example welding of casing and the replacement of labyrinth fins in labyrinth seals. Furthermore, the case study of the maintenance at Hellisheiði power plant shows that stationary steam turbine components require frequent maintenance and it is economical to repair them locally. It can thus be concluded that it is both possible and economical for geothermal power plants in Iceland to carry out maintenance of stationary steam turbine components either on-site or at nearby workshops. Construction of stationary steam turbine components is, however, a lot more complicated than simple repairs. The required equipment is in most cases available domestically but important information like material composition of components and surface treatments are often not available or hard to come by. It is possible to build some parts domestically, like the labyrinth packing in a gland seal system and the labyrinth fins for a labyrinth seal. It is, however, not yet known if those parts are fully compatible with parts made by the original manufacturer but first results are promising. Furthermore, experience indicates that parts, which are constructed locally, are less expensive than part made by foreign companies or the original manufacturer. It is not yet known if it is possible to construct stationary turbine components that are fully compatible with original ones domestically or if it would be economical in the long run. First indications are, however promising.

No repairs of rotating components in the steam turbines at Hellisheiði power plant are carried out in Iceland today although a lot of the required equipment is available. This is because most of the knowledge, which is required for maintenance and construction of these parts, is not available. Common repairs, which are required for rotors and rotor blades, are welding and machining. These components are highly stressed as was described in Chapter 2.3 and it can have severe effects if they fail. The knowledge of making specifications for welding procedures or machining these parts without causing residual stresses, distortion or reducing the original strength is, therefore, very important. Construction of rotating steam turbine components is complicated and components can cause severe damages to a turbine if they are not fully compatible with original ones. A thorough study of the cost of establishing the required equipment and knowledge has to be carried out in order to find out whether it would be economical and possible to build up an geothermal turbine maintenance industry in Iceland.

The need of building up an industry to carry out the overhauling of steam turbines in geothermal power plants and repair, replace or construct their parts is present. There are two reasons that support this. The first is that steam turbines in geothermal power plants generally require frequent maintenance as can be seen from the case study of Hellisheiði power plant. The second is that the number of components that need repairs is high. There are for example 104 diaphragms, 7 rotors and 14 gland seal systems in the steam turbines at Hellisheiði power plant. These components are then fitted with smaller parts like labyrinth seals and blades. The following are only a few of the advantages of building up a maintenance expertise for geothermal turbines in Iceland:

- Experience from Hellisheiði power plant shows that carrying out overhaul of steam turbines or repairs, replacement or construction of their parts either on-site or at local workshops is less expensive than purchasing this service either from specialized foreign overhauling services or the original manufacturer.
- Every geothermal power plant is working at specific conditions, which depend on the chemical composition of the geothermal steam. If maintenance is carried out on-site it can help the power plants to find solutions for specific problems that occur and even improve their turbines with regard to local conditions.
- This can contribute to the economy in Iceland as new jobs will be created domestically and currency can be reserved.

- Cooperation with local machine shops can be easier when it comes to overseeing of the maintenance work and communications.

There are, however, some disadvantages as well.

- The startup cost of the equipment required is high and could be difficult to fund.
- Insufficient repairs, especially on highly stressed rotating components due to lack of knowledge can have severe effects with associated costs.

It can be concluded from this case study of Hellisheiði power plant that the environment for further build-up and development of an industry for the maintenance of steam turbines in Iceland is promising. The next step in the build-up of such an industry could possibly be to establish cooperation between the power companies and the interested machine shops. That way it would probably be easier to fund the startup cost and the already existing knowledge of these parties could be combined. The required knowledge can be acquired through collaboration with either the original manufacturer or specialized workshops in the overhaul and maintenance of steam turbines. Further work regarding the subjects of this thesis could include:

1. More detailed analysis of the failures that were identified and their causes.
2. Verification of the conclusions made regarding the causes of the failures that were analyzed.
3. Analysis of each stage in the turbines with computational fluid dynamics (CFD) programs to better understand the characteristic of the steam flow.
4. Exploration of possibilities to improve frequently failing turbine parts.
5. Development of methods to extend the intervals between dismantling.
6. Finding new methods to clean components.
7. Analysis of failures in steam turbines in other geothermal power plants in Iceland.
8. Estimation of what parts, that are not being repaired domestically today, can be repaired without high initial investment.
9. Comparison of different designs of turbines at different environments in order to see what design is suitable for what conditions. This could answer questions like whether or not an impulse turbine is more suitable to operate in a geothermal power plant than a reaction turbine.
10. Assessment of repairs, which are made domestically, of components and analysis of their compatibility with original components.

Further steps to be taken regarding the FMEA are mainly to make a more thorough analysis on components where either severity or RPN is high. Such an analysis would be in the form of dividing chosen components into parts that would be further analyzed. Another task is to develop the RPN scale in such a way that it represents only intervals where errors in calculations and evaluation have been considered.

References

[1] R. Bertani, “Geothermal power generation in the world 2005–2010 update report,” *Geothermics*, vol. 41, no. 0, pp. 1–29, Jan. 2012.

[2] World Energy Council, *2010 Survey of Energy Resources*. London: World Energy Council, 2010.

[3] R. DiPippo, *Geothermal Power Plants, Second Edition: Principles, Applications, Case Studies and Environmental Impact*, 2nd ed. Amsterdam: Butterworth-Heinemann, 2008.

[4] A. Ragnarsson, “Geothermal development in Iceland 2000-2004,” in *Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005*, 2005, pp. 24–29.

[5] “Orkuveita Húsavíkur - Bilun í Orkustöð.” [Online]. Available: http://www.oh.is/news/bilun_i_orkustod0/. [Accessed: 07-May-2013].

[6] Orkustofnun, “Orkumál Raforka,” vol. 8, no. 1, p. 11, Jun-2012.

[7] “Electricity Generation | National Energy Authority of Iceland.” [Online]. Available: http://www.nea.is/geothermal/electricity-generation/. [Accessed: 07-May-2013].

[8] S. Thorhallsson, “Common problems faced in geothermal generation and how to deal with them,” in *Proceedings of the Workshop for Decision Makers on Geothermal Projects and ManagementNaivasha*, 2005.

[9] C. Karlsson, J. Arriagada, and M. Genrup, “Detection and interactive isolation of faults in steam turbines to support maintenance decisions,” *Simulation Modelling Practice and Theory*, vol. 16, no. 10, pp. 1689–1703, Nov. 2008.

[10] S. Guðlaugsson, “Interview,” 2013.

[11] G. H. Guðmundsson, “Interview,” 2013.

[12] K. Fujiyama, S. Nagai, Y. Akikuni, T. Fujiwara, K. Furuya, S. Matsumoto, K. Takagi, and T. Kawabata, “Risk-based inspection and maintenance systems for steam turbines,” *International Journal of Pressure Vessels and Piping*, vol. 81, no. 10–11, pp. 825–835, Oct. 2004.

[13] K. Salahshoor, M. Kordestani, and M. S. Khoshro, “Fault detection and diagnosis of an industrial steam turbine using fusion of SVM (support vector machine) and ANFIS (adaptive neuro-fuzzy inference system) classifiers,” *Energy*, vol. 35, no. 12, pp. 5472–5482, Dec. 2010.

[14] K. Salahshoor, M. S. Khoshro, and M. Kordestani, “Fault detection and diagnosis of an industrial steam turbine using a distributed configuration of adaptive neuro-fuzzy inference systems,” *Simulation Modelling Practice and Theory*, vol. 19, no. 5, pp. 1280–1293, May 2011.

[15] H. Matsuda, “Maintenance for Reliable Geothermal Turbine,” *GRC Transactions*, vol. 30, 2006.

[16] G. Thorolfsson, “Maintenance history of a geothermal plant: Svartsengi Iceland,” in *Proceedings of the World Geothermal Congress 2005, Antalya, Turkey*, 2005.

[17] J. W. Ndege, “Maintenance challenges in the operation of a geothermal power station: a case for Olkaria II plant-Kenya,” United Nations University, Geothermal Training Programme, Report 14, 2006.

[18] C. K. Bore, “Analysis of Management Methods and Application to Maintenance of Geothermal Power Plants,” MSc thesis, Dept. of Mechanical and Industrial Engineering, University of Iceland, Iceland, 2008.

[19] S. Gebregiogis, “Energy analysis and plant operation optimization of the Aluto Langano plant, Ethiopia, related to plant problems.,” United Nations University, Geothermal Training Programme, Report 6, 2007.

[20] Y. Sakai, Y. Oka, and H. Kato, “The Latest Geothermal Steam Turbines,” *Fuji Electric Review*, vol. 55, no. 6, 2009.

[21] Y. Sakai, K. Nakamura, and K. Shiokawa, “Recent Technologies for Geothermal Steam Turbines,” *Fuji Electric Journal*, vol. 78, no. 2, pp. 140–145, 2005.

[22] A. Sakuma, T. Matsuura, T. Suzuki, O. Watanabe, and M. Fukuda, “Upgrading and life extension technologies for geothermal steam turbines,” *JSME International Journal Series B*, vol. 49, no. 2, pp. 186–191, 2006.

[23] J. A. Kubiak and G. Urquiza-beltrán, “Simulation of the effect of scale deposition on a geothermal turbine,” *Geothermics*, vol. 31, no. 5, pp. 545–562, Oct. 2002.

[24] Z. Mazur, G. Urquiza, F. Sierra, and R. Campos, “Numerical analysis of erosion of the rotor labyrinth seal in a geothermal turbine,” *Geothermics*, vol. 31, no. 5, pp. 563–577, Oct. 2002.

[25] Z. Mazur, R. García-Illescas, and J. Porcayo-Calderón, “Last stage blades failure analysis of a 28 MW geothermal turbine,” *Engineering Failure Analysis*, vol. 16, no. 4, pp. 1020–1032, Jun. 2009.

[26] B. Staniša and V. Ivušić, “Erosion behaviour and mechanisms for steam turbine rotor blades,” *Wear*, vol. 186–187, Part 2, no. 0, pp. 395–400, Aug. 1995.

[27] H. Arabian-Hoseynabadi, H. Oraee, and P. J. Tavner, “Failure Modes and Effects Analysis (FMEA) for wind turbines,” *International Journal of Electrical Power & Energy Systems*, vol. 32, no. 7, pp. 817–824, Sep. 2010.

[28] R. de Queiroz Souza and A. J. Álvares, “FMEA and FTA analysis for application of the reliability-centered maintenance methodology: case study on hydraulic turbines,” in *ABCM Symposium Series in Mechatronics*, 2008, vol. 3, pp. 803–812.

[29] H. Bauer J. and R. Koch, *Thermische Turbomachinen*. Karlsruhe: Karlsruhe Institute of Technology, 2011.

[30] H. Sigloch, *Strömungsmaschinen: Grundlagen und Anwendungen*. München: Hanser Verlag, 2006.

[31] K. Menny, *Strömungsmaschinen: Hydraulische und Thermische Kraft- und Arbeitsmaschinen*. Wiesbaden: Springer DE, 2006.

[32] W. Traupel, *Thermische Turbomachinen: Erster Band. Thermodyna*. Berlin: Springer DE, 2001.

[33] Mistubishi Heavy Industries, “A New Geothermal Steam Turbine with a ‘Single-Cylinder Axial Exhaust Design’ (Outline of the Hellisheidi Geothermal Turbine in Iceland),” *Technical Review*, vol. 44, Dec-2007.

[34] C. Proppe, *Machinendynamik*. Karlsruhe: Karlsruhe Institute of Technology, 2012.

[35] *Handbook of maintenance management and engineering*. Dordrecht ; New York: Springer, 2009.

[36] G. Sullivan, R. Pugh, A. P. Melendez, and W. D. Hunt, “Operations & Maintenance Best Practices - A Guide to Achieving Operational Efficiency (Release 3),” Aug. 2010.

[37] R. J. Mikulak, R. McDermott, and M. Beauregard, *The Basics of FMEA, 2nd Edition*, 2nd ed. New York: Productivity Press, 2008.

[38] D. Press, *Guidelines for Failure Mode and Effects Analysis for Automotive, Aerospace and General Manufacturing Industries*. Richmond Hill: Dyadem Press, 2003.

[39] E. Gunnlaugsson, “The Hellisheidi Geothermal Project Financial Aspects of Geothermal Develpoment,” presented at the Short Course on Geothermal Development and Geothermal Wells, 2012.

[40] S. Guðlaugsson, “Maintenance Reports for overhauling of steam turbines,” Orkuveita Reykjavíkur.

[41] Pubilshed with permission from Orkuveita Reykjavíkur, 2013.

[42] N. MØller, J. P. Greenberg, and J. H. Weare, “Computer modeling for geothermal systems: predicting carbonate and silica scale formation, CO2 breakout and H2S exchange,” *Transport in porous media*, vol. 33, no. 1, pp. 173–204, 1998.

[43] M. Ahmad, M. Schatz, and M. V. Casey, “Experimental investigation of droplet size influence on low pressure steam turbine blade erosion,” *Wear*, vol. 303, no. 1–2, pp. 83–86, Jun. 2013.

[44] H. Pollak, E. W. Pfitzinger, N. Thamm, M. A. Schwarz, and A. G. Siemens, “Design And Materials For Modern Steam Turbines With Two Cylinder Design Up To 700 MW,” 2004.

[45] I. Thorbjörnsson, “Corrosion fatigue testing of eight different steels in an Icelandic geothermal environment,” *Materials & Design*, vol. 16, no. 2, pp. 97–102, 1995.

[46] A. Stefánsson, S. Arnórsson, I. Gunnarsson, H. Kaasalainen, and E. Gunnlaugsson, “The geochemistry and sequestration of H2S into the geothermal system at Hellisheidi, Iceland,” *Journal of Volcanology and Geothermal Research*, vol. 202, no. 3–4, pp. 179–188, May 2011.

[47] Þ. Jóhannesson, “Lecture in design of geothermal power plants at University of Iceland,” 2012.

[48] E. Gunnlaugsson, “Chemical composition of seperators fluids at Hellisheiði geothermal power plant,” Reykjavík Energy (2013), Tech. rep.

[49] K. Geirsson, “Interview,” 2013.

[50] E. Commission, “Europe’s energy position–markets & supply,” *Luxembourg: Publications Office of the European Union*, 2010.

[51] “Chemical composition, Mechanical, physical and environmental properties of AWS ER309Mo,Steel grades,Mould steel,” [Online]. Available: http://www.steel-grades.com/Steel-grades/Mould-steel/aws-er309mo.html. [Accessed: 25-May-2013].

[52] C.-H. Lee and K.-H. Chang, “Finite element computation of fatigue growth rates for mode I cracks subjected to welding residual stresses,” *Engineering Fracture Mechanics*, vol. 78, no. 13, pp. 2505–2520, Aug. 2011.

[53] “Wencon - Product Program.” [Online]. Available: http://www.wencon.com/index.php?option=com_content&task=blogcategory&id=25&Itemid=35. [Accessed: 07-May-2013].

[54] “Sulzer - Rotor Repairs.” [Online]. Available: http://www.sulzer.com/en/Products-and-Services/Turbomachinery-Services/Repair-Services/Rotor-Repairs. [Accessed: 07-May-2013].

[55] F. Romero and L. Rodriguez, “Design modifications and repair of a 90 MW steam turbine after a catastrophic failure,” *Sulzer Technical Review*, vol. 3, p. 4039, 2010.

[56] Á. Pálsson, “Interview,” 2013.

[57] C. Ballzus, H. Frimannson, G. I. Gunnarsson, and I. Hrolfsson, “The geothermal power plant at Nesjavellir, Iceland,” in *Proc. World Geothermal Congress*, 2000.