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Identification of Failure Modes and Their Effect in Geothermal Power Plants

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ABSTRACT

This work provides failure mode and effect analysis (FMEA) results for a variety of different geothermal power plants based on answers from power plant operators. The focus of this analysis was on erosion, corrosion and scaling occurring on metal components within the plants. The components in the different sections of the plants were considered. This includes the components in the steam production system, steam transmission system, reinjection system and cooling system.

Severity, occurrence and detectability scales adjusted to geothermal power plant operations were used to evaluate the failure modes and their effects. Analysis of the results showed that using only the risk priority number (RPN) to evaluate the issues is limiting. The severity and occurrence were therefore also used separately to obtain an overview of the most critical problems. These values were used to rank the highest failure mode and corresponding effect for each major component.

The overall highest-ranking issue based on the RPN was leaking of pipes in the gas extraction system due to corrosion. Following this problem was leaking of steam gathering pipes, clogging of brine pipelines and labyrinth seals, and crack formation in diaphragms due to erosion. Erosion, corrosion and scaling of valve components preventing them from operating properly and scaling to slotted liners downhole, were also high-ranking issues. The most severe issues were determined to be leaking of the gas extraction pipes, sticking and leaking of valves, and cracking of turbine components. Erosion, corrosion and scaling of vessels, sticking of valves and leaking of pipes were given a highest occurrence rating by some of the operators answering the FMEA.

Despite the rating schemes being relatively well defined there is always the potential of bias in the answers from the operators. These results are also highly dependent on the issues encountered at each power plant. Instead of providing a listing of which types of problems can be expected at each plant and their impact, the results therefore provide an overview of the most critical problems that can potentially be encountered in geothermal power plants. This allows for identification of where new material and design solutions for components within geothermal power plants can be incorporated to lengthen the lifetime of components, make the operation of the plants safer and reduce operational cost.

1. INTRODUCTION

Geothermal power plant components can experience issues during operation which can reduce the efficiency of the plant and increase the overall cost of operation. Erosion, corrosion and scaling are among problems that can be faced and Figure 1 shows resulting damage that can be encountered. The extent of these problems varies depending on the operating conditions such as fluid temperature, pressure and composition. The methods that can be used to minimize the effects of these issues include adjustment of the fluid properties and/or material selection. The use of higher-grade alloys can for instance protect components from erosion and corrosion damages but making components out of solid high-grade alloys can be expensive. The use of coatings can therefore increase tolerance against common issues at a potentially lower cost than using solid higher-grade material. The Geo-Coat project focuses on development of high enthalpy alloys, cermets and duplex coatings applied through high velocity oxy fuel (HVOF), laser cladding, electrospark deposition and electroless plating, with the intention of protecting geothermal power plant components from erosion, corrosion and scaling. To identify where such solutions can be the most effective, a failure mode and effect analysis (FMEA) was constructed based on experience from geothermal power plant operators. This entails rating failure modes to produce ranking that reveals the locations of the most crucial areas. The answers from the operators were reviewed and combined to provide a general overview of potential failure modes and effects geothermal power plant components can experience.

Figure 1: Erosion damages to a) a rotor disc and b) outer edge of a turbine diaphragm.

1.1. FAILURE MODE AND EFFECT ANALYSIS (FMEA)

Failure mode and effect analysis (FMEA) is a tool that is used to identify and prevent product and process failure before it occurs [1]. In this sense failure can either refer to how a process or component fails or its capability reduces, as will be done in this report. Once identified, the failure modes can then be rated based on the severity (S) of each effect, the frequency of occurrence (O) and its detectability (D).

To perform a basic FMEA the failure mode, failure effect and failure cause have to be clear to be able to rate the severity, occurrence and detectability appropriately. It is therefore imperative that the individuals filling out the FMEA have a good understanding of the functionality and effects damage can cause to the system. Once this has been identified and rated the vales for S, O and D can be multiplied together to produce a risk priority number (RPN). This number can then be used as a method for identifying critical areas in the system. While this can be represent by the RPN value, this number can be misleading as it is highly reliant on the values for S, O and D, and views each of these with equal weight. To achieve more applicable results this number therefore has to be used in conjunction with other values to provide results that are more tailored to what is desired. Using the severity or occurrence value as extra criteria can provide such balance. Another method could be to use S*O as this removes the detectability factor and can therefore provide a more appropriate reference if the main focus is on the severity of a failure mode and its frequency. This value is used to analyse results from FMEA and is commonly referred to as the criticality of the failure mode [2].

2. METHOD

A draft for the FMEA along with drafts for the S, O and D scales were constructed based on literature review and experience. These drafts were then showed to geothermal power plant operators and knowledgeable parties. With their assistance these documents were finalized. Operators and individuals with connections to operators were then contacted in order to ask for their assistance in filling out the FMEA. They were informed that the information they would provide would be confidential and not traceable back to them without their consent. This was necessary to facilitate a wider range of operators.

2.1 Outline of the FMEA

To make the process of filling out the FMEA more straight forward the base components of geothermal power plants were listed. They were categorized based on their location in the plant and were split into the steam production system, the steam transmission system, reinjection and cooling systems. The focus was on components experiencing erosion, corrosion and scaling due to fluid exposure. Failures of components such as those in the electrical system were therefore not included. Further information on the components being concentrated on can be found in Deliverable 1.1.

2.2 Rating of S, O and D

The method by which severity (S), frequency of occurrence (O) and detectability (D) are rated can vary depending on the field the FMEA is being used for. Each indicator is split into a specific number of categories and the number pertaining to the category is used to rate each failure listed in the FMEA depending on its nature. The definition of the categories can therefore be highly specific to the area for which the FMEA is being used. For this project the categories for S, O and D were adapted and adjusted from other projects and templates [3-8]. Direct input from experienced operators also shaped the categorization.

Severity and occurrence were split into 10 categories, ranging from 1 to 10, and detectability was given a range from 1 to 6 as splitting it into more categories was considered unnecessary. Additionally this value was not considered to be as important as the severity and occurrence for this project and by having a lower scale this therefore also lowers the impact this indicator has on the results. The categorization of each rating is shown in Table 1.

Table 1*: The severity, occurrence and detectability ratings designed for the project*

	Value	Definition	Description
Severity	10	Hazardous	Catastrophic failure that can cause severe damage to property or people
	9	Critical	System inoperable and failure can lead to substantial damage of other equipment in the system
	8	Very high	System inoperable and requires immediate maintenance
	7	High	System operable with considerable reduction in performance of the system
	6	High	System operable with notable reduction in performance of the system
	5	Moderate	System operable with slight reduction in performance of the system
	4	Low	System operable, only slightly reduced capability of the component and minor effects to other parts of the system
	3	Very low	System operable and only slightly reduced capability of the component without it effecting other parts of the system
	2	Minor	System operable and no significant effect on the component
	1	None	No effect
Occurrence	10	Extremely high	Failure is likely to occur in 6 months
	9	Very high	Failure is likely to occur in 9 months
	8	High	Failure is likely to occur in a year
	7	High	Failure is likely to occur in 2 years
	6	Moderate	Failure is likely to occur in 3 years
	5	Moderate	Failure is likely to occur in 4 years
	4	Low	Failure is likely to occur in 6 years
	3	Low	Failure is likely to occur in 8 years
	2	Very low	Failure is likely to occur in 10 years
	1	Remote	Failure is unlikely to occur under 10 years
Detection	6	None	Maintenance procedures will not/cannot detect the failure mode (damage) before effects are noticeable
	5	Very low	Maintenance procedures have a very low chance of detecting the failure mode (damage) before effects are noticeable
	4	Low	Maintenance procedures have a low chance of detecting the failure mode (damage) before effects are noticeable
	3	Moderate	Maintenance procedures may detect the failure mode (damage) before effects are noticeable
	2	High	Maintenance procedures have a high probability of detecting the failure mode (damage) before effects are noticeable
	1	Very high	Maintenance procedures will almost certainly detect the failure mode (damage) before effects are noticeable

2.3 Processing of results

To protect the confidentiality of the answers from the operators it was decided that a combined FMEA could be used to prevent direct traceability. Such a combined overview could then either be based on a mean average for each component, based on the ratings for each operator, or by selecting the highest rating. Using average results is considered to skew the outcome of the FMEA as the most critical failure modes would then not be included and the nature of the failure mode may be inherently different based on location. By using the highest ranking results the most significant failure modes within the worldwide geothermal community will therefore not be overlooked due to average ratings giving too low a value.

The failure mode containing the highest RPN value is chosen but if another failure mode has a higher value for either S or O it is also included in the combined FMEA to prevent loss of such information. This can therefore result in a similar failure mode and effect having two widely different rankings for the same component. This information can then be used to determine how critical each failure mode is compared to another, based on different ranking systems.

3. RESULTS AND DISCUSSION

Within Europe the individuals who were contacted to fill out the FMEA were located in Iceland (3), Belgium (1), Germany (3), France (1), Italy (2), Portugal (1) and Turkey (1). Outside of Europe individuals based in Kenya (2), the US (2), Mexico (1), New Zealand (8) and the Philippines (2) were contacted.

It was challenging to get the operators to answer the FMEA questionnaire as they either did not have time to fill out the detailed questionnaire or they were not in a position to divulge such information. Out of those contacted, 13 individuals eventually answered but only 5 were able to provide a filled out FMEA. This is nonetheless better than expected and gives enough information to get an overview of the different failure modes that can be experienced. Additionally, 4 operators who could not fill out the FMEA were willing to answer broader questions regarding failure they encounter in their systems.

Based on the results from the FMEAs, all the operators reported experiencing erosion, corrosion and scaling to different degrees. This is highly dependent on the fluid properties, material selection and design of the power plant. Some of the operators answered for more than one plant including ON Power who answered for both the Hellisheiði and Nesjavellir power plant, HS Orka who answered for the Reykjanes and Svartsengi power plants, and EDA who answered for Ribeira Grande and Pico Vermelho. The majority of the plants were single-flash while one was double flash and two of them were binary.

Table 2 gathers the information from the FMEA and gives an overview of the top values for each main scale within each system. Using such a setup prevents components from a system which is not as demanding from being lost as they can nonetheless be important especially if certain systems are targeted rather than the whole. The components are categorized based on the same categorization as was used in Chapter 3.6. The failure mode and effect with the highest value for each scale is chosen for each case and their values are shown to the right in the table. The bolded numbers indicate the highest values for each case within each category. For instance, there are numerous pipes in each system. For the steam transmission system the pipe that had the highest RPN number was the gas removal pipe transporting H2S. This component was therefore placed in the table. Additionally the RPN number 280 is also the highest RPN for any of the pipes. This value is therefore bolded. Within the steam transmission system the H2S pipe was also the one that had the highest severity. This component is therefore listed under severity and the severity value is bolded as this was also the highest for all the pipes. Lastly, there were a few types of pipes which had the same occurrence rating. All these components are therefore listed and the occurrence rate bolded since it is the highest value. If for instance scaling in the reinjection well casing would have an occurrence rating of 10 instead of 8, this value would also have had to be bolded.

From this table it can for instance be gathered that the NGC pipe is the most critical of the pipes with regard to the RPN number, and indeed the most critical of the components in these systems. Comparing failure modes through RPN shows for instance that the most critical failure mode within the steam cleaning system can be considered less critical than the most critical failure mode for valves in steam transmission system. Similarly this failure mode is more critical than the most critical form of damage experienced by the wellhead of the production well all the while being categorized as having lower severity than material reduction of the casing at the production wellhead.

These tables can be used to analyse the system as a whole. According to the RPN number the most critical failure mode throughout the system is cracking of pipes due to corrosion. This applies to the pipes in the gas removal system as well as the two phase pipes from the wellhead and steam pipes flowing to the turbine (not seen in Table 12). Additionally brine pipelines are also among those with the highest RPN as they can experience clogging. Following these problems are those experienced by the turbine. This includes scaling in the labyrinth seals and erosion of both rotor blades and the diaphragm. After this comes erosion and wear damage to the pin and seat of valves in different locations within the system. Cavitation of impellers in the brine pumps is also among the highest rated and so are the damages to the steam scrubbing equipment, erosion-corrosion of the ring tool joint on the wellhead, scaling in the preheater and erosion, corrosion and scaling of the pipes to the silencer.

In terms of severity, corrosion and cracking of the pipes in the gas removal system and the two phase pipes from the wellhead pose the most serious threat as leaking and blowout of these systems can cause severe damage to both personnel and property. Leaking of components containing high temperature fluid is generally hazardous in addition to also reducing efficiency of the cycle. Erosion and corrosion of turbine components can lead to reduced efficiency and eventual cracking of components if not monitored. These cracks can result in severe damage to the turbine if they cause parts of the components to break off. Pump components can also suffer damage due to corrosion and this can both lead to efficiency drop and cause vibration in the system.

Scaling in valves and the condenser are the most frequent failure modes along with cracking of pipes. Scaling of the condenser is not considered severe but this form of failure reduces efficiency and requires regular cleaning. Scaling in valves can be serious if it manages to build up and leads to the valves being inoperable. This results in the flow not being controllable and can for instance prevent shut off. This rarely occurs however as regular maintenance cycles involve checking these valves for sticking. Scaling can also promote under-deposit corrosion. If the valve components experience corrosion or erosion this can lead to imperfect sealing when closed which is also a problem. Scaling in pipes and the wells can cause clogging and lead to an imbalance in the system. It can also influence the steam intake and reinjection capacity. This can therefore be problematic for the entire system.

Table 2: The highest rated components of the FMEAs within each system based on RPN, S and O

System	Component	Part	Scale	Failure mode	Effect	RPN	S	O	S*O
Steam production	Wellhead	Ring tool joint	RPN	Erosion-corrosion	Leaking	**120**	5	4	20
		Casing	S	Corrosion	Material reduction	54	**9**	1	9
		Ring tool joint	O	Erosion-corrosion	Leaking	120	5	**4**	20
	Pipes	Liner	RPN	Scaling	Reduced flow	144	8	3	24
		Liner	S	Scaling	Reduced flow	144	8	3	24
		Casing	O	Scaling	Reduced flow	48	4	6	24
	Valves	Control valve - seat	RPN	Erosion	Can't seal	**144**	4	6	24
		Master valve - seat	S	Erosion	Can't seal	126	7	3	21
		Master valve - stem	O	Corrosion	Can't seal	84	6	7	42
	Pumps	n/a							
Steam transmission	Pipes	H2S removal	RPN	Corrosion	Leaking	**280**	10	7	70
		H2S removal	S	Corrosion	Leaking	280	**10**	7	70
		2 phase	O	Cracking	Leaking	40	4	**10**	40
		2 phase - inlet	O	Cracking	Leaking	240	4	**10**	40
		Steam pipe	O	Cracking	Leaking	240	4	**10**	40
	Valves	Working fluid valve - pin	RPN	Wear/abrasion	Can't seal	**144**	9	4	36
		Level control valve	S	Scaling	Sticking	10	**10**	1	10
		Ball check valve	O	Scaling	Sticking	80	4	**10**	40
	Pumps	Working fluid - shaft	RPN	Wear/abrasion	Vibration	48	8	3	24
		Working fluid - bowl/barrel	RPN	Corrosion	Reduced efficiency	48	8	2	16
		Working fluid - shaft	S	Wear/abrasion	Vibration	48	**8**	3	24
		Working fluid - bowl/barrel	S	Corrosion	Reduced efficiency	48	**8**	2	16
		Working fluid - shaft	O	Wear/abrasion	Vibration	48	8	3	24
	Steam cleaning/ separating	Separator - vessel	RPN	Erosion, corrosion	Strength reduction	**128**	8	8	64
		Steam scrubbing	RPN	Erosion, corrosion	Strength reduction	**128**	8	8	64
		Rupture discs	RPN	Corrosion	Premature bursting	**128**	8	8	64
		Separator - vessel	S	Erosion, corrosion	Strength reduction	128	**8**	8	64
		Steam scrubbing	S	Erosion, corrosion	Strength reduction	128	**8**	8	64
		Rupture discs	S	Corrosion	Premature bursting	128	**8**	8	64
		Stack	S	Corrosion	Leaking	96	**8**	2	16
		Mist eliminator - wire mesh	S	SCC	Breaking	40	**8**	5	40
		Separator - vessel	O	Erosion, corrosion	Strength reduction	128	8	**8**	64
		Steam scrubbing	O	Erosion, corrosion	Strength reduction	128	8	**8**	64
		Rupture discs	O	Corrosion	Premature bursting	128	8	**8**	64
	Heating/cooling	Pre-heater - tubes	RPN	Scaling/corrosion	Clogging/leaking	**105**	7	3	21
		Vaporizer - tubes	RPN	Erosion/fatigue	Leaking	**105**	7	3	21
		Pre-heater - tubes	S	Scaling/corrosion	Clogging/leaking	105	**7**	3	21
		Vaporizer - tubes	S	Erosion/fatigue	Leaking	105	**7**	3	21
		Condenser	O	Scaling	Reduced efficiency	80	2	**10**	20
Reinjection	Pipes	Brine pipelines	RPN	Clogging	System upset	192	8	6	48
		Casing	S	Scaling	Reduced capacity	64	8	8	64
		Casing	S	Corrosion	Leaking	80	8	2	16
		Brine pipelines	S	Clogging	System upset	192	8	6	48
		Brine pipelines	S	Corrosion under insulation	Leaking	6/5	8	3/2	24/16
		Casing	O	Scaling	Reduced capacity	64	8	8	64
	Valves	Seat	RPN	Erosion	Can't use to regulate	**144**	4	6	24
		Brine check valve - pin		Wear/abrasion	Can't close	**144**	9	4	36
		Brine check valve - pin	S	Wear/abrasion	Can't close	144	9	4	36
		At wellhead - seat	O	Scaling	Sticking	80	8	**10**	80
	Pumps	Impeller	RPN	Cavitation/scaling	Reduced efficiency - no fluid	**128**	8	8	64
		Impeller	S	Cavitation/scaling	Reduced efficiency - no fluid	128	**8**	8	64
		Impeller	O	Cavitation/scaling	Reduced efficiency - no fluid	128	8	**8**	64
Cooling	Pipes		RPN	Scaling	Hinders flow	48	4	3	12
			S	Scaling	Hinders flow	48	4	3	12
			O	Scaling	Hinders flow	48	4	3	12
	Valves	n/a	RPN						0
	Pumps	n/a	RPN						0
	Heating/cooling	Air cooling condenser - tubes	RPN	Corrosion	Leaking	72	6	2	12
		Air cooling condenser - tubes	S	Corrosion	Leaking	72	6	2	12
		Air cooling condenser - supports	O	Corrosion	Material reduction	12	2	3	6

Table 2 does not contain the turbine components as they were considered to require a separate table to allow for damage of different parts of the component to be compared. The values for the turbine can be seen in Table 3.

Table 3: The highest rated damages for each component within the turbine based on RPN, S and O.

Component	Part	Scale	Failure mode	Effect	RPN	S	O	S*O
Turbine	Labyrinth seals	RPN	Scaling	Stock up	**192**	8	6	48
		S	Scaling	Stock up	192	8	6	48
		O	Erosion	Reduced efficiency, leaking	56	4	7	28
	Diaphragm	RPN	Erosion	Vibration, cracks	168	7	8	56
		S	Erosion	Vibration, cracks	168	7	8	56
		O	Erosion	Vibration, cracks	168	7	**8**	56
	Rotor	RPN	Erosion	Imbalance, vibration	84	4	7	28
		S	Corrosion and erosion	Reduced efficiency	10	5	1	5
		O	Erosion	Imbalance, vibration	84	4	7	28
	Rotor blades	RPN	Cracking	Breaking of blades	108	9	3	27
		S	Cracking	Breaking of blades	108	**9**	3	27
			Erosion	Vibration, cracks	90	**9**	5	45
		O	Scaling and corrosion	Clogging, material reduction	98	7	7	49
	Casing	RPN	Scaling/corrosion	Reduced strength	98	7	7	49
		S	Scaling/corrosion	Reduced strength	98	7	7	49
		O	Erosion	Steam bypass	96	4	**8**	32

The answers for the FMEA from the operators give a good overview of the different failure modes which can be experienced in geothermal power plants. These results therefore give a basis on which a form of protection could be determined from requirements such as the most severe forms of failure, the most frequent, the hardest to detect or a combination of these criteria.

The results from the FMEAs answered in this project are somewhat different to those reported by Feili et al. [4]. They for instance reported that sticking of valves was not considered severe and that scaling build-up leading to production loss and reduced efficiency was more severe than corrosion problems such as cracking of turbine components and failure of pipes. They also reported such corrosion failure as frequent. The discrepancy is likely originated from the difference between the power plants on which the answers are based. Since the results from Gunnarsson [6] were used for the turbine components in the FMEA from ON Power the results are similar although a few failure modes were added.

The operators who could not answer the FMEA but were willing to answer broader questions mainly specified that they experience corrosion which causes damage to piping and heat exchangers, and scaling which causes issues for their pipes, valves, the separator and heat exchanger. This is similar to what was seen in the answers for the FMEA. Additionally, the Soultz-sous-Forêts power plant in France is exposed to highly corrosive fluid around 160°C and requires the use of line-shaft pumps in the production well. These components have been reported to suffer from abrasion, corrosion and scaling during operation. This included highly corroded impellers and bowls. Damage to downhole pumps was not reported in the FMEAs as the plants under consideration did not require the use of such equipment but it does show the need for potential protection of such components where they are present.

4. CONCLUSIONS

An FMEA was constructed and sent to operators around the world to get their opinion on the severity, frequency and detectability of failure and their subsequent effect on their geothermal power plants. The answers were combined and the most critical cases noted to get an overview of where the most sensitive areas are located within geothermal power plants to be able to adjust our products better to the need of the power plants.

A preconceived list of components was sent the operators to provide guidelines for the FMEA and they were asked to focus specifically on failure due to scaling, corrosion, erosion and wear to minimize the effort involved in filling it out. Their answers showed that these failure modes influenced components in all the plants although the degree of effects varied with different fluid properties. The following bullet points summarize what can be deduced from the FEAM results.

- All the failure modes being focused on are linked to severe cases in the system.
- According to the RPN value the most critical cases occur due to leaking of pipes which is generally caused by corrosion.
- Scaling leads to reduced efficiency of the plant in general but can also become hazardous if accumulated in valves leading to them being inoperable.
- Scaling mainly affects valves, well equipment, heating/cooling equipment (i.e. condenser) and turbine components.

- Corrosion problems can be found in the majority of components but the most serious cases generally appear to be connected to pipes but issues are for instance also present in turbine components, steam cleaning/moisture removal equipment and valves.

- There are numerous components which could potentially benefit from the use of more erosion resistant material including turbine components, valves, the wellhead, pipes, pumps etc.

The results from the FMEA support the fact that erosion and corrosion resistant solutions are needed for geothermal power plants and have provided a better basis to estimate the effect such protection would have on the system. Even if the solution could not protect the system from what the risk priority number draws attention to that does not mean that issues with lower RPNs or severity ratings could not lead to substantial gain as the financial aspect behind each damage was not considered. The FMEA results will be used as guidelines for the continuation of the project to provide focus for the coating solutions and justify the requirement for protective solutions.

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