Geothermics 53 (2015) 147–153

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Geothermal wellhead maintenance: A statistical model based on documented Icelandic experience

R.S. Atlason [a,*], O.P. Geirsson [b], A. Elisson [a,b], R. Unnthorsson [a]

[a] University of Iceland, Department of Industrial Engineering, Mechanical Engineering and Computer Science, Centre for Productivity, Performance and Processes, Hjardarhagi 6, 107 Reykjavik, Iceland
[b] University of Iceland, Department of Physical Sciences, Dunhagi 5, 107 Reykjavik, Iceland

ARTICLE INFO

Article history:
Received 17 January 2014
Accepted 19 May 2014
Available online 12 June 2014

Keywords:
Geothermal
Wellhead
Maintenance
Iceland
Statistics

ABSTRACT

Icelandic geothermal industry has been shown to operate in an efficient manner. We investigated how geothermal wellheads are maintained at the largest geothermal power plant in Iceland. Interviews were conducted with maintenance personnel on site, maintenance diaries were retrieved where detailed description on the maintenance activities had been recorded. Also, maintenance data was gathered from the dynamic maintenance management system (DMM). Methods of major overhauls and maintenance activities were identified, as well as the frequency of these activities. Using this data, a statistical analysis was conducted to see the estimated intervals between maintenance activities and compare them to the recommendation provided to staff. This paper concludes by recommending a wellhead maintenance management system based on the results from the statistical analysis.

1. Introduction

Icelandic geothermal power plants have been shown to operate in an efficient way (Atlason and Unnthorsson, 2013a). The industry has also been shown to be systematically innovating and seeking new ways to further optimise its operations (Atlason and Unnthorsson, 2013b). Geothermal wellheads play an important role in the overall efficiency at geothermal power plants (Atlason and Unnthorsson, 2013c). Where they serve the role of allowing the steam and fluid to flow from the ground to the separators and subsequently to the turbines (DiPippo, 2008). Maintenance of the wellheads is therefore of great importance so the operation of the power plant can go without major incidents. At first, wellheads come across as simple equipment, but when interviews are conducted with maintenance staff, the wellheads are often referred to as Christmas trees, referring to the complexity of all the components. Wellheads used in the Icelandic geothermal sector are often designed for the oil industry, and have therefore some characteristics of that particular industry. Various problems, not frequently observed in the oil industry have been experienced at geothermal power plants with regards to wellheads. Some of these problems are listed in Section 2.2. In this study, wellhead maintenance at the Hellisheidi Power Plant is investigated. The power company has developed maintenance management methods throughout the years. These methods have been developed to address and minimise the possible negative effects the geological conditions on the area can have on the wellheads. Even though methods have been developed, they consist greatly within local knowledge of the maintenance staff. In this study, this knowledge is documented, diagnosed and statistically analysed. Subsequently a statistical model describing wellhead maintenance is developed based on the findings of this research. Geothermal projects are currently under way in different parts of the world. When such geothermal power plants will begin operating, it should prove valuable to possess the wellhead maintenance plan from another successfully established power plant. Even though the plan is tailored to the corrosion and scaling effects of the particular field the plant is located at. It is also valuable to see how the maintenance has developed from the original recommendations throughout the years. This can be seen in this article, as original recommendations are shown as well as statistical analysis to visualise how wellhead maintenance procedures have developed to date. In theory, such model should be usable by geothermal power plants operating under similar conditions as described in this article. The literature is essentially void of such documentation and analysis as is presented in this article, however, general recommendations are presented by Thorhallsson (2003) where general problems associated with wellheads are listed. However, the objective of this paper is not to present a list of common problems related to geothermal

* Corresponding author. Tel.: +354 6605725; fax: +354 5255802.
E-mail addresses: rsa3@hi.is (R.S. Atlason), opg2@hi.is (O.P. Geirsson), are9@hi.is (A. Elisson), runson@hi.is (R. Unnthorsson).

http://dx.doi.org/10.1016/j.geothermics.2014.05.006
0375-6505/

Table 1
Brine chemical composition of the studied power plant (Gunnlaugsson, 2013).

mg/kg	Hellisheidi
pH/°C	9.2/100
SiO_2	822
Na	213
Cl	170
K	38.4
SO_4	19
Al	1.7
F	1.1
B	1.039
Ca	0.456
As	0.09
Ba	0.078
Fe	0.03
Zn	0.0097
Cu	0.002
P	0.004
Mg	0.0035
Pb	0.0035
Ni	0.0003
Cd	0.00017
Cr	0.00008
Hg	0.00002
H_2S[a]	20

[a] Gas.

wellheads, but rather to provide a model to maintain them to minimise problems.

2. Methods and materials

This section will discuss the main components of geothermal wellheads and list the main problems associated with them. Subsequently it will go through the method used to retrieve and analyse data from the power plant under study.

2.1. Description of the power plant and the brine chemical composition

One of the major causes for the difference in maintenance activities and problems with the mechanical equipment at geothermal power plants are the different geological conditions. Data showing the chemical composition of the brine was gathered from Reykjavik Energy, which owns the Hellisheidi Power Plant. Table 1 shows the chemical composition from the power plant under study. Reykjavik Energy provided data about the fluid chemical composition when it leaves the separators. One can see that the fluid consists mostly of SiO_2 (822 mg/kg), Na (213 mg/kg), Cl (170 mg/kg), K (38.4 mg/kg), and SO_4 (19 mg/kg) (Gunnlaugsson, 2013). Further clarification of the fluid composition is shown in Table 1.

2.1.1. Hellisheidi Geothermal Power Plant

The Hellisheidi Geothermal Power Plant is owned by Reykjavik Energy and began its electric production in 2006 (OR, 2014a). The plant is located on the southern part of the Hengill geothermal field, a detailed location can be seen on Fig. 1. It produces approximately 303 MW of electric power and 133 MW of hot water through a double flash process. Around 50 wells have been drilled to harness hot water for the power production (OR, 2014b).

2.2. Geothermal wellhead at Hellisheidi

A typical geothermal wellhead at Hellisheidi consists of the following 9 parts is shown in Fig. 2. These are (1) survival valve. This valve is used for temperature and pressure measurements. It is also used to prevent too much pressure in the wellhead by allowing it to blow. (2) Working valve. This valve has the role of opening

Fig. 1. Location of the power plant under study. The lake north-east of the power plant is lake Thingvallavatn.

and closing flow from the well. This valve is located on top of the head valve. (3) Choke valve. As the name suggests, the choke valve has the role of allowing the well to be choked by injecting cold water into it (Mannvit, 2010). (4) Head valve. This valve is located on top of the expansion spool and has the role of being the closing valve for the well. (5) Expansion spool, allowing for thermal expansion of the wellhead assembly and casings, (6) casing head and (7) silencer valve. The silencer valve allows the flow to enter the silencers. This is merely done when the hole is allowed to blow full steam but not entering the gathering system. This is often done when holes have been dormant and attempts are made to activate them again. (8) Control valve. The role of the control valve is to control the flow from the well as is needed by the power plant. (9) Gathering system valve. Normally, two gathering system valves are located at each wellhead, one on each side of the control valve. This is done so the steam system can be isolated from the well or if the control valve needs repairs. By closing both gathering system valves the control valve can be isolated and removed (Mannvit, 2010).

2.3. Common geothermal wellhead problems

Even though many valves are located on the wellheads, only one is regularly or continuously moved. This is the control valve, which controls the amount of flow from the well (Thorhallsson, 2005). This valve is often located outside the well house. Scaling is one of the most common problems known within geothermal power plants and the wellheads are no exception. To avoid scaling to occur in the control valve, a special design is used that wedges against the seats

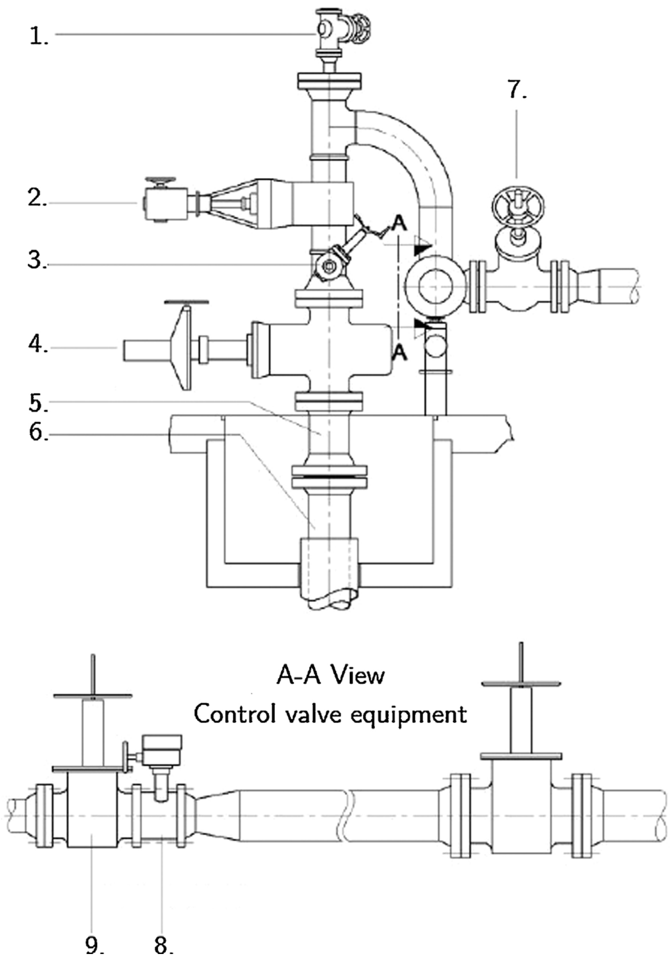

Fig. 2. Typical wellhead assembly used at Hellisheidi geothermal power plant (Mannvit, 2010). The pipe assembly shown in view A-A is vertical in the top view: (1) survival valve, (2) working valve, 3) choke valve, (4) head valve, (5) expansion spool, 6) casing head, (7) silencer valve, and (8) control valve.

in the open as well as closed position (Thorhallsson, 2005). Using this special design, scaling is avoided in the closing seats. Operating the wellhead in the pressure zone of 10–25 bar also assists with avoiding scaling. Wherever leaking occurs, scaling builds almost instantly (Thorhallsson, 2005). The importance of the glands and joints such as at the expansion spool to be packed adequately is therefore of high importance.

2.4. Data collection

Daily operation diaries were provided by Reykjavik Energy. The diaries include all day by day activities taking place with regards to the wellheads. These diaries were investigated three years retrospectively, looking at the year 2010, 2011 and 2012. The energy company also provided their staff operation manuals, which sheds light on the guidelines set to the employees. The activities were put in a time sequence for further investigation, shown in Fig. 3. Subsequently hot spots were identified to see which activities are taking place at the wellheads to maintain them and avoid breakdowns. These hotspots can be seen in Fig. 4. Frequent visits took place to the power plant between January and April where interviews were conducted with maintenance staff. The operations conducted on site at the power plant are thoroughly documented and should give a very clear image on the wellhead maintenance.

Table 2
Overall guidelines at Hellisheidi.

Part	Activity
Four year intervals	
Silencer valve	Pressure test
Yearly maintenance	
Head valve	Check movement
Shaft seal	Check tightness
Spindle	Lubricate on valves
Weekly maintenance	
Seals	General cleaning
Measure	Power
All valves	Visual inspection
Leakhole	Visual inspection
All seals	Search for leaks

2.5. Statistical model

The waiting times between wellhead maintenance at Hellisheidi Geothermal Power Plant are assumed to be independent and identically distributed. Maintenance activities are inferred separately. Furthermore, the waiting times are assumed to follow a Weibull distribution (Kotz et al., 2004; Pierskalla and Voelker, 1976). That is, let y_{ij} denote the jth waiting time for the ith activity, then the corresponding probability density function is given by

$$f_i(y_{ij}) = \frac{\kappa_i}{\lambda_i}\left(\frac{y_{ij}}{\lambda_i}\right)^{\kappa_i-1} e^{-(y_{ij}/\lambda_i)^{\kappa_i}}, \quad y_{ij} \geq 0 \tag{1}$$

where λ_i and κ_i denote the scale and shape parameters respectively of the ith activity. The interpretation of the shape and scale parameters κ_i and λ_i in this framework is as follows. The cases where $\kappa_i < 1$, $\kappa_i = 1$ or $\kappa_i > 1$ correspond to the rate of the ith maintenance activity is decreasing, constant or increasing, respectively, over time. The scale parameter λ_i is related to the mean and standard deviation of the times between ith maintenance activity.

A survival Weibull model (Kalbfleisch and Prentice, 2011) is implemented for the waiting times for each activity, where some of the observations are right censored as the corresponding wellhead maintenance occur after the end of the study. Maximum likelihood estimates are obtained for the scale and shape parameters (Cohen, 1965), along with standard deviations and 95% confidence intervals, which in turn yields estimates for expected waiting times. Standard deviations of expected waiting times are obtained with the delta method (Casella and Berger, 2002). The results were then tested for Kaplan–Meier goodness of fit (Miller and Gong, 1981), which are shown in Appendix A.

3. Results

This section outlines the findings from this study. First, it outlines general guidelines with regards to the wellheads provided by the power company. It subsequently shows the real frequency of attendance to the wellheads. Then activities when the wellheads are attended are analysed and the frequency is shown. Finally, a model based on the findings of this study is provided.

3.1. Guidelines at Hellisheidi Power Plant

Preventive maintenance is the maintenance method mostly carried out at Hellisheidi Power Plant with regards to wellheads. This means that certain actions are taken at regular intervals to avoid breakdowns. General recommendations on what should be conducted at each hole weekly, yearly or four-yearly is listed in Table 2.

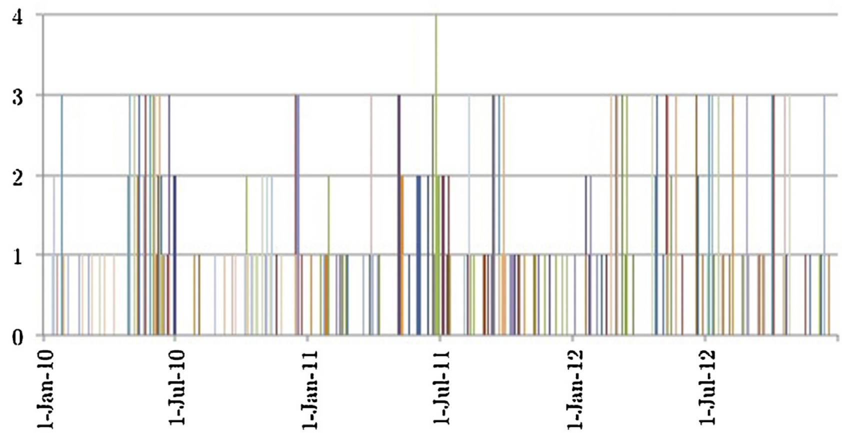

Fig. 3. Maintenance activities shown in a time sequence at Hellisheidi geothermal power plant. Bars reaching value of 3 represent a major overhaul, values of 2 mean that two or more maintenance activities were conducted at the wellhead at that time. Bars reaching 1 represent one minor operation.

As one can see, the guidelines are very general. However, more detailed operating instructions are also given to staff.

(1) Seals are kept on pipes not in use, fully preventing any flow. This is done to prevent pipe tearing.
(2) To prevent corrosion on the exterior, silencers (mufflers) and pipes are frequently sandblasted and painted.
(3) When yearly maintenance is conducted at the wellheads, the blow-out (exhaust) equipment is checked.
(4) Only experienced personnel are allowed to open the wells. If an extensive period has passed since the well was shut, the occupational, safety and health authority must be consulted.
(5) In case of any change in the pressure system of the plant, materials selected shall be according to international standards, and all welding shall be conducted by professionals. Independent inspector shall be consulted to inspect the quality of all weld work.

The operational stages of the wellheads are divided in three. (1) Well in usage. The pipes shall be tested for pressure consistency as often as is needed depended on the exterior condition. This shall however never be conducted with larger intervals than four years. (2) Well is ready to use. In this stage, the well is connected to the collection pipes. It is monitored so the blowing mechanism can be put in use without much notice. (3) Well in waiting stage. In this stage the well is either closed or has no pressure. The wellhead equipment is protected against corrosion, on the inside and outside.

3.1.1. Maintenance procedures at Hellisheidi for valves

The preventive maintenance procedures conducted at Hellisheidi differ between different valves.

• Master valve 10 in. and 12 in. – 900 Class

If any leakage is detected in the shaft seal, sealing filler shall be injected to the shaft seal. Leak holes shall be examined and checked if they are working accordingly. The spindle shall be lubricated regulary. This valve shall be moved at least yearly. Under no circumstances shall this valve be half open, as turbulence forms, which causes deterioration. Reykjavik Energy replaces 900 class valves instead of repairing them, therefore no instructions have been provided for the repairs of such valves.

• Working valve 10 in. and 12 in. – 900 Class

Any leakage in the shaft seal shall be repaired by tightening the seal or insert new insulation rings if needed. Any chemical buildup on the seals shall be cleaned. The spindle and shaft shall lubricate regularly.

• Choke valve 2 in. – 1500 Class

If leakage is detected in a power seal valve, it shall be instantly filled with seal filler. In the case of normal sliding valve, the shaft seal shall be tightened or new gaskets shall be inserted. As is the case with the 900 Class valves, the 1500 Class valves are also not repaired, but instead replaced. No guidelines are therefore provided for the repairs of these valves.

• Survival valve and other 3 in., 8 in., 10 in. and 16 in. valves – 600 Class

These valves include the survival valve, silencer valve and gathering system valve. If any leakage is detected the seal shaft shall be

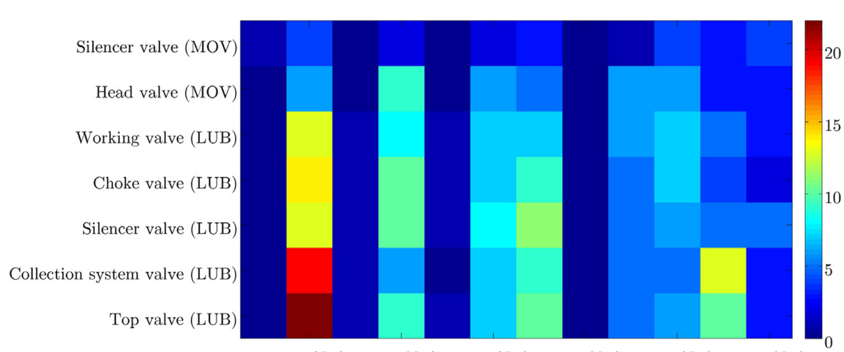

Fig. 4. Most frequently conducted maintenance activities at Hellisheidi geothermal power plant over 3 years, divided in quarters.

tightened or new gaskets shall be put into place if needed. The 600 Class is the only valve class that is repaired by Reykjavik Energy.

- Bolts and threads

Bolts and threads shall be lubricated regularly and kept clean. Leakage shall be repaired instantly.

3.1.2. *Valve repair procedures at Hellisheidi*

Like mentioned previously, only the 600 Class valves are repaired. This section outlines the guidelines provided to staff when such repairs are conducted at Hellisheidi.

- General

It is estimated that these valves are constructed out of A 216 WCB steel in accordance with ANSI or GS-C 25 in accordance with DIN. If the valve consists of any other chemical composition, a consultant should be advised. This should be done to avoid formations of cracks or other fractures, which may occur because of the material composition.

- Grinding

Special consideration shall be taken when grinding, where the grinding must occur outside the area that is to be repaired. Production faults can differ between valves and an expert should be advised with each case.

- Pre-heating

For A 216 WCB steel or comparable steel, the area which is to be welded shall be pre-heated to 100 °C.

- Welding

Electric welding shall be used when welding. The wire used shall be composed of C – 0.07%, Si – 0.7% and Mn – 1.0%. However, when valves need repair, the wire SAFER GTi has been used, as it is approved by DIN 1913 as E 43 45 R(C) 3 and has the following composition: C – 0.07%, Si – 0.3%, Mn – 0.5%, S – 0.018% and P – S 0.022%. The manufacturer of the valve should however be consulted before repair of the valve.

- Sound wave testing

As repair of the valve has finished, the repaired area shall be sound wave tested 100%. If any faults are located on the weld work, it shall be fixed and sound wave tested again.

- Post heating

As the repair has finished, the repaired area is heated to 620 °C and wool insulation put on the area to slow down the cooling. Heating shall be conducted well outside the repaired area so deformation of the repaired part can be avoided – relieving stresses.

- After repair on the valve house (Class 600)

Test for leakage is conducted with air under 2 bar pressure at 20 °C. The valve is kept shut, where the other end of the valve opening is completely closed off. Air is then blown into the valve and soap mixed water put on the repair area and the area which is keeping the valve tight. When this procedure has been conducted at one end of the valve it is conducted at the other.

Pressure testing with water is conducted under 150 bars at 20 °C for 1 min. Both openings of the valve are completely shut off. The valve is opened half way and filled with water. The valve should contain no air. Pressure should be kept constant while the pressure test is conducted.

- After repair on tongue, seats or spindle.

Leak testing of back seal with air under 2 bar pressure with 20 °C. Both openings of the valve are completely closed off and the valve itself kept completely open. Gaskets are loosened and pressure allowed to build inside the valve. Pressure shall be kept steady as long as the examination requires.

Pressure and leakage testing with water under 100 bar at 20 °C. The valve is kept completely shut, and one of the openings shut off completely. Pressure is then let build up in the closed area. While the testing is conducted, any leakage is thoroughly searched for.

3.2. *Real measures taken and frequency*

In the guidelines provided to the staff at Reykjavik Energy, it is often stated that certain parts should be lubricated or checked frequently. It is however not stated how frequent these repairs should be. It also does not take into account if maintenance needs to be less frequent as time goes by since the geothermal field becomes more stable and less amount of minerals exit the wells. Therefore real data, showing frequency of major overhauls at the power plants, and what is done at these overhauls was acquired. Also, it was investigated which maintenance measures are most frequently undertaken at the wellheads, regardless if they are a part of major overhauls. The frequency can be seen in Fig. 3. In Fig. 3, bars reaching the value 3 represent that a major overhaul was conducted at some wellhead at that point in time. When a bar reaches value of 2, two or more procedures were conducted at that wellhead at that

Table 3
Results from the statistical analysis of different maintenance activities. Ev is expected waiting time in days between preventive maintenance activities.

	Estimate	Std. dev.	2.5%	97.5%
Lubrication of top valve				
Scale	813.01	112.99	619.16	1067.56
Shape	1.41	0.21	1.05	1.90
Ev (days)	739.90	110.21	523.89	955.91
Lubrication of working valve				
Scale	791.48	86.45	638.94	980.43
Shape	2.17	0.37	1.55	3.03
Ev (days)	700.94	76.56	550.87	851.00
Lubrication of choke valve				
Scale	868.99	109.41	678.96	1112.20
Shape	1.95	0.34	1.38	2.74
Ev (days)	770.55	98.44	577.60	963.50
Lubrication of silencer valve				
Scale	727.93	73.88	596.63	888.14
Shape	2.05	0.31	1.52	2.75
Ev (days)	644.89	65.80	515.93	773.85
Lubrication of collection system valve				
Scale	851.64	118.86	647.82	1119.59
Shape	1.55	0.25	1.13	2.12
Ev (days)	766.15	112.56	545.54	986.75
Movement of head valve				
Scale	935.48	194.75	622.05	1406.83
Shape	1.67	0.38	1.07	2.63
Ev (days)	835.55	182.27	478.31	1192.80
Movement of silencer valve				
Scale	130.5	562.81	560.77	3039.01
Shape	1.33	0.48	0.65	2.71
Ev (days)	1201.04	573.08	77.83	2324.25

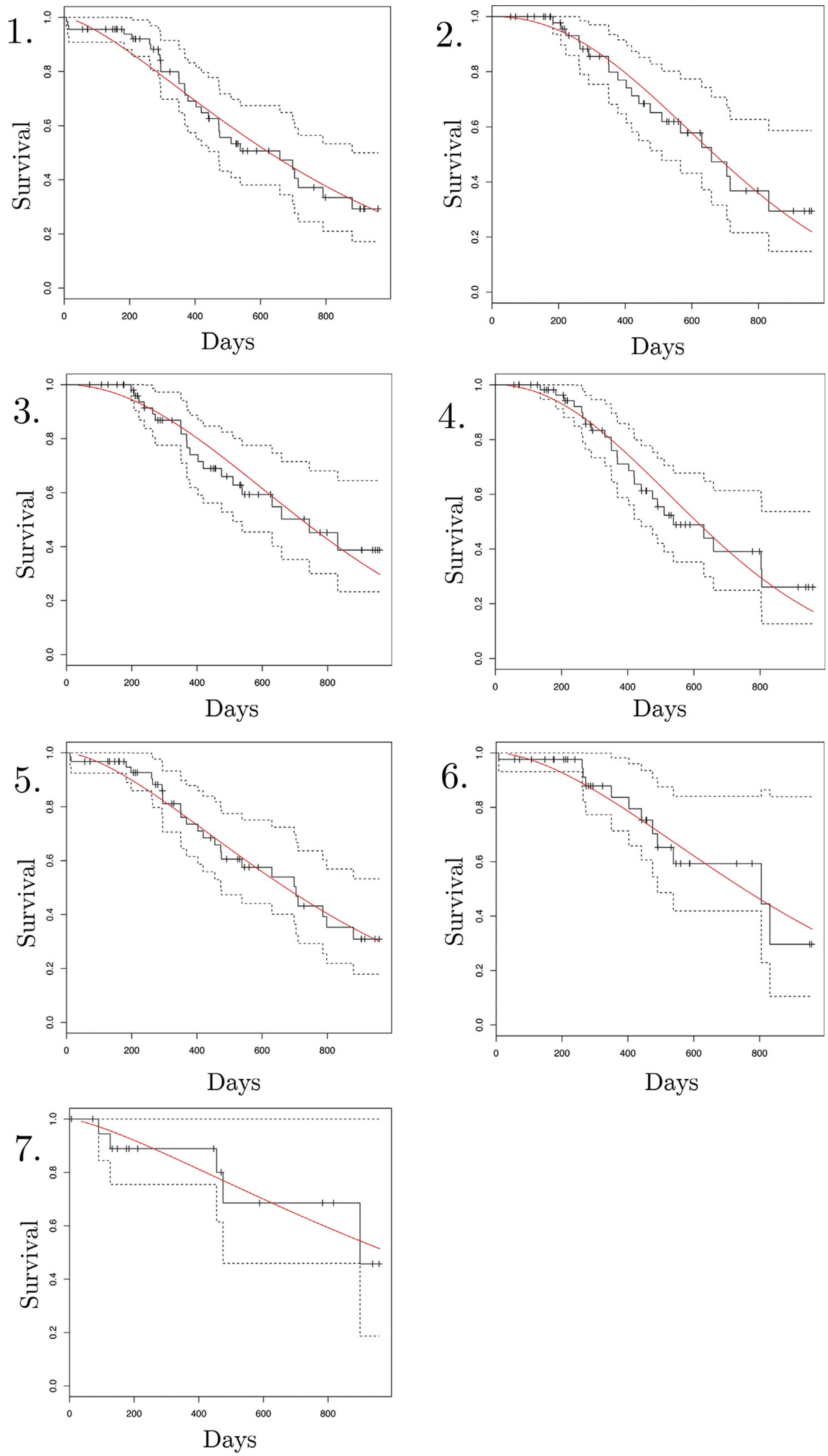

Fig. 5. Results from the Kaplan–Meier goodness of fit test: (1) lubrication of top valve, (2) lubrication of working valve, (3) lubrication of choke valve, (4) lubrication of silencer valve, (5) lubrication of collection system valve, (6) movement of head valve, and (7) movement of silencer valve.

point in time. When a bar reaches a value of 1, one minor procedure was conducted. As can be observed, one bar reaches a value of 4, this was done to indicate an accident that occurred at the wellhead and required a major repair.

Certain hot spots can be located when Fig. 3 is observed with regards to major overhauls. The hot spots at Hellisheidi seem to be three. First is from early May 2010, through June the same year. Another is from early July 2011, through September same year. 2012 seems to be more dispersed than the two previous years. However, Mars, May and July are particularly active in this regard. When all activities conducted are diagnosed in more detail, one can notice which activities are undertaken at each visit at the wellheads. In Fig. 4 the 7 most frequently conducted procedures are listed and their frequency. The most frequent procedures are diagnosed in this study and used to create a maintenance model.

These activities include (1) lubrication of top valve, (2) lubrication of working valve, (3) lubrication of choke valve, (4) lubrication of silencer valve, (5) lubrication of collection system valve, (6) movement of head valve, and (7) movement of silencer valve. The results from the statistical analysis are shown in Table 3. The table includes the scale and shape parameters of the estimated Weibull distribution for each of the seven activities. The table also includes the expected waiting times between maintenance activities (Ev). Furthermore, the standard deviation (Sd) and the 95% confidence intervals are provided. It is evident that most activities have the expected waiting time of approximately 2 years (Ev). The movement of the silencer valve does however have the expected waiting time of 1201 days, which is in accordance with the recommendations, stating that the silencer valve is to be pressure tested every four years. Moreover, the lower bounds of the 95% confidence intervals for the shape parameters of all maintenance activities, expect "Movement of silence valve", are above 1. That indicates that the rates of the corresponding maintenance activities are increasing over time.

Since these activities can all be regarded as preventive maintenance, it is possible to put the activities with similar waiting time in a maintenance package, where those activities are conducted simultaneously. That means that lubrication of top valve, working valve, choke valve, silencer valve and collection system valve would have the expected waiting time of approximately 2 years (eV). The movement of head valve would then be done approximately after 830 days, and the movement of the silencer valve every four years, along with its pressure testing.

4. Discussions

The statistical maintenance model presented should be of interest to geothermal power plants. In the beginning stages of developing their maintenance management procedures for their wellheads, this can be used to get a feeling for the required maintenance intervals. This is of course dependant on the geological condition of the field. After the numbers have been established, the model can be used to optimise the maintenance management of the wellheads. Due to the dynamic nature of the power plant, the statistical model has to be updated regularly.

In the case study presented, the power plant had been operating for several years. This means that the frequency of maintenance activities had dropped to some extent. This is evident in the expected waiting time , which is for most actions approximately 2 years which is almost double the recommended time originally outlined by the power plant. The extended waiting times can be explained with the fact that the wells at Hellisheidi where not allowed to clean themselves by blowing for some period of time, but were put instantly in production. This leads to wearing of the mechanisms since minerals in great quantities are flowing through the wellheads. At present, the amount of the mineral flow has gone down greatly, leading to the extended waiting time between maintenance activities. It can also be assumed that operational experience in combination with preventive maintenance procedures has assisted with the lower frequency of maintenance conducted. It should also be noted that over 50 different maintenance activities were recorded over the timeframe studied. The seven activities that are used in this study cover however the vast majority of maintenance conducted at the Hellisheidi geothermal power plant with regards to the wellheads.

5. Conclusion

This article presented a statistical model for visualising and establishing the time intervals between maintenance activities. Such a model is necessary because the provided guidelines do not state precisely how frequently the maintenance procedures should be conducted.

A statistical model such as the one presented here is intended as a practical tool for geothermal power plant managers developing a maintenance model and procedures for the geothermal wellheads.

Acknowledgement

Our gratitude goes to GEORG (Geothermal Research Group) (Grant no. 11-04-005) for funding this research.

Appendix A.

See Fig. 5.

References

Atlason, R.S., Unnthorsson, R., 2013a. Hot water production improves the energy return on investment of geothermal power plants. Energy 51 (0), 273–280, http://dx.doi.org/10.1016/j.energy.2013.01.003.

Atlason, R.S., Unnthorsson, R., 2013b. Operation and maintenance in Icelandic geothermal power plants – structure and hierarchy. In: Proceedings of the ASME Power 2013 Conference (accepted), ASME.

Atlason, R.S., Unnthorsson, R., 2013c. New Design Solves Scaling Problems on Geothermal Control Valves.

Casella, G., Berger, R., 2002. Statistical Inference, Duxbury Advanced Series in Statistics and Decision Sciences. Thomson Learning http://books.google.is/books?id=0x_vAAAAMAAJ

Cohen, A.C., 1965. Maximum likelihood estimation in the Weibull distribution based on complete and on censored samples. Technometrics 7 (4), 579–588.

DiPippo, R., 2008. Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact, Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact. Elsevier Science & Technology http://books.google.is/books?id=YsSN8gdqKWEC

Gunnlaugsson, E., 2013. Chemical composition of separator fluids at Hellisheidi Geothermal Power Plant, Tech. Rep. Reykjavik Energy.

Kalbfleisch, J.D., Prentice, R.L., 2011. The Statistical Analysis of Failure Time Data, vol. 360. John Wiley & Sons, Hoboken, New Jersey.

Kotz, S., Balakrishnan, N., Johnson, N.L., 2004. Continuous Multivariate Distributions, Models and Applications, vol. 1. John Wiley & Sons, New York.

Mannvit, 2010. Borholur og utblastursbunadur – hellisheidi, Tech. Rep. Orkuveita Reykjavikur.

Miller, R., Gong, G., Muñoz, Á., 1981. Survival analysis. In: Wiley Series in Probability and Mathematical Statistics: Applied Probability and Statistics. Wiley http://books.google.is/books?id=cttQAAAAMAAJ

OR, 2014a. Leading The Way in Energy. Reykjavik Energy.

OR, 2014b. Hellisheidavirkjun. http://www.on.is/virkjanir

Pierskalla, W.P., Voelker, J.A., 1976. A survey of maintenance models: the control and surveillance of deteriorating systems. Nav. Res. Log. Q. 23 (3), 353–388, http://dx.doi.org/10.1002/nav.3800230302.

Thorhallsson, S., 2003. Geothermal well operation and maintenance. In: IGC2003 Short Course, Geothermal Training Programme, The United Nations University, Iceland, September 2003, pp. 195–217.

Thorhallsson, S., 2005. Common problems faced in geothermal generation and how to deal with them. In: Proceedings of the Workshop for Decision Makers on Geothermal Projects and Management, Naivasha.