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Casing failure analysis and proposed repair for well OW-740A in Olkaria Geothermal Field

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ABSTRACT

Geothermal wells experience extreme temperature changes during production and if the wells are not properly designed and the casings cemented in place properly, the wells are likely to experience failure during production (Kaldal et al., 2015). Well OW-740A is an example of this failure where casings have parted in three locations i.e., 187, 198, and 318 m. The well started developing steam leakage between 20" and the 13-3/8" casings after about one year of being shut-in after drilling and testing. A quenching operation was conducted to try and reduce the wellhead pressure and to replace the leaking master valve followed by a caliper logging to establish the condition of the casing string. This is where the casing failure was detected at the three locations.

The main cause of these multiple failures in the casing string is largely unknown but the most logical hypothesis points to faults in cementing of the production casing and thermal stresses induced in the well due to acute changes in temperatures during quenching from a high of about 300 °C to around 26 °C. These stresses must have taken a huge toll on the K55 grade material of the casing leading to plastic deformation followed by snapping of the casing during cooling.

Currently, the well is under vertical discharge through a 10" blowpipe at a discharge pressure of 6 bar_g, and from the analysis in this study, the well formation has enough containment pressure to prevent a blowout. Therefore, the safety of the well and surface equipment is ensured when the well is discharging.

In this study, an analysis is done on the well including the drilling data, pressure-temperature analysis, casing caliper logs, and cementing of the well. This will form a basis to compare the casing design to the Africa code of standards for geothermal drilling through a casing failure evaluation. Establishing the root cause of the failure helps to find the best intervention procedure and forms a basis in designing future geothermal wells in Olkaria. A remedial operation procedure is proposed for repairing well OW-740A.

1. INTRODUCTION

Olkaria geothermal field is located in the central segment of the East Africa Rift system as shown in Figure 1 (Mwangi and Mburu, 2005), and currently produces 865 MW_e. It is the largest geothermal field in Kenya with an estimated area of about 205 square km (Atwa; 2018). Approximately 318 wells have been drilled to date with the first production well drilled in the 1970s.

Well OW-740A, located in Olkaria Northeast (Kengen, 2017), experienced casing failure and forms the basis of our study of how exposure to extreme geothermal temperature variation can compromise the integrity of a well. Based on the initial well discharge data, well OW-740A has the potential to produce 7.9 MW_e for a steady discharge condition at a pressure of 12 bar_a and an average enthalpy of 2613 kJ/kg.

The well was drilled in 101 days using two rigs in two sections and was completed on March 27, 2018. It was designed as a production well to supply steam to the proposed Olkaria VII power plant project (KenGen, 2017). After exactly one year and four months of completing the well, on July 3, 2019, steam leakage was reported on the well during a well-sitting committee forum. The steam leakage developed between the surface and anchor casings. In addition, there was observable steam leakage also at the master valve and along a fracture at the bottom of the cellar which was trending in the E-W direction as shown in Figure 2 below.

This leakage increased in quantity over time, to the point that fumaroles developed at the well pad in the areas surrounding the cellar and it was threatening to be uncontrollable if it was left uncontained (see Figure 3). It was at this point that a quenching operation was recommended to lower the wellhead pressure and investigate the cause of the steam leakage. Quenching was done on the 8th of August 2019 at a rate of 25 l/s using a high-pressure triplex pump cementing unit and after 4 hours the well was successfully killed. Continuous pumping was allowed so that a logging operation could be conducted. The multifinger caliper survey conducted suggested that the casing had parted at various locations i.e., 187 m, 198 m, and 318 m.

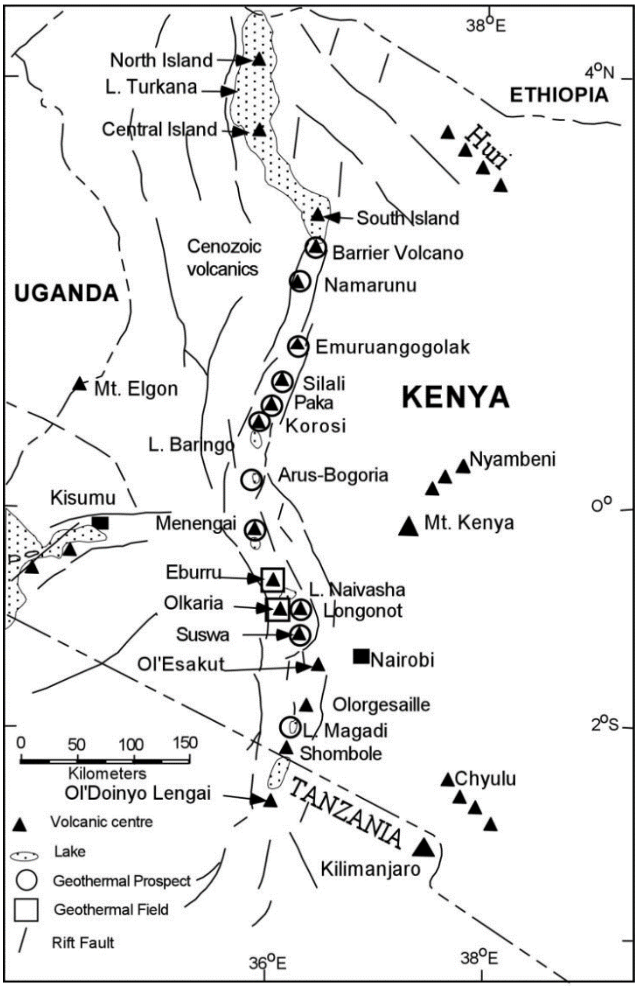

FIGURE 1: Location of Olkaria geothermal field (Mwangi and Mburu, 2005)

FIGURE 2: Situation at well OW-740 at the initial stages of steam leakage development (July 2019)

FIGURE 3: Steam leakage at later stages of development.

After the survey, the well was let to discharge vertically to avoid pressure build-up. Furthermore, an additional containment measure of conducting a squeeze cementing operation was done to try and seal the conduits that transmit steam to the surface. This was done by welding in place two halves of the 20” casings, then pumping through a valve to squeeze as much cement slurry as possible while the well was discharging. The cement slurry pumped during this operation was about 4 m^3. This process is described in Figure 4 below. After this squeeze cement job, leakage between the casings stopped including steam that was escaping between the fractures.

1. Welding the containing casing in place

2. Welded casing ready for the squeeze operation

3. Conducting the cementing squeeze operation

4. After conducting the squeeze operation and pumping 4m^3 of slurry

FIGURE 4: Squeeze cementing operation at well OW-740A

A permanent solution is however urgently needed to repair the well of the failed casings to ensure long-term production from the well. The purpose of this study is to look for the most economic, realistic, and technically feasible solution to the Olkaria situation. To arrive at this, the methodology presented in section 3 was followed. The timeline for the activities is shown in table 1 below.

TABLE 1: Timeline of activities at OW-740A

Start date	**End date**	**Description**	**Duration (days)**	Q1, 2017			Q2, 2018			Q3, 2018			Q4, 2018			Q8 2019			Q10, 2020			Q10, 2020			Q17, 2021		
				O	N	D	J	F	M	A	M	J	J	A	S	J	A	S	J	F	M	A	M	J	O	N	D
29/09/ 2017	26/10/ 2017	1st Rig (N370)	27																								
12/01/ 2018	27/03/ 2018	2nd Rig (KGN 1)	74																								
11/07/ 2018	05/09/ 2018	Discharge test	56																								
03/07/ 2019	04/07/ 2019	1st steam leakage observed	1																								
08/08/ 2019	09/08/ 2019	Quenching	1																								
08/08/ 2019	09/08/ 2019	Calliper log	1																								
03/02/ 2020	04/02/ 2020	Squeeze cement	1																								
24/02/ 2020	25/02/ 2020	Quenching																									
04/02/ 2020	15/11/ 2021	Vertical discharge	650																								

2. LITERATURE REVIEW

In petroleum drilling, the most important factors to consider in casing design include casing weight, fluid pressure, and tensile loading. However, in geothermal casing design, high temperatures contribute to most failure modes. Given the fact that most steel grades for the casing materials are designed to cater to the petroleum industry, this further complicates the material selection process in geothermal environments which experience extremely high temperature in the reservoir formations (Hole, 2008). During the lifetime of a geothermal well, the casings are subjected to thermal-mechanical loads which may lead to various modes of failure. These loads mainly consist of casing weight, changes in temperature and pressure and therefore, ideal casing design focuses primarily on (i) axial tension, (ii) burst, and (iii) collapse pressures. (Kaldal et al., 2015). The casing must be able to withstand the expected loads during its lifetime.

The casing material used in a geothermal well that is exposed to high temperatures (250-300 °C) and high enthalpy 1000-2800 kJ/kg is bound to experience a considerable decrease in the material's yield strength (Pudyastuti et al., 2020). Therefore, in a geothermal well design, it is prudent to consider temperature changes that are likely to be experienced to make the appropriate choice of casing design and material selection to be used. Once the casing is installed in the well and cemented, it is restricted and temperature changes create axial compressive stress within the casing string. Temperature changes within a geothermal well can vary from a high of about 310 °C in shut-in conditions to as low as 26 °C in quenched or killed conditions (Pudyastuti et al., 2020), and this temperature variation causes a considerable effect on the material properties which needs to be investigated to prevent casing failure.

Geothermal well cementing is done in much the same way as oil and gas wells with a major variation on the environment with which the cement is exposed (Nelson and Guillot, 2006). The bottom hole reservoir temperature in the geothermal well can be as high as 370 °C. The failure of several geothermal fields has been directly attributed to cement failure (Southon, 2005). In addition to high temperatures, the formations encountered while drilling these wells comprise of highly fractured to poorly consolidated which are ideal for good production of steam. Consequently, lost circulation presents a serious challenge to successfully cementing geothermal wells. It is not uncommon to have total losses before the intended setting point of the production or intermediate casing string (Nelson and Guillot, 2006). All these obstacles make getting a quality cement job in a geothermal environment such a challenging task.

3. METHODOLOGY AND WORK PLAN

The methodology adopted for this study involved a comprehensive analysis of the casing failure with a view of finding the best possible workover intervention. This involved analysis of the available well data, doing case studies of wells in the geothermal industry with similar casing failure and their recommended workover operations, and finally a proposal of the best well intervention that is realistic, good value for money, and technically viable.

Integrity assessment of the well was done through pressure and temperature and multi-finger calliper logs. These data were analyzed to find where the casings have parted. However, a cement bond log was not carried out and therefore the competence of the cement between the casings could not be ascertained. Casing failure evaluation was done by looking at the drilling challenges encountered and performing the casing depth analysis.

Benchmarking with other wells is important in this study to benefit from the experience of other geothermal fields that have had the same challenge of casing failure and how they have been able to do their intervention. The wells analyzed in this study include well HE-53 in Iceland´s Hverahlíð area, relief well 5R-13D in the Philippines, and well explosion in Onikobe geothermal power station in Japan.

Following the study results, a workover plan was proposed. The methodology is shown in Figure 5 below.

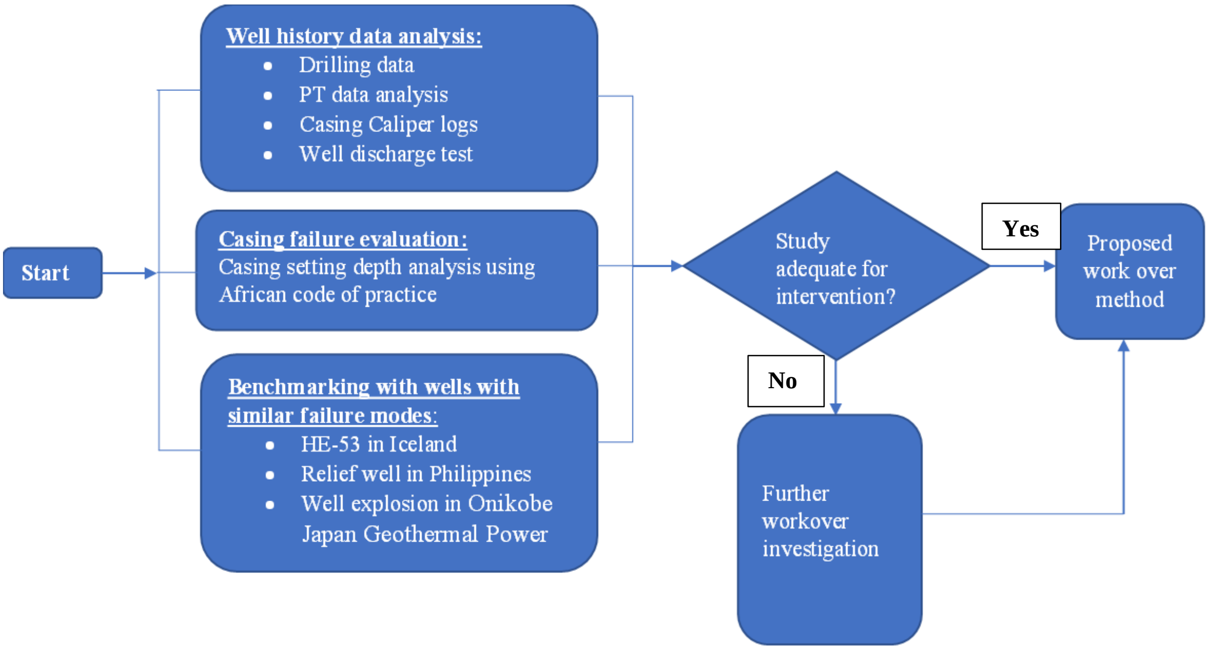

FIGURE 5: Methodology and scope of work for well OW-740A intervention

4. WELL INVESTIGATION OF OW-740A

4.1 Drilling history

Well OW 740A was designed as a production well to provide steam for the proposed Olkaria VII power plant project. The drilling of this well took a total of 101 days to a total drilled depth of 3000 m (RKB[1]) using two rigs, with the first rig (Rig N370) top holing it to 307 m between 29th September 2017 to 25th October 2017. The second rig (Rig KGN1) drilled the remainder of the well to 3000 m between the 12th January 2018 to 27th March 2018.

The 26” surface hole was drilled to a depth of 62 m (RKB) and the surface casing was set at 60.45 m (RKB). A total of 5 pieces of 20” K55 grade casings were used with a weight of 94 lb/ft. They were cemented in place using 50.11 tons of cement. The 17½” intermediate hole was drilled to a depth of 307 m (RKB) with the anchor casing placed at 304 m (RKB). 30 pieces of 13 3/8” OD, 54.5 lb/ft, and 2 pieces of 68 lb/ft respectively were used all K55 grade of steel. They were cemented in place using 109.79 tons of cement. The 12-1/4” production hole was drilled to a depth of 1007 m (RKB) with the production casing set at 991.08 m(RKB). 90 pieces of K55 9⅝", 47.0 lb/ft casings were used. A total of 59.16 tons of cement was used to hold the casings in place. The 8 ½” hole was drilled to TD of 3000m and a total of 185 pieces of 7”, K55, 26 lb/ft slotted liners were run in hole and squatted at the bottom with 2 plain liners. The summary of the casing data is presented in table 2 while the summary of drilling activities is shown in Figure 6.

TABLE 2: Casing data for well OW-740A

Nominal Size (OD)	**Nominal Weight (lb/ft)**	**Grade**	**No. of Joints**	**Length (m)**	**Casing Shoe Depth (mRKB)**	**Rig used**
20"	94	K55	5	60.1	60.45	Rig N370
13⅜"	54.5	K55	30	292.5	304	
	68	K55	2	22		
9⅝"	47	K55	90	979.18	991.08	Rig KGN1
7" Slotted liners	26	K55	185	2018.21	3000	
7" Plain liners	26	K55	2	22		

[1] Depth of the well in this report is referred to Rotary Kelly bushing (RKB) which is 10.7 m above the ground

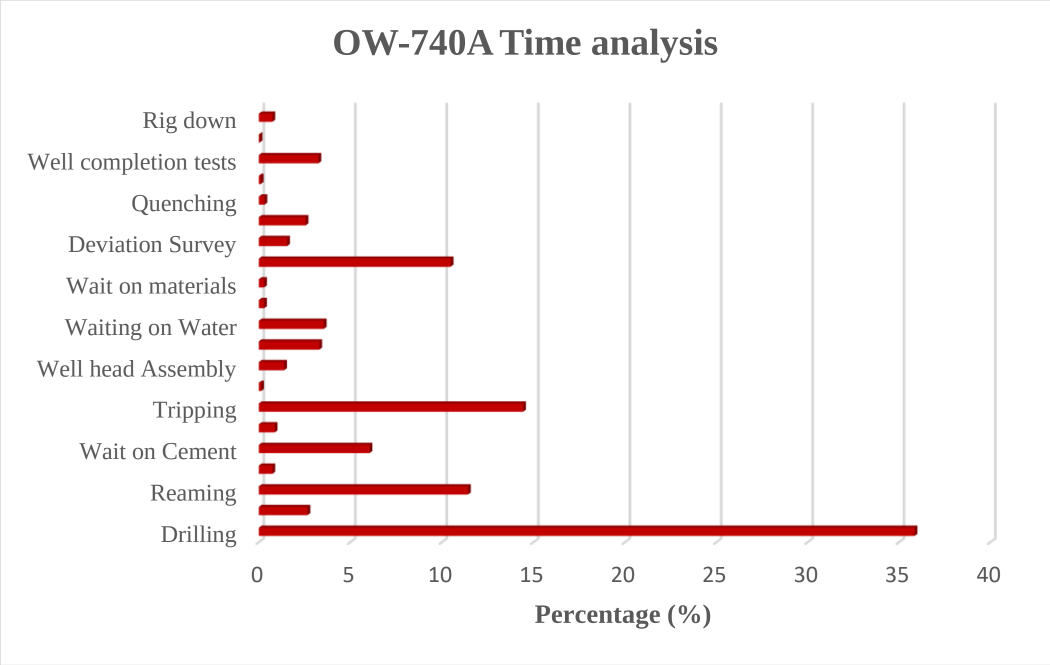

FIGURE 6: Well OW-740A drilling activities time analysis

4.2 Challenges encountered during drilling

From the drilling completion report, the following were the major drilling challenges encountered; (KenGen internal report, 2017)

- Several obstructions were encountered while drilling the 12¼" hole sections. These obstructions were encountered at 381 m, 385 m, 393 m, 394 m, 436 m, 560 m, and 759 m which resulted in many days spent reaming the wellbore.
- The tight hole at 387m (below casing shoe)was the most troublesome leading to many days of reaming and challenges while RIH of the casings.
- These obstructions became more apparent while RIH 9⅝" casings. Efforts to circulate wellbore to ensure smooth RIH casings were not fruitful compelling the team to remove one casing. This resulted in the change of the original casing depth from 1007 m to 991m.
- While drilling the 8½" hole section using aerated water and foam, the well kicked at various depths i.e., at 2605 m, 2643 m, and 2930 m resulting in quenching before drilling ahead. This quenching may have damaged (possibly) the badly cemented casing.

4.3 Geological formations encountered

Stratigraphy encountered during drilling was as presented below in Figure 7 (KenGen internal report, 2018)

0-50 m: Pyroclastics. loose unconsolidated cuttings mainly of tuffs, trachytes, lithic material, obsidian, volcanic glass, and pumice. Washouts and cavings are likely to be experienced in this zone.

50-200 m: Rhyolite. This zone consists of relatively fresh to slightly altered and oxidized rhyolitic lavas with minor intercalations of scoria and tuff. Formation is mainly medium-hard and generally massive although fractured. Circulation losses may occur.

200-600 m: Rhyolite and tuff. This zone consists of mainly weakly altered rhyolite. Generally, the tuff formation is expected to be medium soft, and blocky lavas are expected in layers with rhyolitic formation.

600-1200m: Trachyte and interactions of rhyolite. This zone consists of trachyte with occasional rhyolite. Minor intercalations of basalts and tuffs may be intercepted. This zone is moderately hard to hard and partial losses may be experienced. Production casing may be set in this zone.

650-3000 m: Trachytes. This zone is mainly made up of trachytes with occasional interactions of thin layers of rhyolitic lava flows. The formation is expected to be medium-hard and moderately altered. Minor losses may be experienced.

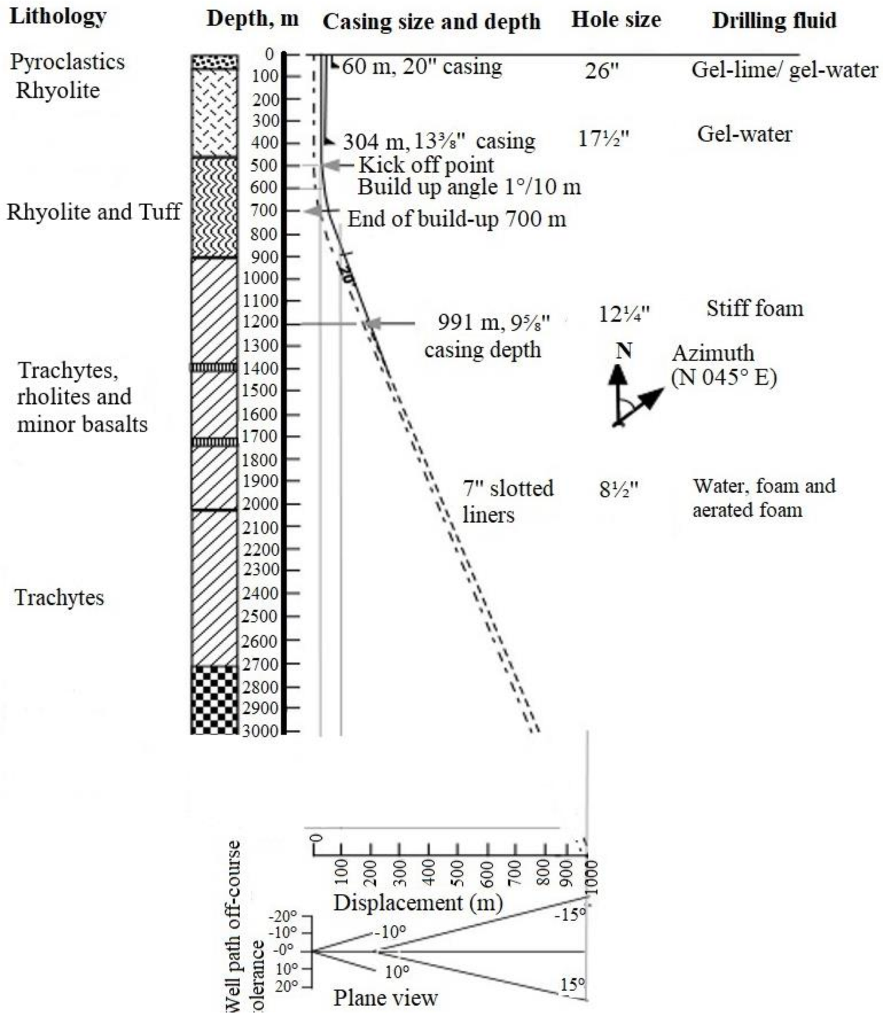

FIGURE 7: Well design for well 740A showing the lithology (KenGen, 2018)

4.4 Well discharge test

Well OW-740A had a shut-in well head pressure of 106 bar (1547 psi). It was opened for discharge on 11th July 2018 at 1030 hrs whereby it was discharged for 63 days before being shut-in on Tue 4th September 2018 at 1200 hrs. During this period, it was discharge tested using the lip pressure pipe method. The well discharged high enthalpy fluids (>2500kJ/kg) and it sustained flow on 8”, 6”, 5”, 4” and 3” lip pressure pipes while maintaining high well head pressure of above 5.0 bar (KenGen, 2018).

From this test, it was confirmed that the well was majorly producing from a steam-dominated zone with water to steam flow ratio of 1:7. For steady flow discharge conditions at a pressure of 12 bar_a, the well discharged 57 t/h steam, 1.5 t/h of water, and 61 t/h total fluid flow with a discharge enthalpy of 2613 kJ/kg and power output of 7.9 MW_e. A summary of the discharge data is shown in table 3.

TABLE 3: A summary of well discharge parameters at stable well head conditions

Lip pipe	**WHP (bar_g)**	**Mass (t/h)**	**Enthalpy kJ/kg**	**Water (t/h)**	**Steam (t/h)**	**Power (MW_e)**
8"	5.8	59.2	2667	0.1	57.0	7.9
6"	7.5	60.3	2654	0.6	58.0	8.0
5"	10.0	59.5	2647	0.8	56.6	7.9
4"	15.3	60.0	2578	2.6	54.7	7.6
3"	24.7	57.2	2521	3.9	51.0	7.1

4.5 Casing failure inspection

A quenching operation was conducted on the 8th of August 2019, followed immediately by a casing inspection survey. At first, a dummy run was done to establish clearance in the production casing. While the water was continuously being pumped, a PT survey was carried out to a depth of 350 m. Thereafter the casing calliper tool was run in close succession while cold water was being pumped. This was performed by a MAC60 tool which is a 60 multi-finger, starting from the bottom, 350 m moving upwards to a depth of 50 m. The survey was not run deeper because there were signs that the well would kick again. The result of the survey is shown in Figure 8 below.

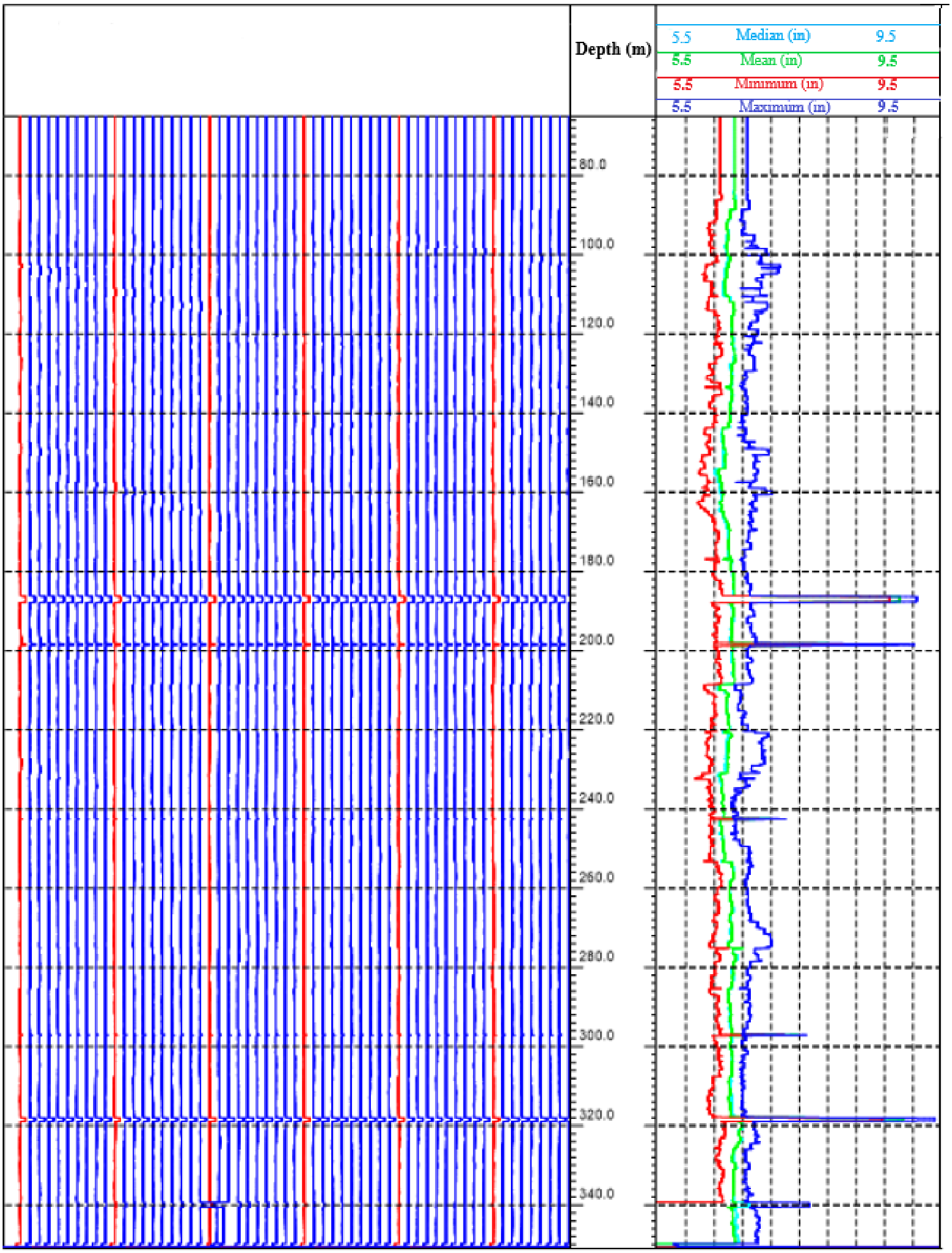

FIGURE 8: Full range calliper results.

The survey shows three locations where the casings have parted. These are at 187 m, 198 m, and 318 m depths. The full extent of these damages is presented in the expounded view in Appendix A and B.

The parted casings at 187 m and 318 m depths seem to indicate a perfectly circular increase in internal diameter that may be attributable to the parting of casing. The breach at 187 m is the widest suggestive of a typical casing failure which may be due to sudden thermal stresses caused by quenching the well suddenly. The casing breakage at 318 m is likely to be responsible for the provision of passageways of steam departure from the well and possible conduits of steam to the crevices leading to the surface. The casing breakage above are inside the anchor casing and should not cause steam leakage out of the well unless the anchor casing is broken as well.

Due to parted casings, the flow of steam to the surface is perceived to flow as shown in Figure 9 below. With time this flow between the surface and anchor casings intensified and grew in magnitude as steam found its way to the surface.

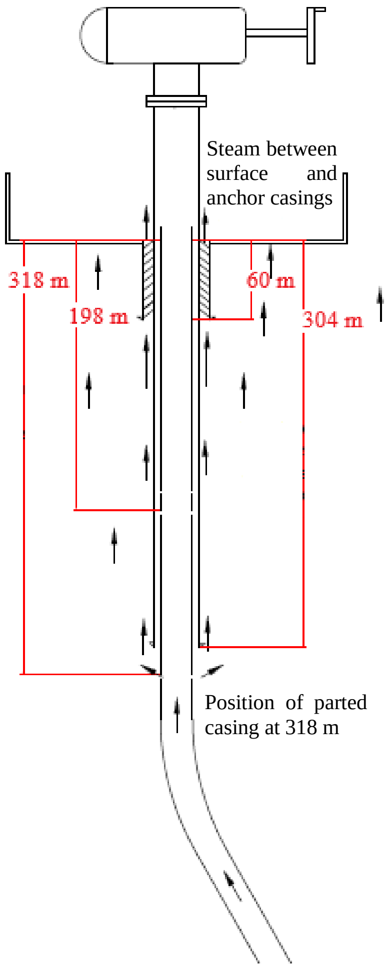

FIGURE 9: Possible flow of steam in well 740A due to the parted casings

5.0 CASING SET ANALYSIS

5.1 Casing set analysis design according to the African code of practice

According to the African code of practice, which was adopted from New Zealand's standard of geothermal wells, the minimum casing shoe depth for each cemented casing should be calculated to the depth where the formation has sufficient containment pressure to equal the maximum design pressure expected to be encountered in the next open-hole section. This is done by plotting the containment pressure of the formation using the Eatons formula shown in equation 1, together with the boiling to depth curve (BPD) which represents the maximum pressure assumed in the well, and finding the point of intersection of various casing depths as shown in Figure 10 below.

$$P_{frac} = P_f + \frac{v}{1-v}(S_v - P_f) \qquad (1)$$

Where,

$$S_v = \rho * g * h \qquad (2)$$

ρ = density

g = acceleration due to gravity

h = depth

v = poisons ratio (depends on the formation and is assumed to be 0.25 in this case)

Since the well was drilled to 3000 m RKB, which is about 2990 m measured depth from the surface, the casing sets for the various casings vary from the actual casings depths used in well OW-740A as presented in table 4 below. The conclusion is that assuming the BPD the casings depths do not comply to the African code. This deviation is though not the cause of the failure in the well.

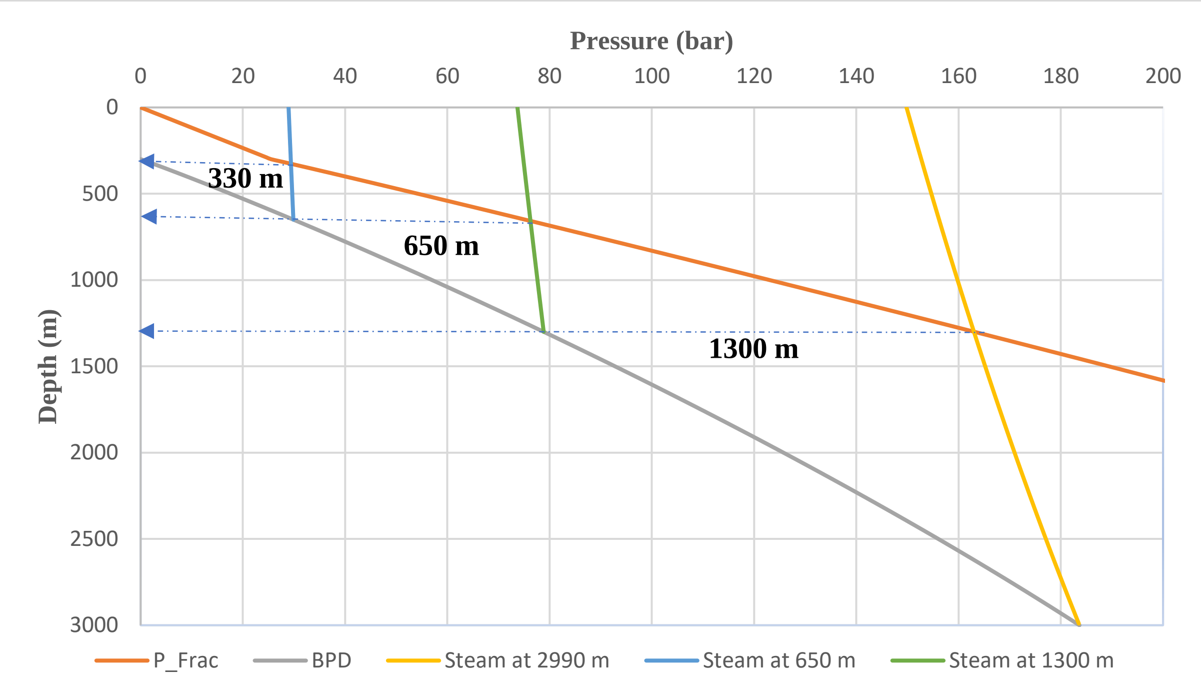

FIGURE 10: Redesigned casing set depth using the African code of practice (the dotted line shows the intersection of pressure and formation pressure curves)

TABLE 4**:** A comparison of the designed depths with the actual setting depths chosen for the well.

Casing	**Well 740A casings depths (KenGen, 2018)**	**Redesigned OW-740A setting depths using African code of practice**
Conductor casing	-	-
Surface casing	60 m	330m
Anchor casing	307 m	650 m
Production casing	991 m	1300 m

5.2 Design of setting depth using the actual WHP

Further analysis was made based on the fact that the actual shut-in wellhead pressure is known. From the well OW-740A discharge report, it was established that the shut-in wellhead pressure was 106 bar_g. With this knowledge, the steam pressure from the wellhead was plotted down to the formation containment curve as shown in Figure 11 below.

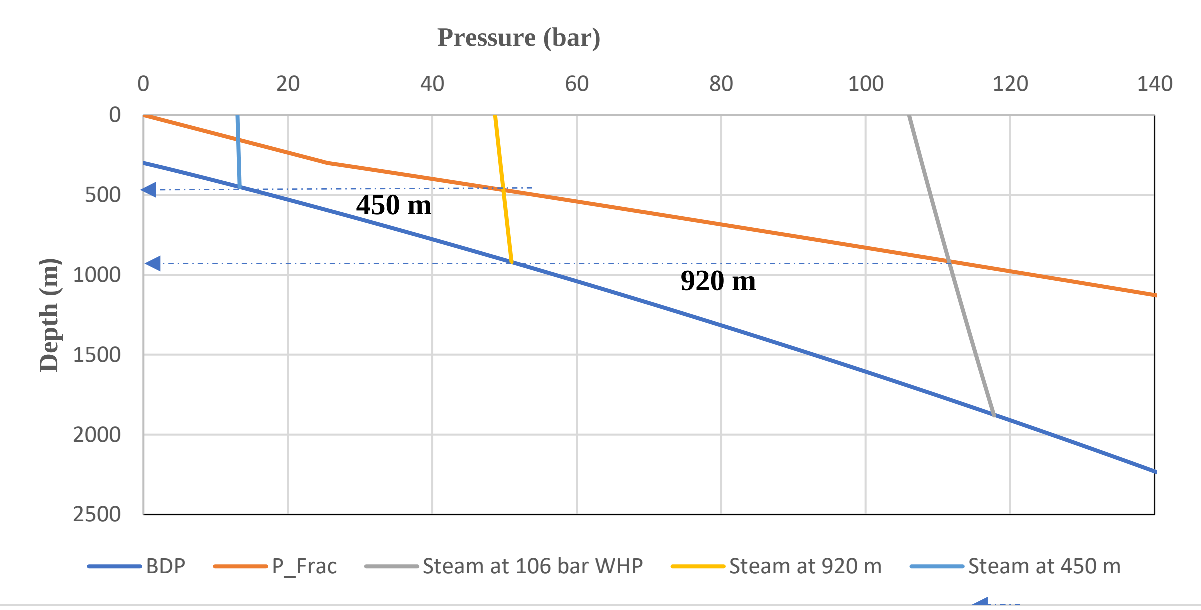

FIGURE 11: Design of the casing depth from the known WHP of 106 bar_g (the dotted line shows the intersection of pressure and formation pressure curves)

From this plot, we see that the minimum casing depths for the production, anchor, and surface casings are 920 m, 450m, and 100m. The comparison with actual setting depths is as shown in table 5.

TABLE 5: A comparison using actual nWHP with the actual setting depths.

Casing	Well 740A casings depths (KenGen, 2018)	Redesigned OW-740A setting depths using the actual WHP of 106 bar_g
Conductor casing	-	-
Surface casing	60 m	150 m
Anchor casing	307 m	450 m
Production casing	991 m	900 m

From this analysis, we can deduce that the production casing was set at the appropriate design depth. However, the plot also shows that the pressure in the well at 318 m where the casings have failed, is way above the containment pressure of the formation.

5.3 Pressure at 318 m at the current discharge condition.

At the time of writing this report, the well was discharging vertically through a 10” blowpipe. Therefore, it is important to ascertain whether the well is safe if left to discharge at the current discharge pressure of 6 bar_g. This was done by looking at the depth where the well can contain this pressure by plotting the steam curve from the surface down to the formation pressure curve as shown in Figure 12 below.

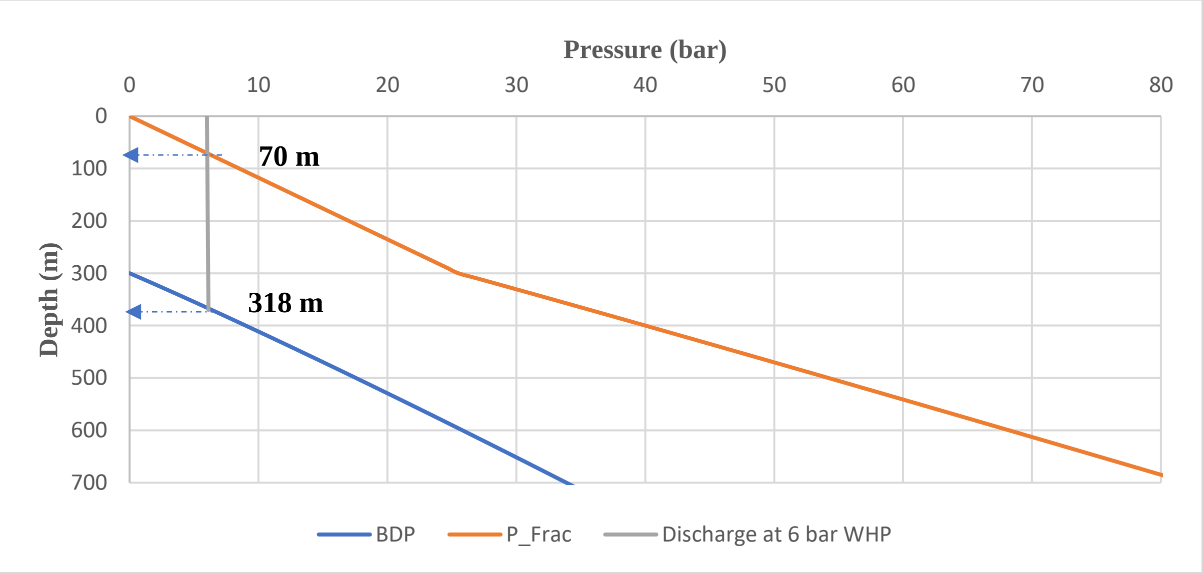

FIGURE 12: Pressure at the parted casing relative to the containment pressure of the formation (the dotted line shows the intersection of pressure and formation pressure curves)

From the plot, we see that the minimum depth that the formation can contain this pressure is about 70m. Therefore, the point where the casing has parted, 318 m, the rock has enough containment strength to sustain the discharge from the surface. It is however not strong enough if the well is shut in.

6.0 Proposed intervention

Currently, the well is under vertical discharge. We have seen from Figure 12 that it is safe to let the well discharge as this does not pose any danger to the surface equipment as the pressure exerted at the parted casings is well below the containment pressure of the formation. Our aim for choosing a workover intervention is to choose a method that is realistic and will enable us to save the well for future production of steam. From the discharge tests, we saw that the well has the potential to produce up to 8 MW_e at a steady pressure of 5 bar. Therefore, the best intervention must keep in mind ways of not compromising the production of this steam to get a return on investment.

The first step will be to kill the well while setting the parker to seal off the production zone and a slurry pumped to form a plug that will prevent the well from kicking. This is because we cannot work on the well while it is discharging. From there a rig will be installed and the following proposed intervention will be undertaken.

1. Conduct a cement bond log. This will be done to assess the integrity of cement behind the 9 5/8” casing.
2. After knowing the status of the cement bond log, we will assess the possibility of bridge plug access by running a taper mill or a full drill mills using twice water melon to mill casing at the parted intervals. Drilling jar must be put in place to avoid stuck pipe situations.
3. Set the bridge plug below the lower parted casing (at around 318m).
4. RIH with cement retainer just above the lower parted casing and perform a squeeze job.
5. Set the bridge plug below the middle-parted casing
6. RIH with cement retainer just above the middle-parted casing and perform a squeeze job
7. Set the bridge plug below upper parted casing
8. RIH with cement retainer just above upper parted casing and perform squeeze job
9. Drill out retainer and plugs
10. Clean well with wellbore clean up run and scrape casing
11. 11RIH with a mechanical liner setting sleeve with cementing basket below the mechanical liner
12. RIH with 7” N1 bridge plug
13. RIH and make up 7inch seal seam connected to 7” casing to surface
14. Land out in setting sleeve, space out and perform cement job on tie back. Ensure the slurry is designed with thickening time, compressive strength, rheology, and free water taken care of.
15. Drill out 7inch n1 bridge plug
16. Consider final clean out
17. Bring well back to production

CONCLUSIONS

During well construction, it is important to follow the steps outlined in section 2.3 of the Africa union code of practice for geothermal drilling. This details the step-by-step process of well design and ensures that the well is properly designed to handle the pressures in the well and the casings shoes are placed at a safe depth. In addition, a proper engineering decision on the casing material’s grade, strength, desired size, weight, and connections of casing strings should be made during this process to ensure the lifelong durability of the well.

The next critical step is to ensure that the well is properly cemented. According to the work done by Won, J et al., 2016, on numerical investigation on the effect of cementing properties on the thermal and mechanical stability of geothermal wells, they found that long-term strength degradation of the cementing might cause the severe structural instability of an entire geothermal well. Therefore, for a well to be long lasting, proper design and cementing should be executed to ensure the well is in production for many years.

In addition to this, the well experiences heat up during production or discharge. When this well is suddenly brought to a low temperature due to quenching or shutting down of the master valve or, the casing in the well is exposed to thermal mechanical loads which can lead to casing failures especially when the stress reaches the yield point and beyond. This is what happened in well OW-740A where sudden quenching led to the production casing failing at three locations i.e., 187 m, 198 m, and 318 m.

Despite this failure, well intervention is possible. From investigations from other fields, we discovered that this problem is not unique to Olkaria, other fields have experienced this type of failure. Of great interest is well HE-53 in Hellisheiði geothermal field which had casings fail in a similar manner as well OW-740A due to quenching of a high temperature well. The proposed solution to repair well OW-740A has been adapted from well HE-53 with a slight modification to ensure that we don't pump cement in the production zone which would compromise the production of the well.

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