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Why and When Does Casing Fail in Geothermal Wells: a Surprising Question?

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ABSTRACT

Casing failures in some geothermal wells cannot be easily explained using simple casing string mechanics. Some of these failures appear to be time dependent while others happen a few hours after the well is brought onto production. The detrimental effect of thermal stresses on casing is well known due to years of experience in steam injection in heavy oilfields and a geothermal well poses even more complex loading issues. After more than 100 years of geothermal experience, geothermal wells are still designed driven by oil and gas rules. However, oil and gas rules have never been developed for geothermal application, even though high pressure / high temperature wells display some similarities. This paper describes by means of analytical and numerical models why and when casing fails in geothermal wells. Casing failure by buckling is generally accepted to occur at high temperatures, but it is problematic to understand such events when cement does not allow buckling. One may ask why casing fails if no buckling occurs. This paper describes the basic casing mechanics of such a failure event using analytical methods and integrates the connection behavior into this modeling. By explaining how casing can collapse and what the possible available solutions are, the results can be used to improve the design of future geothermal casing. The case studies are supported by FEM and analytical calculations, so that the paper can become a good compendium of how to improve your casing design.

1. INTRODUCTION

Geothermal wells usually use casing for production purposes, exposing the casing to excessive thermal loads, corrosion and fatigue. The cement behind the casing can also be affected. An overview of the world wide geothermal well construction methodologies shows that most of the actual geothermal wells follow the “state of the art” in oil and gas well construction. It is worthy of note that the final diameter for more than 70% of the investigated projects was only 7”. All geothermal wells were drilled using conventional telescopic design. The typical well construction can be therefore defined as follows:

- 30” conductor pipe
- 20” surface casing
- 13 – 3/8” intermediate casing
- 9 – 5/8” production casing
- 7” slotted liner or production liner

Teodoriu and Falcone (2009) and Hahn (2010) performed a review of casing grades and connections used in geothermal projects:

- H 40: Salton Sea (USA); Brawley well (USA); Westmorland well (USA); East Mesa well (USA); Heber well (USA); Geysers well (USA); Baca well (USA); Roosevelt Hot Springs (USA); Cerro Prieto well M-8 (México); Cerro Prieto well M-120 (México); Cerro Prieto well M-150 (México); Cerro Prieto well M-110 (México)
- J 55: Hawaii well (USA); Cerro Prieto well M-8 (México); Larderello (Italy)
- K 55 (usually used for deep applications): Salton Sea (USA); Brawley well (USA); Westmorland well (USA); East Mesa well (USA); Heber well (USA); Geysers well (USA); Baca well (USA); Roosevelt Hot Springs (USA); Raft River well IV (USA); Hawaii well (USA); Cerro Prieto well M-120 (México); Cerro Prieto well M-150 (México); Cerro Prieto well M-110 (México); Krafla well (Iceland); Urach III well (Germany)
- X 56: Krafla well (Iceland)
- L 80 (used in the presence of H_2S): Larderello (Italy)
- N 80: Brawley well (USA); Westmorland well (USA); East Mesa well (USA); Heber well (USA); Roosevelt Hot Springs (USA); Hawaii well (USA); Cerro Prieto well M-8 (México); Cerro Prieto well M-120 (México); Cerro Prieto well M-150 (México); Cerro Prieto well M-110 (México); Urach III well (Germany)
- T 95: Krafla well (Iceland)
  - The following casing couplings have been commonly reported: API Buttress: Salton Sea (USA); Brawley well (USA); Westmorland well (USA); East Mesa well (USA); Heber well (USA); Geysers well (USA); Baca well

(USA); Roosevelt Hot Springs (USA); Hawaii well (USA); Cerro Prieto well M-8 (México); Cerro Prieto well M-120 (México); Cerro Prieto well M-150 (México); Cerro Prieto well M-110 (México); Krafla well (Iceland)

- API Round: Cerro Prieto well M-8 (México); Cerro Prieto well M-120 (México); Cerro Prieto well M-150 (México); Cerro Prieto well M-110 (México);
- Hydril F.J.P.: Hawaii well (USA)
- Hydril S.E.U.: Cerro Prieto well M-120 (México); Cerro Prieto well M-150 (México); Cerro Prieto well M-110 (México)
- Hydril 563 and Tenaris ER: Krafla well (Iceland)

2. WELLBORE TUBULARS FATIGUE CONSIDERATIONS

Most geothermal wells push the well construction, especially casing and its connectors, to the technical limit. Tubular fatigue is not an unknown failure mode, but it has been considered unimportant for well tubular such as casing or tubing. During its lifetime, the casing string is exposed to a variety of cyclic loads. Some of them will be discussed in the following section. Teodoriu and Schubert (2007) performed a first attempt to classify the casing string fatigue. Over the operating life of a well, the casing string is generally subject to external loads that can be considered static or quasi-static. Current industry design standards consider the casing string to be statically loaded, yet it can be subject to variable loads due to changes in temperature or internal pressure in geothermal operations. In what follows, the casing fatigue will be analyzed from the point of view of geothermal exploitation. All cases presented below do not consider classical casing failure sources like overloading, corrosion or massive wear.

Fatigue induced while running the casing. The main objective while running a casing string is to join the connections with the optimum make-up torque. During the running procedure, repeated stops are performed while lowering the casing string. The speed of this operation must be as high as possible to reduce running time, but increasing the running speed increases the dynamic loads induced while stopping. The maximum load appears in the slips zones and for a successful run the maximum of cycles for each connection must be? low, while the maximum stress will be located at the last connections of the casing string. Although it has not been documented yet, running casing in deep wells may lead to such fatigue load. Additionally, running of expandable /folded tubular may also contribute to casing fatigue while running the casing.

Drilling induced fatigue. During drilling of the next casing section, the drill string vibration may be transmitted to casing. Mostly, drilling through hard formation will inevitably generate vibrations. Hard formations are specific for hot hard rock drilling applications. Although the effect is considered small, some published results have shown such strong drill string-casing interaction that can lead to casing break-out (Schuh, 1987), especially when low rate of penetration is present. These types of vibrations may induce fatigue if the contact time between casing and drill string is high, for example in the lower part of a geothermal well, where low rate of penetration and hard formation are present.

Casing drilling. Casing drilling is considered to be one of the best techniques because it allows to reduce time, costs and wellbore problems. Geothermal drilling can profit from this technology as it shows a huge increase in casing drilling operations in the last years. Nowadays, casing drilling goes deeper and even directional casing drilling has been achieved. The large diameter of the casing used for geothermal applications amplifies the fatigue of casing used for casing drilling applications.

Internal pressure induced fatigue. Pressure variation may induce ballooning of the tubing or casing strings and result in a special type of fatigue. Although the problem has not been reported as fatigue, several tubing failures in underground storage wells could not be entirely explained. Usually, a connection leak occurs at pressures lower than the connection resistance but after a certain service time. Furthermore, as presented above, the casing-cement system may suffer from ballooning effects, which may occur in geothermal wells where stimulation is performed through casing only.

Temperature variation induced fatigue. Enhanced Oil Recovery (EOR) of heavy oils is traditionally achieved by heating the reservoir fluids, which reduces their viscosity, thereby increasing their mobility, and improving recovery. Two methods have been proved to be particularly effective for heavy oil recovery: steam flooding and hot water flooding. Since the heat is produced at the surface, some wells are used to transport the heat down to the reservoir. By doing this, the casing and tubing are exposed to high temperatures. Because the casing string has no or low mobility (due to cement sheath around the casing) high stresses are induced. When temperature variation becomes large, so does the stress inside the connections. It has been shown in many papers (Ulmanu and Teodoriu, 2005, Kaiser and Yung, 2005) that typical loads of steam injection wells may subject the casing to stresses over its yield limit. Moreover, the casing failures in such wells are visible after a certain numbers of cycles. This leads to the conclusion that the failure mode is produced as effect of fatigue. Geothermal wells may also subject their casing strings to temperature variations, especially during survey and workover operations. Well stimulation contributes also to temperature changes in geothermal wells.

3. A DISCUSSION ABOUT WHEN AND WHY DOES CASING FAIL IN GEOTHERMAL WELLS

Four cases related to casing failure in geothermal wells will be presented in the following. The first two refer to cement and casing failure due to fatigue, whereas the last two show a different aspect of casing buckling: local buckling. It is worth to mention that the local buckling is independent of the cement bonding.

3.1. Failure of cement samples exposed to variable loads

The heating and cooling process leads to expansion and shrinkage of all materials in all scenarios in the well. Especially the casing is affected from temperature changes as metals provide higher thermal expansion coefficients than cement. Thermal expansion induces forces in the cement sheath, which might lead to a cement failure. The experiments recreate the stress situation and geometry of the situation in the wellbore. The analysis utilizes the adaption of a fatigue model for metallic materials which is the stress-cycle-curve (S/N- Curve) to class G wellbore cement. The stress distribution inside the cement sheath is determined using a combination of numerical and analytical methods. An ANSYS 2D model is used to determine the casing-cement contact pressure and the stress distribution itself is evaluated with analytical equations.

The idea behind the principle of fatigue is that cyclic loading causes on any material a special form of damage called fatigue. This damage accumulates over the course of several cycles and can lead to failure. A load on a sample does not necessarily cause damage if it is rather low, but intermediate loads can cause accumulating damage. Over time this can lead to the formation of fissures starting at molecular dimensions. The fissure may widen up to cracks and result in a total material failure. For cement and concrete there are only few studies on the fatigue behavior, but a lot of research has been performed on the fatigue of metals. According to Ugwu (2008), the fatigue process passes the following stages: “Crack initiation which occurs as a result of cumulative damage in a localized region under successive cycles of loading; Crack accumulation resulting in crack growth as a result of continued loading; Crack propagation where the specimen fractures and fails.”

Kosinowski and Teodoriu (2012) show that the three steps stated above can be experimentally observed when cement is exposed to cyclic loads, as shown in figure 1. The first visible failure is the radial crack along the sample. If the load on the sample is increased and more cycles are executed more cracks can develop. Typically, these cracks grow perpendicularly to the initial crack and will start from near the middle of the cement sheath and grow towards the ends. More axial cracks are developed with increasing load. After the sample is damaged and has been loaded to the same stress for several times, the crack system starts to stabilize and no new cracks form. This implies that the casing cement bond has been lost and the pipe cannot induce additional loads on cement.

Cement cracking may lead in time to total loss of bonding, resulting in formation fluids entering the external casing surface and generating corrosion, or in extreme cases the cement can be washed out leading to classical buckling due to wellbore cave ins.

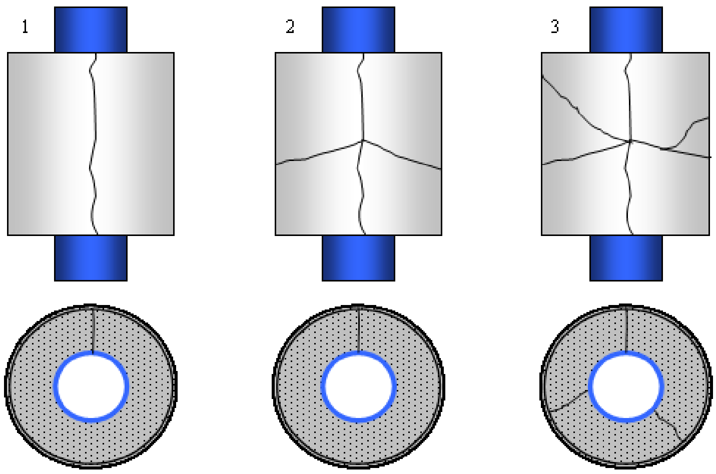

Fig. 1. Cement fatigue failure modes, after Kosinowski and Teodoriu (2012)

3.2. Failure of casing samples exposed to variable loads

As casing movement is restricted by the presence of a cement sheath, temperature variations induce thermal stresses in the casing string which may become greater than the material’s yield strength. Thus, the fatigue behavior of the casing material during a well’s operational life can be classified as LCF. The presence of geometrical variations in the casing body such as connection threads will amplify the local stress distribution, and reduce the casing’s LCF resistance.

As shown by Teodoriu and Falcone (2008), for high-enthalpy geothermal well producers with temperatures of produced fluid between 100 and 250°C the fatigue resistance of the tested N80 Buttress connections varies between 10 and 110 cycles. This information should be considered for the planning process to evaluate the minimum project life time as well as optimizing the well operations. The thread geometry, especially the incomplete thread turns finishing, strongly affects the value of stress concentration factor. For example, a lower stress concentration factor will increase the life time of the casing with over 1000 cycles, as shown in Figure 2.

3.3. Local buckling due to geometry changes (casing coupling?? effect)

Since the main load in geothermal load is axial compression, an experimental testing program was started. The experimental program consists of making up, tension and compression of three specimens with a diameter of 18 5/8” each. The connections are standard API Buttress. The investigations were focused on connection resistance under compression to failure tests. The results were later compared with those obtained by finite element analysis. The specimen was subjected to axial tension and compression in 7 load steps. First, the specimen was subjected to axial tension load up to 80% of its catalogue recommended load. The final load step was conducted until the connection had failed. Two other specimens were tested using the same procedure.

After makeup, the specimen was mounted in the ITE OCTG testing facility. The specimen was loaded under axial tension up to an axial force of 7900 kN which represents about 80% of the catalogue recommended Buttress coupling resistance of 9675 kN. After that, the load was decreased down to 0. The zero point was used to verify the accuracy of the measurement system. No deviation was observed and therefore the specimen was subjected to axial compression in steps up to 7900 kN and then continuously up to failure. The specimen failed due to local buckling of the pin under the last engaged thread turn. The failure zone is shown in Figure 3.

The load steps for the next specimens were the same as for the first specimen. The failure test of the second specimen shows the same failure mode as for the first one: local buckling at the last thread turns region, see Figure 3. Both finite element analysis and the first failure test showed that the zone of last engaged threads and incomplete threads is the critical area under compression load, see Figure 4.

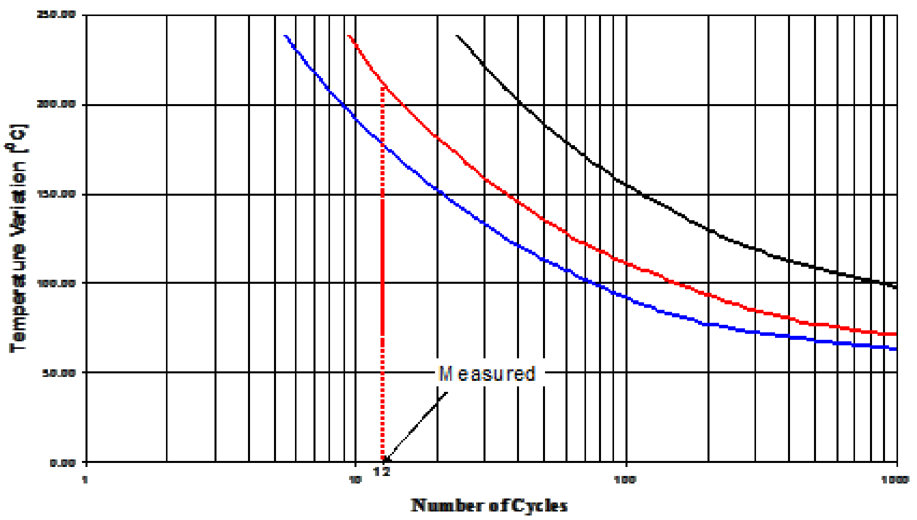

Figure 2. N80 Casing fatigue as a function of temperature, after Teodoriu and Falcone (2009)

Fig. 3. View of the local buckling of the specimen No. 1 and No. 2

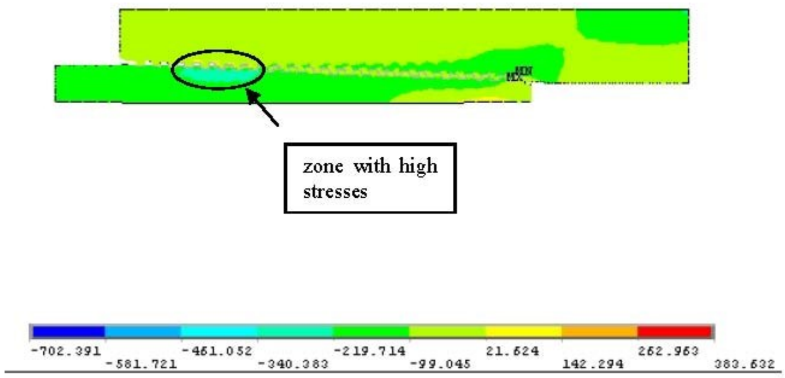

Fig. 4. View of the local buckling zone obtained using finite element analysis

3.4. Local buckling due to corrosion

Since geothermal well life is expected to exceed 50 years, corrosion of casing may pose an additional risk to buckling. In the following we will consider uniform corrosion effects (generally existing when proper protective measures are taken). A uniform corrosion will reduce casing wall thickness on the entire casing surface, as shown in Figure 5. The reduction of wall thickness will generate an increase of the stresses in this zone. The following equation can be used to estimate these stresses:

$$\sigma_A = \frac{F}{A_A} = \frac{\sigma \cdot A}{A_A} = \sigma \cdot \frac{1}{c}$$

where:

σ_A are the stresses in the corrosion zone.

A is the cross sectional area of the casing body (undamaged).

A_A is the cross sectional area of the corroded zone.

c is the ratio between A_A and A.

$$c = \frac{A_A}{A} = \frac{\frac{\pi}{4}(ODA^2 - ID^2)}{\frac{\pi}{4}(OD^2 - ID^2)} = \frac{(ODA^2 - ID^2)}{(OD^2 - ID^2)}$$

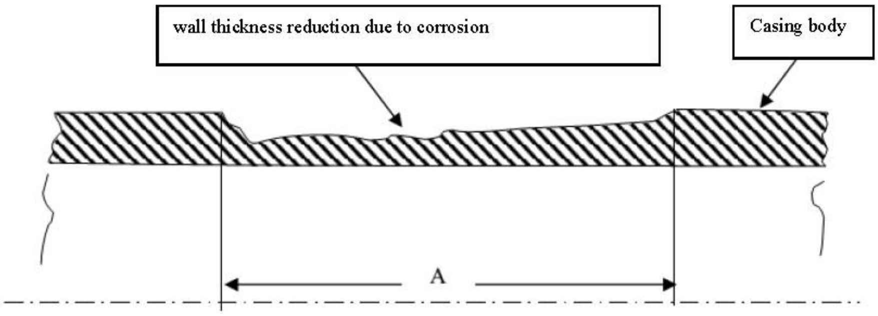

Fig. 5. External corrosion on casing can reduce the wall thickness

Physical tests were performed in order to investigate the corrosion influence on casing resistance under compressive load. The specimens were machined, according to Figure 6. The effective wall thickness after machining was between 40 and 70 percent of initial wall thickness. The reduction of wall thickness was applied on the entire casing circumference, and in the middle of it, thus simulating a uniform corrosion environment. The tests were performed up to failure of specimen (both tension and compression). It is worth to mention that during tensile test the specimen failure was a fracture located in the weakest zone of the specimen, while for compression test all specimens failed due to local buckling. A true buckling failure was not possible due to short length of the specimens.

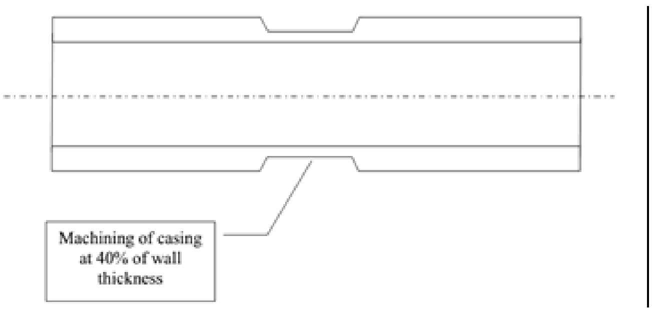

Fig. 6. Mimicking of external corrosion on casing by machining the wall thickness

The tests results are shown in Figure 7, where the stresses are compared as a function of the remaining wall thickness (rest WT) and also test type (tension or compression). Although the maximum force applied was different, the axial stress at which the local buckling was observed (failure mode for compression tests) was comparable and slightly above the measured yield strength of the material. The tensile test showed a much higher stress level before fracture (failure mode specific to tension test). Figure 8 shows the tested specimen, where the local buckling is visible in the corroded simulated zone. The loss of stability generates deformation of the pipe both inside and outside, making running of completion equipment through this zone difficult.

4. CONCLUSIONS

Designing geothermal wells requires special attention to the long time integrity of the well which may be affected by fatigue and/or corrosion. A combination of those two failure modes is not excluded.

The paper shows five possible scenarios that lead to casing failure in geothermal wells. These scenarios are: fatigue induced while running the casing, drilling induced fatigue, casing drilling, temperature variation induced fatigue, and internal pressure induced fatigue.

This paper describes several aspects of well integrity losses due to cement-casing and casing connection fatigue, as well as local buckling. It has been shown that cement can suffer cracks due to cycling loading, resulting in loss of cement-casing system integrity.

Local buckling as failure mode can affect the well integrity as well as the ability to run completion equipment in or out of the hole. Local buckling does not require free radial movement (hence, good cement bonding may not help). However, when cement integrity is lost due to fatigue cracking, corrosion may occur which will lead to local buckling as well.

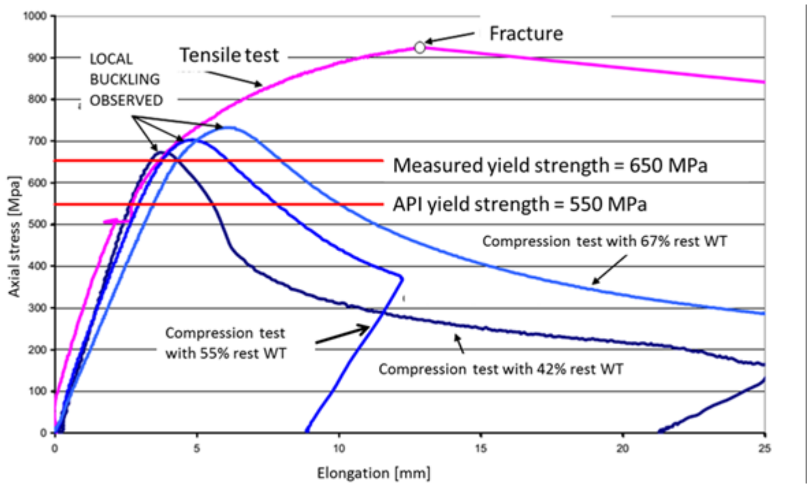

Fig. 7. Local buckling produced by external corrosion on casing is reached when the local stresses exceed the yield strength of the material

Fig. 8. Local buckling produced by external corrosion on casing: experimental results

REFERENCES

Hahn, F. "Comparing completion designs in geothermal wells", Bachelor Thesis, TU Clausthal, 2010.

Kaiser, T.M.V., Yung, V.Y.B "Cyclic Mechanical and Fatigue Properties for OCTG Materials" SPE 97775, 2005 SPE International Thermal Operations and Heavy Oil Symposium, Calgary, 1–3 November. 2005.

Kosinowski, C., Teodoriu, C. "Study of Class G Cement Fatigue using Experimental Investigations", EAGE European Unconventional Resources Conference and Exhibition held in Vienna, Austria, 20-22 March 2012.

Schuh, F.J."Failures in the Bottom Joints of Surface and Intermediate Casing Strings", SPE1845, SPE 42nd Fall Meeting, Houston, 1987.

Teodoriu, C., Falcone, G. "Comparing completion design in hydrocarbon and geothermal wells: the need to evaluate the integrity of casing connections subject to thermal stresses", Geothermics Journal, doi:10.1016/ j.geothermics.2008.11.006, 9 January 2009.

Teodoriu, C., Schubert, J. "Redefining the OCTG Fatigue – A Theoretical Approach", 2007 Offshore Technology Conference held in Houston, Texas, U.S.A., 30 April – 3 May 2007.

Ulmanu, V., Teodoriu, C. "Fatigue Life Prediction and Test Results of Casing Threaded Connection", Mecanica Ruperii, Buletinul ARMR, No. 17, July 2005, ISSN14538148.