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Geothermal well design: extending feasibility under challenging geomechanical and thermal loads

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ABSTRACT

The aim of this paper is the presentation of the analysis of a casing design in a geothermal well in the Larderello field where the drilling of the third well from the same pad was planned. In this case applying normal casing design a residual risk is present, in fact as the shallower sections of the well are considered with not high temperature of the formations. Just because in the same pad other very productive wells were present since many years, also the warming effect of the fluid production of these wells in the shallower sections have to be considered in case the distance between wells them is very low. To consider also this effect in the casing design verifying the role of the influence of the induced thermal load, it was decided to apply a different methodology.

This paper presents a methodology which complements “working stress design” with “thermal load strain-based design”. This approach allows to better define loads typical of high enthalpy geothermal wells, extending projects feasibility and optimizing well design.

The analysis explores the main complexities of well design in such environment, including annular pressure buildup (extremely important in case of very high temperature environment), materials plastic regime, thermal cycling effects and critical buckling lengths. When cementing formations with large fractures, with the aim to have a fully cemented casing string due to mitigate thermal loads effects, there is a high risk of low-quality casing cementing, with which leads to possible problems of APB and buckling. Moreover, geothermal wells are critical in case of thermal cycles because normally operates with high temperature and a fast-quenching effect on the casing may introduce high axial thermal loads under which the string may enter plastic regime introducing residual stresses. Another relevant phenomenon investigated is “cold collapse”, which is the reduction of collapse resistance when tubulars are subjected to high axial loads.

In conclusion, a case study in which a production well in the same pad produced an anomaly in the temperature profiles of a nearby well compared to the geothermal gradient is presented. Design modifications and best practices are defined by applying this design methodology to the well.

1. INTRODUCTION

This paper describes the effect of a thermal anomalies and geomechanical loads encountered while drilling a high enthalpy geothermal well. To optimize the energy recovered from a field and minimize the surface impact, multiple wells are typically drilled in a pad (Figure 1).

Figure 1 Configuration of the pad with the three wellheads.

Well C is the last of three wells drilled from a homonymous pad that already included Well A and Well B. Both existing wells are steam producers. Well A is a vertical well while the others are directional wells.

Well A is drilled up to 3.916m (all depths where not specified are considered MD) in 2014, while well B is drilled up to 4.253m in 2015. Well C is drilled up to 4.400m MD in 2020 (Figure 1).

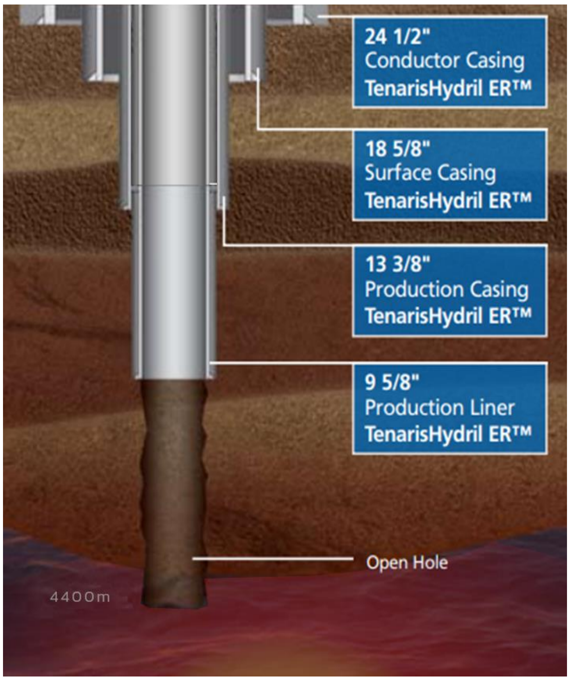

Figure 2 Well schematic

Once completed drilling, the reservoir zone is acidized and subsequently production tests are performed. At this stage the drilling activities, typically, are considered completed, however a production casing check is performed before proceeding with the rig de-mobilization. During the production casing check on Well C, a deformation of the inner diameter is detected on the 13 3/8” 68# liner at the depth of about 875m.

The severity of the deformation is enough to restrict tool passage below 875m, even with narrower diameter tools; the minimum tool diameter tries is 60 mm considering a drift of 311,4mm (12.259”) for the 13 3/8” casing. Recovery operations are conducted to regain access to the well, during which is confirmed that the diameter restriction is related to casing deformation. The deformation is confirmed at a depth between 875m and 883m.

While reviewing the operations performed at the well, the following relevant events are identified:

- During drilling of the last section of the well a total loss of circulation occurred, this is a necessary condition for the well production, otherwise the injectivity index would be so poor to not allow any interesting steam production. During recovery operations, instead, circulation came back partially or even totally. This could be an indication of complete obstruction of the well at the damaged depth. It is worth highlighting that the productive formation is characterized by large fractures and loss of circulation is a common event for this site.
- During recovery operations, with milling tools, from 875m, metal chips mixed with cement and formation cuttings are collected on the mud shakers. This is evidence that casing, cement, and formation are all displaced inside the hole.
- Total loss of circulation reappears below the depth of around 882m in the final stare of recovery operations.

The presence of cement and formation debris in the circulated mud, could suggest the presence of a strong geomechanical load and induced displacement as cause of casing deformation. Detailed analysis is shown in the following of this paper.

Casing deformation under geomechanical loads, even if not frequent, is reported in literature for oil & gas wells and more often for geothermal wells, due to the typical formations of conventional geothermal fields. Moreover, in geothermal applications, casing deformations are reported after production tests or alternate production shut-in cycles characterized by high temperature variations.

2. GEOLOGICAL AND GEOMECHANICAL LOADS

The interval analyzed is composed by an alternance of shale and marly limestone belonging to the “Dominio Ligure” formation. These types of formations are characterized by high instability that impacts the wellbore solidity.

Formation collapse problems appeared while drilling the 17.5" hole, in the interval 640m - 900m. Below this depth mud weight is been increased by 0.1 kg/l, in order to improve the wellbore stability.

Once drilling of the 17.5” hole is complete, a 3D profile of the bore obtained by a 4-arms caliper log highlights a great ovalization with a diameter up to 28" from 640m to 900m, probably related to hydration of shales and their plastic behavior. Below this depth the wellbore geometry returns regular.

Instability of formations can generate radial, shearing, loads on the wellbore and consequently on the casing string. From a geomechanical analysis performed according to Coulomb/Mohr criteria, the loads induced by formation shearing forces at the collapse's depth, are estimated in about 120bar (collapse rating according to API TR 5C3:2018 is 156bar).

3. WELL LOGS

As already mentioned, after cementing the 13 3/8” string, several logs are performed including cement bond logs. Dimensional analysis, measuring inner diameter and wall thickness, of the string show a high grade of ovalization between 850m and 882m, mostly at 873.35m and 881.50m with ovalization peaks up to 2%. No concerns are highlighted from cement logs in this portion of the well.

After recovery operations, cased hole logs are repeated. In this case, multi-finger and ultrasonic calipers are used respectively to analyze the status of 13 3/8” casing and to compare data with previous logs.

Comparison of Corrosion Logs data shows a significant ovalization, compared to the neighboring portions of the well, increase in ranges from 380m to 490m and from 640 to 860m. Moreover, increased ovalization punctual peaks are over 5% at 773.35m and 881.50m. MFC Log confirmed data from Corrosion Log. The tools recorded clear ovalization around 770m and 850m.

4. WELL TRAJECTORY ANTICOLLISION

As the collapse of Well C happens at the depth of 875m, the distance between Well C and the other two wells may be considered as another key factor. While During drilling operations special care is used to maintain the proper distance between different wells adjusting drilling parameters to maximize well verticality, acquiring many surveys for well trajectory monitoring. While drilling, there is a reasonable risk of “collision” because there is a tendency for the trajectory of Well C to get close to Well A. This tendency is not predictable during the design stage since geomechanical loads are expected to be oriented in the same direction, while during drilling these loads are found to be pushing one well towards the other.

In fact, the surveys during drilling, while planning shows at the depth from 800m to 950m, a distance of 2.3m - 2.5m while the lowest distance between the actual wells is about 1.6m at 882m. This behavior is clearly recognized and managed during drilling, however wellbore instability (with high risk of getting the BHA stuck) requires to drill as fastest possible this section, not allowing a not run with PDM and MWD as planned. For this reason, it is decided to continue in rotary drilling, acting on drilling parameters to minimize the undesired effect.

Shall be highlighted that while drilling Well C, Well A is in production. Drilling operations of Well C and thermal cycles of Well A combined with the current configuration (e.g. proximity of two wells) can be regarded as an element of destabilization for that portion of Well C.

5. THERMAL CYCLES

While drilling and during production tests, casing strings are subject to different thermal cycles and corresponding loads.

An important thermal load took place during the 13 3/8” cement job. Before cementing, the circulation temperature is about 90ºC. During wait on cement, circulation stops and the temperature profile goes back to the static temperature profile (inducing a geothermal gradient 50ºC higher than circulating profile at the depth of interest).

As described above, the actual trajectory of Well C is closer to Well A than designed with the anticollision analysis, with a minimum distance of 1.6m at 880m (depth of interest). The presence of a productive well near the wellbore induces a perturbation in thermal gradient, and the temperature at the minimum distance reaches 215ºC, inducing an average thermal anomaly in the geothermal gradient of 120ºC. The consequence of this anomaly impacts on many different aspects: actual thermal loads change from the ones predicted in the design phase, higher temperatures induce a higher casing strength thermal de-rating reducing the yield stress and last the resistance and stability of the formation, especially at shallower depths, is degraded by being subject to high temperature during the production trials.

6. CEMENTING

Cementing job of 13 3/8" liner is subject to some issues due to wellbore geometry and in-situ geomechanical stresses, particularly at deformation depth.

In the section involved by the casing deformation, due to borehole instability and caving, a large variation of diameter from 17 1/2" to 26" is present (data acquired by 4 arms Caliper Log after the end of the 17 1/2” drilling section). This generated a low standoff index and a decrease in centralization effect, accompanied by a decrease in spacer's effect and a lower well cleanness. The results is a bad separation between mud and cement and a high contamination and canalization. Trapped mud pockets in the cement of thermal wells are at risk of inducing localized annular pressure build-up (APB) and the induced overpressure is known to bulge the casing restricting the inner diameter. Additionally, uncemented or poor cemented segments under compressive loads may be subject to localized buckling where the induced tortuosity over a short length may restrict tool passage, especially when considering tools that have small clearance and high bending stiffness.

7. STRING DESIGN APPROACH

As common practice for geothermal wells, the string design process extends with some specific analyses that apply only to thermal wells, the same methodology as an example applies also to Steam Assisted Gravity Drainage (SAGD). The string design process starts with a similar process to oil and gas wells, well loads for drilling and production are evaluated under static conditions and simulating temperature profiles related to drilling, production and shut-in operations. This process is also known as "working stress design" and it is worth highlighting that during these analyses, the material is always in the elastic regime. It is also well established in the industry that some load cases, typically collapse, do not verify for geothermal wells. In this specific well, setting aside for a moment geomechanical loads, two severe collapse loads are identified, the first is full evacuation and then production loads where the well is partially full of steam. Typically, full evacuation is a severe load case, but in this application it shall be considered since the reservoir rocks in this formation are significantly fractured and losses of circulation are common during drilling and cementing. Loss of circulation during cementing has an additional problematic related to the quality of the cement job and the top of cement achievable against planned. Geothermal wells commonly are cemented top-down.

It is worth mentioning, for those readers not familiar with geothermal wells, that there is no tubing string and steam is produced through the production casing.

Even if under collapse load modes these wells may not comply with the design factors used in the oil and gas industry, the field experience tells that these wells are possible to put in production and remain productive to their expected life. Therefore the design criteria are enhanced to allow a reliable well design for thermal applications. These design methodologies apply for geothermal but also for other wells like steam assisted gravity drainage (SAGD).

The first step is to expand the material working window outside the elastic regime, allowing a certain amount of plastic deformation. The plastic regime for steel is well known to be no longer governed by stresses, but by strains. The methodologies are somewhat in common with the Thermo-mechanical fatigue (TMF) approach. The thermal mechanical cycles, derived by production and shut-in stages, are a source of plasticization in the string and induce fatigue. Since plasticization of the string is allowed, the plastic behavior should be characterized. To do this references from standards used in oil and gas are adopted, as an example the limit for strains as 0.5% of the total strain, the definition of Yield stress in API 5CT. Then also plastic hardening is considered, including both isotropic and kinematic hardening.

Bauschinger effect, which is an anisotropic behavior of the material after plasticization, is accounted by the contribution of the kinematic hardening.

The amount of hardening accumulated during the first thermal-mechanical cycles should be enough to generate a plastic shakedown, which means that a stable elastic-plastic regime is reached, with no more accumulated plastic strains after the first few cycles. If this is the case after a limited number of thermal cycles our well will be in stable conditions. On the other side, if the design does not comply with this preliminary verification then requires the extension to more advanced TMF analyses involving finite element methods (FEA) to assess the damaging mode of the string. Typically, these FEA analyses involve a full evaluation of the connections.

The method to assess the plastic shakedown is also known in the industry as "Holliday", from the author that first presented the methodology (Holliday1969). The cycling is composed of different stages (Figure 3):

- Initial stage at which thermal loads are in the elastic regime and continuously increase with temperature (0-1);
- Then at a certain point a combination of temperature de-rating of the yield stress and plasticity, decrease the slope of the curve until the 0.5% strain limit is reached (1-2);
- At this stage, if the casing string remains long enough at this stress-temperature level thermal relaxation (creep) will reduce the stress levels at constant strain (2-3);
- After that, if the well is cooled down (e.g. well stop production), temperature decreases (3-5), but when returns at the undisturbed geothermal gradient there will be no longer the initial stress-free configuration, but due to plasticity residual stresses are now in the string (5).
- During the second cycle (5-7-5'), if the strain hardening accumulated in the first cycle isn't enough to avoid plasticity, additional plastic strain will be added (4'-5'). In this case shall be highlighted that the onset of plasticity will be changed by hardening. Since thermal loads induce compression in the string also the Bauschinger effect shall be accounted for, which means that the increase in yield in tension (4') will be lower than the one in compression.

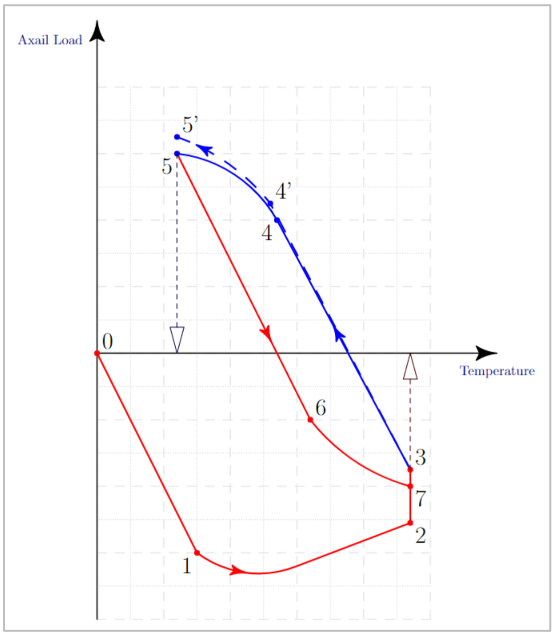

Figure 3 Typical thermal cycling loads.

The Holliday criteria states that if the stresses during the thermal cycles are below a certain limit the casing string will be in plastic shakedown conditions; this limit is expressed as a ratio between the maximum stress in the string and yield stress of the material. On top of the original Holliday method, designers have integrated the limit ratio based on thermal cyclic testing. The tubular supplier for this well inside its R&D centers can perform TMF characterization, using a Gleeble® thermo-mechanical testing machine, to define a proper coefficient for each steel grade. For the string in this well (13 3/8" 68# L80 type 1) a limit coefficient of 1.4 is defined.

In thermal wells there are failure modes other than TMF that have to be verified: one is the effect of tensile residual stresses induced by production and cooling during the thermal cycles at shut-in. This phenomenon is first introduced by Maruyama (1989) and then developed by Suryanarayana (2021) and referred as "cold collapse". As stated in API RP 5C3 and well known in the industry, tensile loads have a contribution on collapse, decreasing the resistance of tubulars. For this reason collapse combined with the tensile residual stresses must also be verified in a geothermal well.

Since geothermal strings are mainly under compression during production, being the production through a two side bounded production casing and not from a tubing, also the effect of buckling must be considered. In wells like the one described in this paper, where formation properties complicate the cement jobs, the effect of poor or missing cemented portions of the well must be considered. If unsupported regions are present in the well, a different buckling named localized buckling may appear. This buckling is different from the one based on Euler's theory for elastic buckling. Short sections not properly supported by cement may locally buckle and become the weak point of the string. This localized buckling may result in an inner diameter restriction, since tools passage may be compromised, but the apparent restriction is due to bending and not to tubular cross section deformations. Localized buckling is very difficult to detect since would require high density surveying (<1m between survey stations).

8. STRING DESIGN FOR WELL C

Well C intermediate liner and tieback are a 13 3/8" 68# L80 type 1 string with an TSH ER™ connection, running inside an 18 5/8" intermediate casing with a 9 5/8" production liner, other strings are omitted since not relevant for this analysis.

Here below the summary table of loads obtained from the working stress design is presented, shall be noted how for this string only axial loads do not comply with design factors.

For each of the load modes also the effect of the thermal anomaly is evaluated: for burst loads the stresses are more severe but do not fall below the minimum required design factor (Figure 4b). In the case of axial loads, especially in tension, many load points fall below the required design factors (Figure 4c).

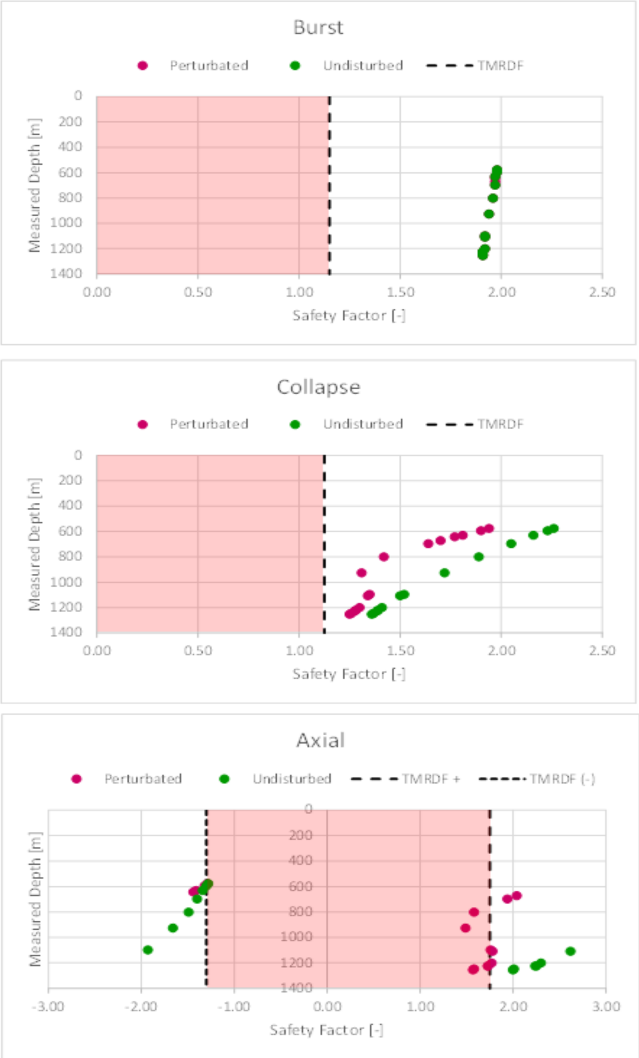

Figure 4 Load point and required design factors.

To apply the TMF method, thermal cycles are defined in a string design software. Several scenarios are considered:

- the production temperature profile;
- the undisturbed geothermal gradient;
- the perturbated geothermal profile (Figure 5). This profile is shown as a ratio with the geothermal undisturbed gradients as this is the input for calculations.

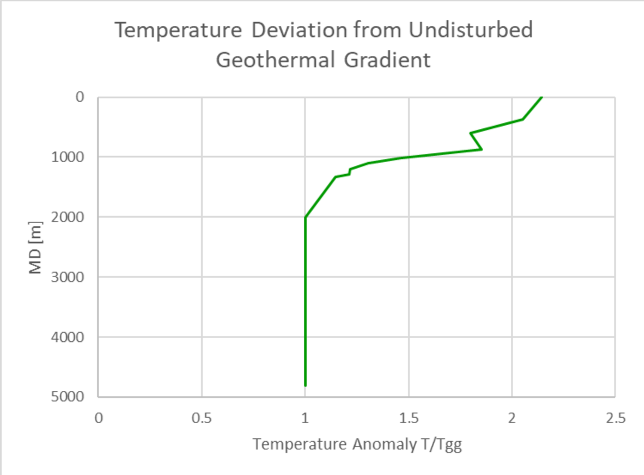

Figure 5 Temperature anomaly as ratio against undisturbed geothermal gradient.

An additional check is performed with a temperature profile corresponding to the acid job. The normalized against yield strength profile of stresses along the string is obtained, which will be to compare with the limit factor of 1.4 defined for the L80 type 1 steel grade.

	Delta Temperature [°C]	TMF Factor [-]
Waiting on cement 13 3/8	100	0.4
Waiting on cement 9 5/8	45	0.2
Drilling 8.5" No circulation Losses	15	0.1
Drilling 8.5" with circulation Losses	0	0.0
Post acid	170	0.7
Production Test I	60	0.2
Shut.in after production test I	75	0.3
After shut-in	35	0.1
Injection	170	0.7
Pre-production test	170	0.7
Production Test II	25	0.1
Shut-in After Production test	60	0.2
After Shut in	35	0.1
Cycles Envelope	210	0.9

Figure 6 Main thermal cycles for the 13.375” casing string

From

	Delta Temperature [°C]	TMF Factor [-]
Waiting on cement 13 3/8	100	0.4
Waiting on cement 9 5/8	45	0.2
Drilling 8.5" No circulation Losses	15	0.1
Drilling 8.5" with circulation Losses	0	0.0
Post acid	170	0.7
Production Test I	60	0.2
Shut.in after production test I	75	0.3
After shut-in	35	0.1
Injection	170	0.7
Pre-production test	170	0.7
Production Test II	25	0.1
Shut-in After Production test	60	0.2
After Shut in	35	0.1
Cycles Envelope	210	0.9

Figure 6 it is evident that during the thermal cycling the design complies with the TMF criteria proposed by Holliday (TMF factor < 1.4), as stated before, in these conditions no further analysis with FEA is required. As a reference also the results for the acid job are presented in

	Delta Temperature [°C]	TMF Factor [-]
Waiting on cement 13 3/8	100	0.4
Waiting on cement 9 5/8	45	0.2
Drilling 8.5" No circulation Losses	15	0.1
Drilling 8.5" with circulation Losses	0	0.0
Post acid	170	0.7
Production Test I	60	0.2
Shut.in after production test I	75	0.3
After shut-in	35	0.1
Injection	170	0.7
Pre-production test	170	0.7
Production Test II	25	0.1
Shut-in After Production test	60	0.2
After Shut in	35	0.1
Cycles Envelope	210	0.9

Figure 6, in this case some of the safety factors, obtained by working stress design criteria, do not comply with the design factors. Nevertheless the well is considered feasible since the acid job is compliant the TMF criteria. As worst-case scenario, is considered the envelope of all cycles, obtained considering the minimum and maximum temperatures at which the string is exposed: also in this case the design falls within the limits for TMF.

Next step is to evaluate what would be the critical unsupported buckling length for this string; based on this a threshold is defined for unsupported portions. These regions are related to difficulties during the cement job derived by the formation which is prone to circulation losses. The losses during casing cementing may not allow reaching the desired top of cement in the annulus or may create problems in properly displacing the drilling mud.

In Figure 7 the critical thermal cycles considering buckling in terms of unsupported length are reported: on the left portion of the chart there are the limit loads for short unsupported buckling, while on the right there are the typical Euler buckling limits. It can be noticed that small unsupported portions have a significant impact on the maximum temperature variation along cycles. In this case, given the clearance between the 17.5” hole and the 13.375” casing string, the limiting cycle amplitude is the fully supported string.

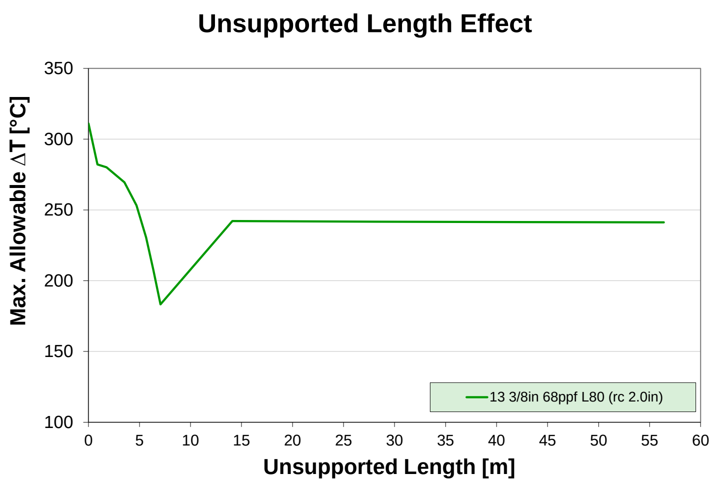

Figure 7 Effect of unsupported buckling

At last, a verification is performed under collapse combined with tensile at shut-in loads, also known as “cold collapse”. Tensile residual stresses generated during thermal cycling are calculated and new collapse limit loads are defined using the correction of collapse under axial loads from API RP 5C3 (Figure 8). From Figure 8 can be seen how the collapse limit loads decrease with the effect of the residual stresses (tension).

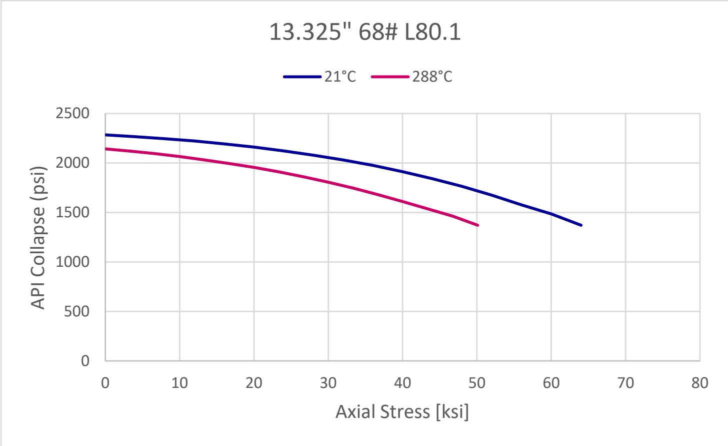

Figure 8 Effect of temperature on collapse resistance.

To complete the assessment of this string, also the effect of ovalization on collapse resistance is considered. Ovalization generates a preferential direction of collapse, reducing the tubular resistance. The ovalization values considered are well beyond both tolerances defined in standards and manufacturer capabilities to understand how the string performance changes under severe geomechanical loads. The effect of ovality chart is obtained by FE analysis (Figure 9).

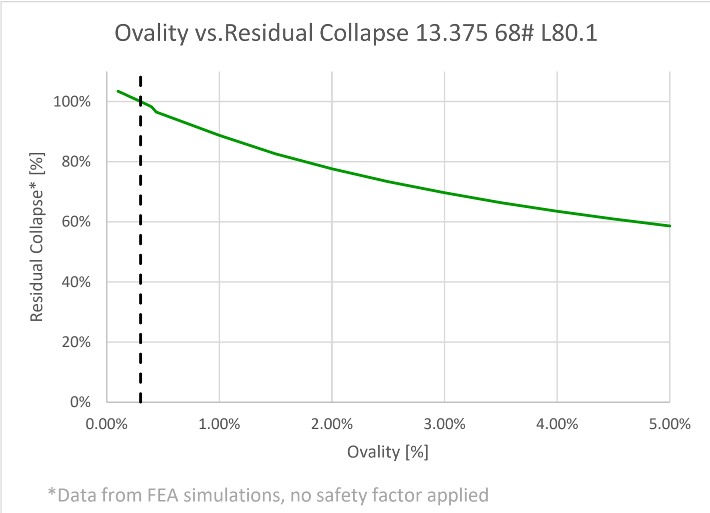

Figure 9 Effect of ovality on collapse resistance.

10. CONCLUSIONS

Considering the findings and the analyses performed after the issues with this well, is possible to identify the thermal anomaly as a root cause of the failure.

Even if the design considered all the typical load cases of a thermal well and properly respected the safety factors, the cumulative effect of: the thermal anomaly, the unpredictable localized geomechanical loads, the caving and difficult cementing operations, all contributed to casing deformation. It is worth highlighting, based on experience in the field, that if each of the effects above occurred individually, probably there would have not been any problem with the well.

In detail after drilling is measured a deformation with punctual ovalities up to 4%. These deformations are generated by a geomechanical load up 77% of the API collapse rating, the thermal anomaly reduces by an 80% the collapse rating against ambient temperature. In these conditions the geomechanical load already equals the tubular collapse rating.

Once generated the ovality, the tubular has a preferable direction of collapse, with its resistance decreasing, with a non-linear behavior, with increasing ovality. In detail with a 4% ovality, this tubular collapse resistance reduces almost by 60%.

With this deformation, the failure is already nucleated, and the elevated thermal loads during the production tests have only propagated the failure, almost entirely collapsing the casing. During production tests, localized buckling may have played a relevant role, considering the caving of the formation and the problematic cement job at that depth.

Based on experience gained with this well, for the other wells in the pad, the string design is modified as following:

- Increasing the nominal weight of the string with a 13.375” 72# (previously 68#);
- Using the enhanced collapse grade L80-ICY;

- Installing and fully cementing the 9.625” tie-back before the production tests.

By changing weight and grade the collapse rating increases by 65%.

Moreover this activity is also being integrated with the development of a series of methodologies and tools in order to complement common string design practices. Comprising an in-house software suite to evaluate the effect of temperature deration and ovality on casing performance, analysis in the plastic regime according to the holiday approach and analysis of unsupported buckling behavior under different thermal cycles.

11. ACKNOWLEDGMENTS

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