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In-depth investigation of casing-cement system failure modes in geothermal wells considering cement voids and improper centralization

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ABSTRACT

Hydraulic fracturing has been used extensively to enhance geothermal reservoirs. Well construction techniques are similar between geothermal, and oil and gas wells, although the former considers additional parameters due to the high temperatures. Failures in the casing and cement have been reported during hydraulic fracturing but their causes remain unclear. The cement sheath is used as a mechanical and hydraulic barrier to support the casing and to prevent premature failures that reduce well life. Hence, cementing operations represent one of the most vital steps while drilling for geothermal or oil and gas resources.

Drilling fluid voids in the cement sheath can be formed during wellbore cementing operations. The chances of cement channeling will increase if the annular clearance between casing and formation, frequently called standoff, is reduced. Therefore, centralization is an important parameter in the long-term wellbore integrity considering that Enhanced Geothermal Systems implement directional drilling in the construction phase. The well-known annular pressure buildup (APB) problem, commonly experienced on wells subjected to thermal heating is caused primarily because of the expansion of trapped annular fluids that cannot be relieved. In this paper, a similar concept considering the contraction of these fluids during hydraulic fracturing will be discussed.

Our work presents a Finite Element Analysis to evaluate the effects of differential temperatures and standoff values at a constant casing internal pressure and in-situ stresses. The modeling involves casing and cement interaction as a function of wellbore eccentricity (standoff). We were being able to demonstrate that an improper centralization, coupled with the temperature differences experienced during hydraulic fracturing, might increase the stress on the casing by more than 100%. These results might explain casing failures reported in geothermal wells.

1. INTRODUCTION

Oil and gas completion is a difficult procedure facing technical, commercial, environmental and social challenges. The current development of geothermal reservoirs shares almost the same challenges with the oil/gas development if they all need hydraulic fracturing to create flow conduits. Therefore, it is necessary to generate more synergy between these two resources and improve the technology transfer (Falcone et al., 2015). The significant topics in the oil and gas, and geothermal industry are not very different, as geologist and geophysics, reservoir, drilling and production engineering are required for both fields. The greater difference is the high temperature exhibit in geothermal wells since only a few wells in oil and gas presents a similar temperature. Therefore, the materials used need to be able to stand these high temperatures (Falcone and Teodoriu, 2008).

It is being a while since the idea of technology transfers from the oil and gas to the geothermal industry was introduce, however it has not been as efficient as one would expect. The main reason is the difference in economics since hydrocarbon industry usually has a return rate much faster than geothermal exploitation (Falcone et al., 2015). Wellbore integrity, for instance, is a crucial concept in hydrocarbon projects which strongly impacts the geothermal projects as well. Wang et al. (2018) gave a thorough review on geothermal wells and their retrofitting from a hydrocarbon production well. It guarantees the release of formation fluids from subsurface to surface facilities through the life cycle of a well. Hence, lack of well integrity can attribute to lost time, extra cost, and accidents, making the diagnosis, and prevention of the casing-cement-formation system crucial. The causes that could lead to wellbore integrity issues are presented in two phases: drilling and completion, and production. A typical well construction consists of a casing that is constrained by the cement and cannot move axially or radially. Since the casing directly contacts with fluid, mechanical cement and casing stresses are commonly induced by pressure and temperature changes in the wellbore due to fluid production, completion and drilling operations.

When a well is being hydraulically fractured, the well system including nearby formation, cement, and casing will experience dramatic changes on pressure and temperature and usually high injection rate in order to break the formation. In this process, in-situ stresses will be altered because of fracturing fluid leakoff. Additionally, when the hydraulically fractured well going through weak formation beddings or faults (Xu et al, 2018[a,b]), the probability of casing deformation and casing failure risk will be significantly increased (Yin et al.2018[a,b,c]). When the geothermal reservoir is being fractured, the permeability of rock can also change significantly (Liu et al. 2018), which cast additional uncertainty about this process.

Geothermal wells exhibit high formation temperatures reaching up to 500 ºF (260 ºC) or higher. These high temperatures reduce the casing steel strength, and through heat transfer impact the properties of the cement sheath (Yang et al, 2018; Han et al., 2017). Hydraulic fracturing fluids on the other hand have temperatures around 20ºC. When they are injected at high rates, the fluid would cool down formation and cause considerable stress increase or decrease in the casing. In addition, casing temperature will not be constant during hydraulic fracturing operation because of variable pump rates during the operation or when the shut-down periods occur, hence cooling and heating will be observed during the operations (Mendez, 2018). Thermal loads might induce casing failure and De Andrade et al (2015) verified how the properties of the cement change through the life cycle of the well due to thermal cycling

In geothermal well most of the well integrity issues occur during completion and production phase. For instance, during cementing displacement, some drilling fluids can be left behind, creating voids in the cement sheath, which might cause an early cement and casing failure. It becomes more critical when the trapped fluids (can be drilling fluid filtrates, completion brine, or formation water) shrinks due to the cooling effect of the hydraulic fracturing fluids reducing considerably their pressure. Voids in the cement will be more frequent in deviated or horizontal wells since the annular clearance between the casing and the wellbore is lower. Therefore, a good centralization is a critical parameter for a complete drilling fluid removal.

The use of centralizers is not new in the oil and gas industry and recent demand in deviated and horizontal wells has improved their design. Several types of centralizers can be use in geothermal wells. Available for all casing sizes, bow spring centralizers are the most commonly used for vertical and slightly deviated wells. Blade helical and solid body centralizers are on the other hand most common in highly deviated and horizontal wells. The latter presents a lower contact area, reducing the drag forces when the casing is tripping into the wellbore.

Mendez, Ichim and Teodoriu (2018) showed the importance of centralization during production in geothermal wells. Improper centralization will affect the stress distribution in casing and cement, increasing the maximum stress in the casing by 7% when standoff and applied differential temperature are considered (Figure 1). Since the completion phase is as important as the production phase in wellbore integrity, this study investigates the effects of an improper centralization, and therefore cement voids, in casing and cement during hydraulic fracturing, and points out the future need for research to improve the prediction of loads generated by standoff and differential temperatures.

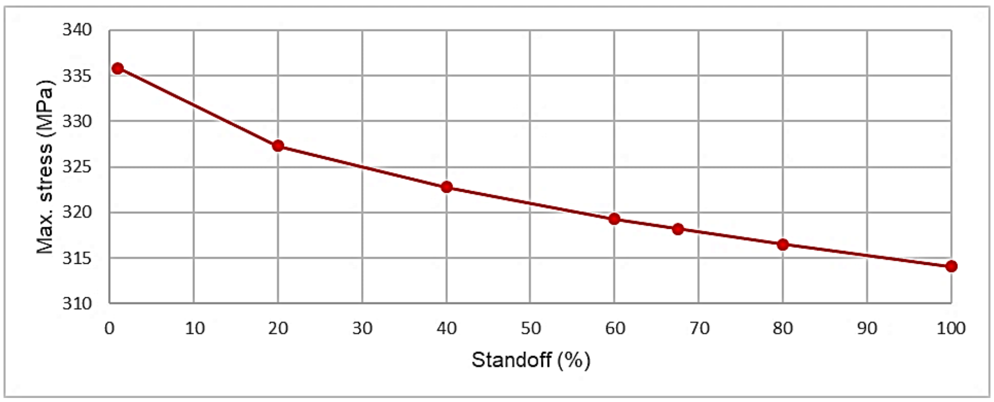
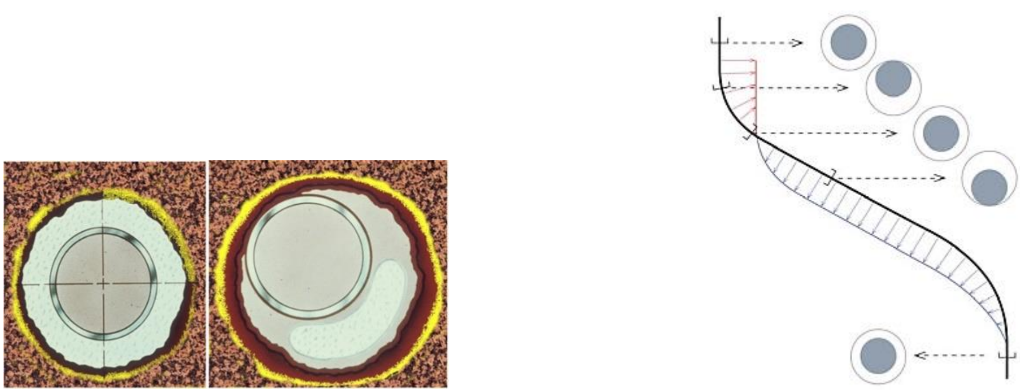


Figure 1. Maximum casing stress at different standoff for a casing temperature of 100 ºC and formation/cement of 22 ºC

2. THE ANALYTICAL MODELS AND PARAMETERS

The interaction between casing, cement, and formation strongly influence the integrity of a wellbore, and makes the understanding of the mechanical properties of all wellbore components vital. The long-term wellbore integrity depends on the eccentricity of the casing in the wellbore and the annular clearance between casing and formation - usually called standoff, with 100% standoff when the casing and the wellbore are concentric, and 0% standoff when the casing touches the borehole or the previous casing (see **Fig. 2(a)**). The eccentricity of the wellbore mainly depends on the forces around the casing, such as material weight and applied tension or compression. Therefore, the casing will be in different positions throughout the wellbore trajectory, as shown in **Fig.2 (b)**.



(a) Concentric Fully Eccentric

(b) Standoff profile without centralizers

Figure. 2 Wellbore eccentricity and casing standoff (Farley and Scot, 2011; Liu and Weber, 2012)

Casing centralization in the wellbore or in another casing string is usually expressed as percentage standoff (%). This is calculated as $Standoff$=C/(A−B) * 100, where C is the shortest distance between the pipe wall and the wellbore, A is the hole radius and B the pipe outer radius, expressed in units of length (**Fig. 3**).

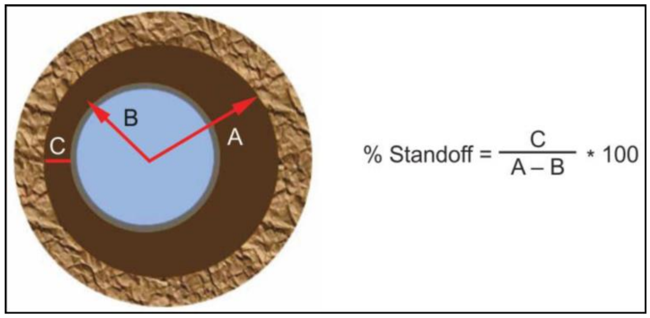
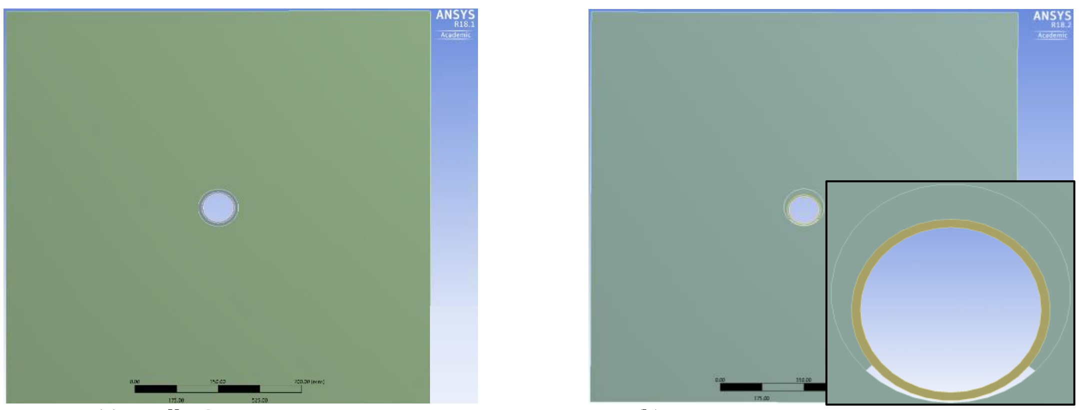


Figure. 3 Standoff ratio (Fry and Pruett, 2015)

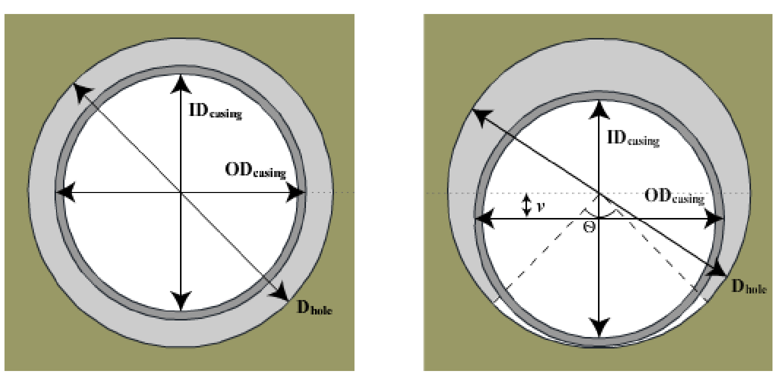
In order to demonstrate the importance of appropriate centralization on casing and cement stress development, a finite element analysis (FEA) study was performed in a 2D model by using the plane strain function of ANSYS R19.1. A segment of a vertical well of unit thickness was built in a two-dimensional plain strain element, since the cement, casing and formation are constrained axially at both ends and the casing internal pressure is uniform. Strain components $\varepsilon_z, \gamma_{xz}$ and γ_{yz} are zero. Rock overburden and formation pressure will not be considered, since the element thickness is small when compared to the well total length. Minimum and maximum horizontal stresses are not considered. Also, we assume an undeveloped and low geo-stress formation. The finite element model for a concentric case is shown in **Fig. 4a** and an eccentric case with drilling fluids voids is shown in **Fig. 4b**.



(a) Fully Concentric (b) Eccentric

Figure. 4 Finite element model for standoff vs maximum stress analysis.

For an accurate depiction of the influence of standoff on casing and cement stresses, two different standoff cases (100%, 10%) were modeled. **Figure 5** shows the physical model for a 100 %, and 10 % standoff with voids. The void's length in Figure 5 is determined by the angle θ. It was more practical for the model to vary the length of the void with the angle (θ) formed between the two edges of the void with respect to the center of the wellbore. The void angle used is 45º.



100% Standoff 10% Standoff

Figure. 5 Cases used for finite element analysis

Table 1. Geometry used for finite element analysis cases

Case	100% Standoff	10% Standoff
Casing offset from hole center, v (in.)	**0**	**0.6725**

For all the seven cases, the borehole outer diameter was 8.5 in. (216 mm) and the cement layer inner diameter was 7 in. (178 mm), equal to the casing outer diameter. The casing inner diameter is 6.538 in. (166 mm), and its wall thickness is 0.462 in. (11.7 mm). The casing offset from the hole center (v in **Figure 5**, expressed in inches) corresponds to the percent standoff and is used in the sketch to ensure accuracy. 0% standoff is not possible to be modeled since this would lead to an intersection of the two faces. The formation boundary was a 70” by 70” (1778 mm x 1778 mm) square with a size around tenfold the size of the borehole, in order to avoid the influence of boundary effects on stress. A different mesh grid was used for of all the components with a finer mesh grid in the casing. All the elements in the mesh were converted from squares to triangles allowing a better transition among different sizes. Also, a mesh refinement was applied to the casing and cement because the size of these elements is smaller and they find themselves in the vicinity of the force exerted by the fluid pressure, theoretically leading to a stress accumulation. The computational time for each case was between 3 and 4 minutes.

Table 2 shows the material properties for casing, cement, and formation from the literature (Xi et al., 2017). We assume that mostly of the geothermal formations are granite and all materials have an isotropic elasticity. It is also assumed that deformation obeys the pure elastic model for the cement and the formation while a non-linear solution such as bilinear isotropic hardening in the casing, the result will be closer to the reality because as soon as casing failed, the behavior will be plastic. A casing grade of P-110 was used for all the simulations; thus, the yield strength input was 758 MPa.

Table 2. Material Properties

Material	Elastic modulus GPa	Poisson's Ratio -	Density kg/m^3
Casing	**210**	**0.3**	**7850**
Cement	**10**	**0.17**	**3100**
Formation	**22**	**0.23**	**2600**

For boundary conditions, an internal pressure of 10,152 psi (70 MPa) was applied uniformly over the casing interior face. The vertical stress is 32 MPa and the horizontal stress is 50 MPa which reflects a fault regime of a geothermal field in Oregon, United States (Davatzes and Hickman, 2011). A pressure of 35 MPa which is lower than internal pressure is applied to the drilling fluid void in the cement.

Considering that geothermal wells exhibit high temperatures, and a cooling effect on casing is present due to the injection of cold hydraulic fluid, three different cases were analyzed at a constant pressure: formation and cement temperatures of 100 ºC, 150 ºC and 200 ºC whereas casing temperatures were 40 ºC, 90 ºC, and 140 ºC respectively.

3. RESULTS

The following equivalent (von Mises) stresses distributions for the three cases were obtained. The von Mises equation calculates the net energy stored by element distortion, and outputs the value as an equivalent stress. Maximum stresses are observed on the casing steel and cement sheath for all the cases.

3.1. Case 1: Formation/Cement:100 ºC and Casing: 40 ºC

A maximum stress of 231.16 MPa occurs at 100% standoff, and a maximum stress of 763.2 MPa occurs at 10% standoff with cement voids, see Figure 6. There is an increase of 143% from a proper to an improper centralization. Since the casing yield strength for a P-110 was exceeded at 10% standoff, a plastic behavior is observed. The locations of the maximum stresses also change with a standoff decrease; a shift being observed toward the lower part of the casing close to the contact between the casing and the edges of the cement void. On the other hand, the minimum stress changes insignificantly.

A maximum cement stress around 66 MPa is observed at 100% standoff, and a maximum stress of 255.95 MPa occurs at 10% standoff, see Figure 7. The cement sheath at 10% is incomplete since it has the drilling fluid void, and the maximum cement stress is observed at the intersections between the cement and the void. A stress of 60 MPa is observed in almost all the incomplete cement sheath.

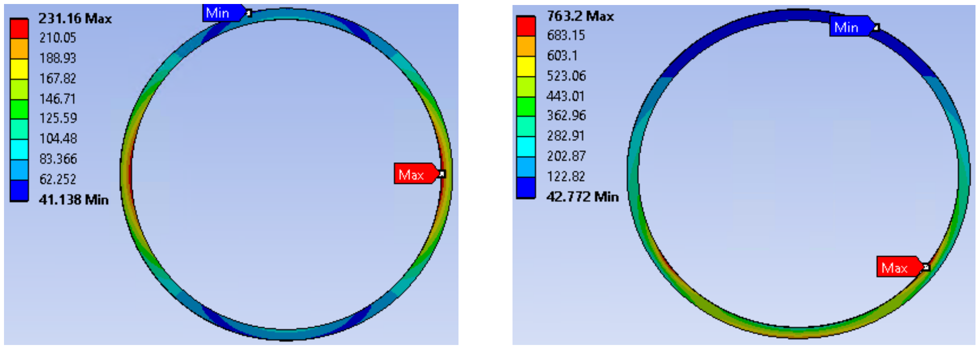


Figure 6. Stress distribution in the casing with 100% standoff (left) and 10% standoff with voids (right) for case 1

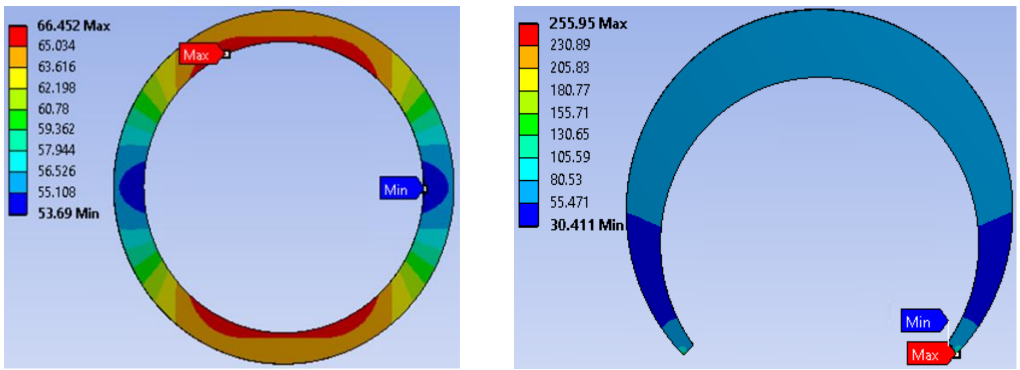


Figure 7. Stress distribution in the cement sheath for 100% (left) and 10% standoff with voids (right) for case 1

3.2. Case 2: Formation/Cement:150 ºC and Casing: 90 ºC

A maximum stress of 291.97 MPa occurs at 100% standoff, and a maximum stress of 763.06 MPa occurs at 10% standoff with cement voids, see Figure 8. There is an increase of 161.97% from a proper to an improper centralization. Similar to case 1, the casing yield strength for a P-110 was exceeded at 10% standoff. Therefore, a maximum equivalent stress increment after this point will be low since a plastic behavior is exhibit. The locations of the maximum stresses also change with a standoff decrease; a shift being observed toward the lower part of the casing close to the contact between the casing and the edges of the cement void. On the other hand, the minimum stress changes insignificantly.

A maximum cement stress of 85.513 MPa is observed at 100% standoff, and a maximum stress of 479.96 MPa occurs at 10% standoff, see Figure 9. The cement sheath at 10% is incomplete since it has the drilling fluid void, and the maximum cement stress is observed at the intersections between the cement and the void. A stress of 90 MPa is observed in almost all the incomplete cement sheath.

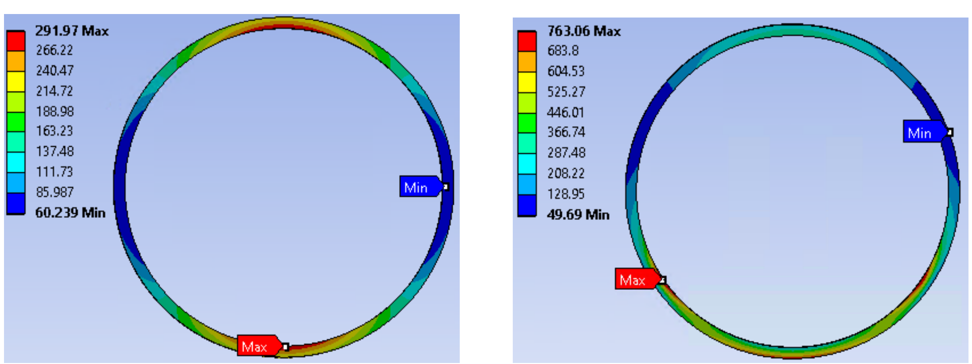


Figure 8. Stress distribution in the casing with 100% standoff (left) and 10% standoff with voids (right) for case 2

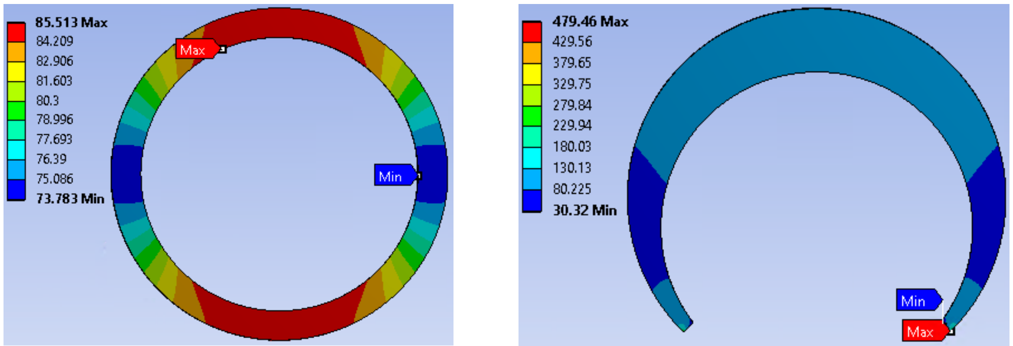


Figure 9. Stress distribution in the cement sheath for 100% (left) and 10% standoff with voids (right) for case 2

3.3. Case 3: Formation/Cement:200 ºC and Casing: 140 ºC

A maximum stress of 501.29 MPa occurs at 100% standoff, and a maximum stress of 763.18 MPa occurs at 10% standoff with cement voids, as shown in Figure 10. There is an increase of 34% from a proper to an improper centralization. Similar to case 1 and 2, the casing yield strength for a P-110 was exceeded at 10% standoff. Therefore, a maximum equivalent stress increment after this point will be low since a plastic behavior is exhibit. In this case, three points of maximum casing stress are more clearly observed in compare with the other previous cases. The locations of the maximum stresses also change with a standoff decrease; a shift being observed toward the lower part of the casing close to the contact between the casing and the edges of the cement void. On the other hand, the minimum stress changes insignificantly.

A maximum cement stress of 106.27 MPa is observed at 100% standoff, and a maximum stress of 712.13 MPa occurs at 10% standoff, as shown in Figure 11. The cement sheath at 10% is incomplete since it has the drilling fluid void, and the maximum cement stress is observed at the intersection between the cement and the void. A stress of 110 MPa is observed in almost all the incomplete cement sheath.

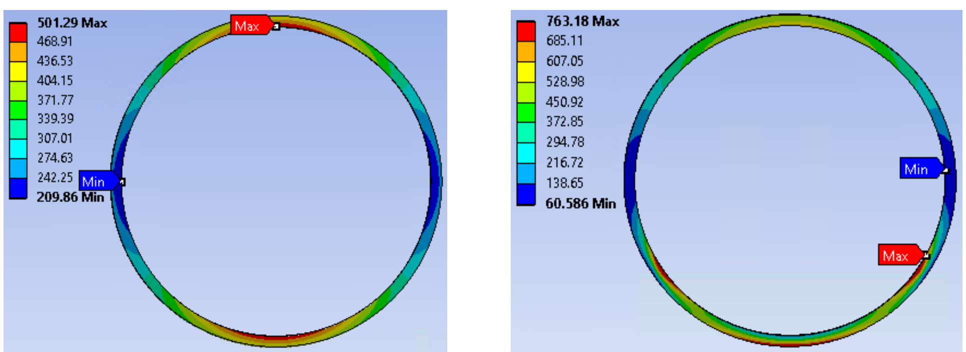


Figure 10. Stress distribution in the casing with 100% standoff (left) and 10% standoff with voids (right) for case 3

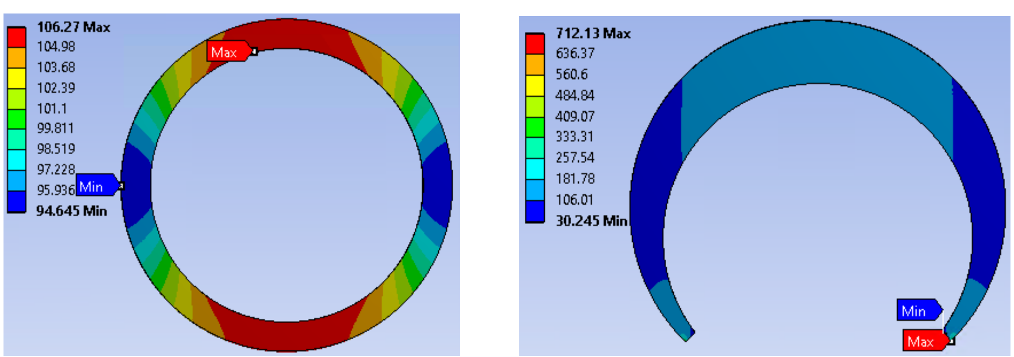


Figure 11. Stress distribution in the cement sheath for 100% (left) and 10% standoff with voids (right) for case 2

4. DISCUSSIONS

The finite element analysis demonstrates that the combination of poor centralization and differential temperature may induce additional stresses in casing and the cement sheath during hydraulic fracturing. By comparing the scenarios at 100 % standoff in Figure 5, Figure 7 and Figure 9, they show that the maximum casing stress increases 54% from 100°C to 200°C in a nonlinear behavior (the increment from 150°C to 200°C is much higher than the one from 100°C to 150°), but it is still below the yield strength of a P-110 casing grade (758 MPa). However, if an improper centralization is made (10% standoff), maximum stress increases higher than 100% of casing yield strength are observed, hence reaching plastic deformation for all three cases **(Figure 12).** Deformation points can be encountered in two to three points in the casing.

If we compare the scenarios at 10% standoff for the three cases, the increase of maximum casing stress is low from 100°C to 200°C. These small increments occur when the stress material has reached the yield strength (plastic behavior)

The maximum cement stress increases 40 MPa (37.5%) from 100°C to 200°C at 100% standoff which validates the effect of temperature in the cement sheath. The cement at 10% standoff is incomplete and a high maximum cement stress is observed at the intersections between the cement and the drilling fluid void. These high values may damage the cement at that location after several hydraulic fractures are performed making the void greater which increases the casing exposure to the formation. Based on all this, hydraulic fracturing in geothermal wells under an improper centralization might induce casing failure during or after the completion operation.

One should note that we only used 45° void angle and void pressure of 35 MPa. Different alternatives might occur depending on the heat transfer, standoff and cement quality. Nevertheless, these values represent a critical scenario according to several authors (Xi et al., 2017, Yan et al., 2016). For instance, a study performed by Mendez (2019) shows how casing deformation occurs in a shale gas field in the Sichuan Basin of China. Even though the study was performed in a shale field, formation properties such as temperature, young modulus and Poisson's Ratio are very similar to some geothermal wells. In this study, casing deformation occurs under a great variety of void pressure and void length values for one of the highest casing grades available in the industry (P-140).

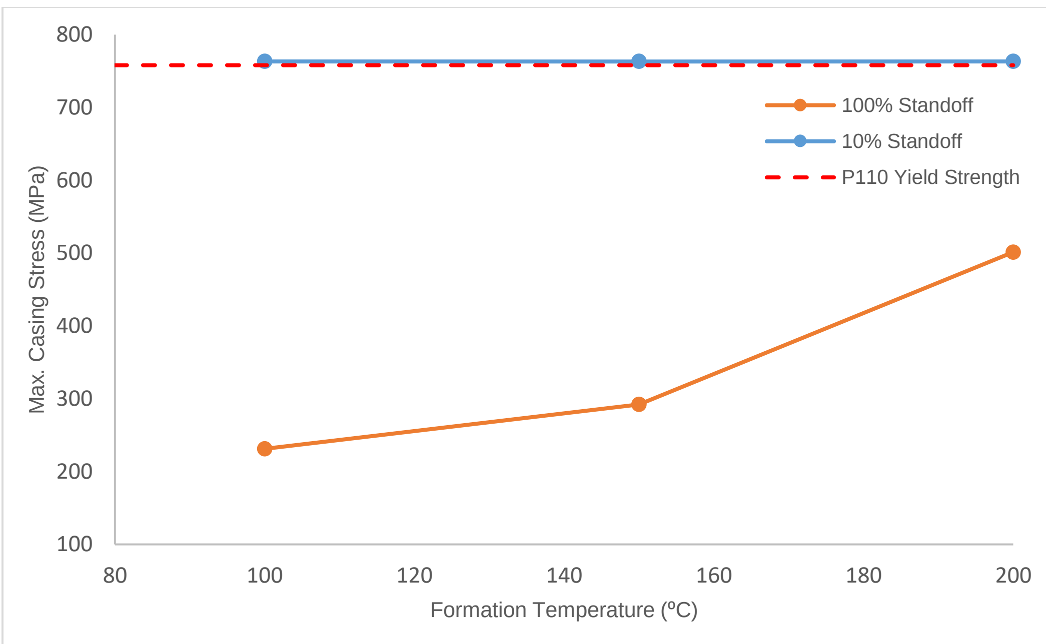


Figure. 12 Maximum casing stress for the three temperature cases at 100% standoff and 10% standoff with voids

5.CONCLUSIONS

This paper presents finite element analysis of casing and cement stress distribution and potential risks of well integrity for geothermal wells when they are hydraulically fractured.

Our study has shown that improper centralization and cement voids will induce additional and significant stresses in casing and cement. The casing alone will suffer plastic deformation under these conditions, which can affect the casing life. The cement will be additionally stressed with over 40 MPa, which may lead to cement mechanical failure.

The worst case shows that at 10% standoff with voids the casing suffers plastic deformation, which will affect the overall well integrity.

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REFERENCES

De Andrade, J., Sangesland, S., Todorovic, J., Vrålstad, T.: Cement Sheath Integrity During Thermal Cycling: A Novel Approach for Experimental Tests of Cement Systems, SPE-173871-MS, SPE Bergen One Day Seminar, Bergen, Norway (2015)

Davatzes, N., and Hickman, S.: Preliminary Analysis of Stress in the Newberry EGS Well NWG 55-29, Transactions - Geothermal Resources Council. 35. 323-332.

Falcone, G., Pawellek, C. and Teodoriu, C.: The First Master in Geothermal Engineering Offered by a Petroleum Engineering School: Curriculum Challenges and Opportunities, SPE-176746-MS, SPE Annual Technical Conference and Exhibition, Houston, (2015).

Falcone, G. and Teodoriu C.: Oil and Gas expertise for Geothermal Exploitation: The Need for Technology Transfer, SPE 113852, EAGE/SPE EUROPEC Conference, Rome (2008)

Farley, D. B., and Scott, T. J.: Field Proven Solutions to the Challenges of Centralizing Solid Expandable Casing. SPE-146507-MS, SPE Annual Technical Conference and Exhibition, Denver, CO 46507-MS (2011)

Fry, D., and Pruett, B.: An Analytical Comparison of Wellbore Deviation and its Effects on Proper Centralization in the Bakken. SPE-174064-MS, SPE Western Regional Meeting, Garden Grove, CA, (2015)

Liu, G., and Weber, L. D.: Centralizer Selection and Placement Optimization. SPE-150345-MS, SPE Deepwater Drilling and Completions, Galveston, TX, (2012)

Liu, J., Tian, W. and Wu, X. 2018. Investigating and Predicting Permeability Variation in Thermally Cracked Dry Rocks. International Journal of Rock Mechanics and Mining Sciences, Vol. 103, pages 77-88.

Han, L., Wang, H., Wang, J., Zhu, L., Xie, B., Tian, Z. and Wu, X. 2017. Strain Based Casing Design for Cyclic Steam Stimulation Wells. SPE Prod & Oper. DOI:https://doi.org/10.2118/180703-PA

Mendez, M., Ichim, A., Teodoriu, C.: The Effect of Wellbore Centralization in Geothermal Wells. 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California (2018)

Mendez, M. (2018). Investigation of casing deformation during hydraulic fracturing considering wellbore centralization and cement voids. University of Oklahoma.

Wang, K., Yuan, B., Ji, G., Wu, X. 2018. A Comprehensive Review of Geothermal Energy Extraction and Utilization in Oilfields". Journal of Petroleum Science and Engineering. Vol. 168, pages 465-477.

Xi, Y., Li, J., Liu, G., Cha, C., & Fu, Y. (2017). Numerical investigation for different casing deformation reasons in Weiyuan-Changning shale gas field during multistage hydraulic fracturing. Journal of Petroleum Science and Engineering, 163(November), 691–702.Xu, Z., Yin, F., Wu, X. 2018[a]. Mechanism Study of Casing Deformation in Multistage Hydraulic Fracturing Shale Reservoir. Presented at Unconventional Resources Technology Conference, July 23-25, Houston, TX.

Xu, Z., Yin, F., Wu, X. 2018[b]. Mechanical Responses of Formation and Well after Injection for Geothermal Development. 43rd Stanford Geothermal Workshop, Feb. 12-14. Stanford, CA.

Yan, W., Deng, J., Ge. H., Zou, L., Li, H., Wang, H.: Investigation of Casing Deformation During Hydraulic Fracturing in High Geo-Stress Shale Gas Play Journal of Petroleum Science and Engineering, (2016).

Yang, S., Feng, Y., Feng, C., Wang, H., Han, L., Wu, X. 2018. Mechanical Performance of Casing in in-situ Combustion Thermal Recovery. Journal of Petroleum Science and Engineering. Vol. 168, pages 32-38.

Yin, F., Xiao, Y., Han, L., Wu, X., W. 2018[a]. Quantifying the Induced Fracture Slip and Casing Deformation in Hydraulically Fracturing Shale Gas Wells. J. of Natural Gas Science and Engineering. Vol. 60. Pages 103-111.

Yin, F., Wu, X., Deng, Y., Yang, S. 2018[b]. Casing Deformation from Fracture Slip in Hydraulic Fracturing. Journal of Petroleum Science and Engineering. Vol. 166, pages 235-241.

Yin, F., Deng, Y., Xiao, Y., Wu, X. 2018[c]. Mechanical Behaviors of Reservoir and Wellbore Under Hydraulic Fracturing. The 52nd US Rock Mechanics/Geomechanics Symposium, Seattle, Washington, USA. 17-20 June.