Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Finite Element Modelling of a Novel Casing Protection for High Temperature Geothermal Wells

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Keywords: Geothermal wells, sacrificial casing, finite element model, thermal analysis

ABSTRACT

Geothermal energy is widely used in Iceland for electricity generation in power plants and direct utilization, e.g. district heating, greenhouses and swimming pools. Although the operational costs of utilizing geothermal energy is low, the maintenance of geothermal wells can be costly. A novel casing protection, the Sacrificial Casing, could be used to decrease the maintenance costs of high-temperature geothermal wells, as well as protecting them from corrosion and high loads due to constrained thermal expansion effects of the geothermal well environment. This paper investigates the advantages of using the sacrificial casing in high-temperature geothermal wells by using finite element methods. Multiple axisymmetric two-dimensional thermal analyses were conducted using the software ANSYS Mechanical. Temperature data from a geothermal well in Iceland (HE-61) was used to analyze and compare three different drilling and production scenarios with and without the sacrificial casing in the well. Thermal results show that the sacrificial casing provides excellent heat insulation and reduces the temperature of the inner casings in all of the scenarios.

1. INTRODUCTION

The casing structure of geothermal wells and problems faced in the geothermal well environment are explained in the introduction section. In the next section, a detailed explanation of the sacrificial casing is given. The sacrificial casing is a novel solution for decreasing the maintenance costs of high-temperature geothermal wells, by protecting them from corrosion and high loads due to constrained thermal expansion effects of high-temperature geothermal fluids. This product has been in development since 2017, by Gerosion, a research and development company based in Reykjavík, Iceland, which specializes in material selection, testing and consulting regarding corrosion and scaling problems in the geothermal industry. The dimensions, boundary conditions and material properties that are used in the finite element model of the geothermal well are explained in the third section. Finally, the results from the thermal analysis are summarized in the results section, followed by the conclusions reached and planned future work for the sacrificial casing project.

Geothermal energy can be defined as the energy stored within the earth's crust. At the boundaries of tectonic plates around the world, geothermal areas are created due to the movement of these plates. Utilization of geothermal resources is made possible through geothermal wells, which produce the geothermal fluid used for district heating, electricity production and direct uses. These wells consist of multiple steel pipes called casings and their main purpose is to seal out unwanted aquifers, support the geothermal well and provide a conduit for production (Thorhallsson, 2017). Figure 1 shows a simple diagram of a regular geothermal well profile with the surface, intermediate, anchor and production casings. Typically, the intermediate casing has a depth range of 50-80 m, the anchor casing has a range of 200-300 m, the production casing has a range of 700-1200 m. All casings are cemented externally except a perforated liner that hangs from the production casing shoe to a total depth of 2000-3000 m.

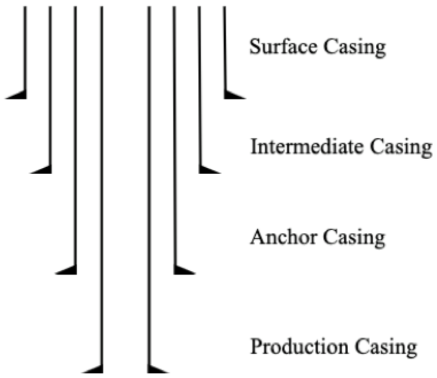

Figure 1: Casing Profile of a Regular Geothermal Well

Depending on the purpose of the geothermal well, the number of casings used and their dimensions can vary. The main well profiles are regular and large diameter geothermal wells. Slimholes are also used, mainly for exploration, due to their ease of implementation compared to the others. They have a depth range of 1000 – 2000 m, with a casing depth of 500 – 1200 m and production casing diameter of 7". Regular wells have a depth range of 1200 – 3000 m with a casing depth of 600 – 1200 m and production casing diameter of 9 5/8". Large diameter wells are similar to the regular wells in terms of their casing depth values, but their production casing diameter is larger: 13 3/8" (Thorhallsson, 2017).

Geothermal wells are subjected to various load cases at different time periods and processes. During drilling and prior to casing installation and cementing, wells are cooled by injection of water or drilling mud. Then, during the warm-up period geothermal wells are allowed to heat up by the formation. During the warm-up period, there is also pressure build up, which impacts the well. During discharge and production periods, the casings are subjected to high enthalpy steam, which increases the temperature of the casings. All of these changes in the well can be harmful to the integrity of the geothermal well (Kaldal, Jónsson, Pálsson & Karlsdóttir, 2015).

Chemical composition and physical properties of geothermal fluids vary extremely depending of the geochemistry of the reservoir that is being utilized (Karlsdóttir, 2012). The main variables that accelerate the corrosion process are the pH level, temperature and flow rate of the geothermal fluid and the corrosive species that are present in the fluid. Most geothermal fluids contain corrosive species such as hydrogen sulfide (H_2S), carbon dioxide (CO_2). Other corrosive species include ammonia (NH_3) and hydrogen chloride (HCl). Hydrochloric acid in geothermal environments is formed, when dry steam containing HCl magmatic gas cools to its acid dew point. This can cause acid corrosion and environmental cracking of the well casings and liner compromising the integrity of the geothermal well's structural system (Hjartarson et al., 2012, Karlsdottir et al. 2013). All of these species mentioned cause the casings to corrode and as a result they can increase the maintenance costs of a geothermal well (Karlsdóttir, 2012). The American Petroleum Institute (API) grade K55 steel is one of the commonly used casing materials. This carbon based steel material is not resistant to the corrosion types occurring in geothermal environments and therefore it can shorten the life of geothermal wells.

Another problem that limits the production potential of geothermal wells is casing failures. Collapse of casings can occur due to the expansion of annular fluids in cement. This problem directly impacts the output of the well, as the maximum output of a geothermal well is directly proportional with its cross sectional area (Kaldal, Jónsson, Pálsson & Karlsdóttir, 2013).

2. SACRIFICIAL CASING

The sacrificial casing is currently being developed as a novel solution for protecting high-temperature geothermal wells from corrosion and thermal effects of geothermal fluids. As mentioned in the previous section, corrosive properties of geothermal fluids can decrease the lifespan of geothermal wells and the sacrificial casing could be a solution for this problem.

Figure 2, shows the conceptual 2D diagram of a geothermal well with the sacrificial casing installed. The first three layers together form the sacrificial casing. These are the corrosion resistant layer (red), carbon steel casing (green), and the insulation layer (blue). The remaining casings are the same as in a conventional geothermal well, i.e. the production, anchor, intermediate, and surface casings.

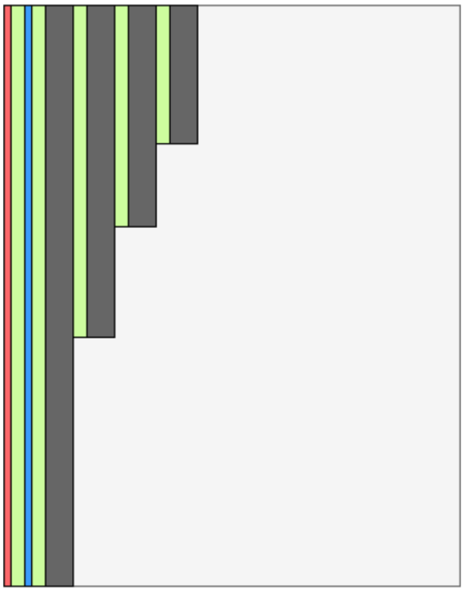

Figure 2: Diagram of a Geothermal Well with the Sacrificial Casing. From left to right: Corrosion Resistant Layer (red), Carbon Steel (green), Insulation Layer (blue), Production Casing (green), Production Casing Cement (dark grey), Anchor Casing, Anchor Casing Cement, Intermediate Casing, Intermediate Casing Cement, Surface Casing, Surface Casing Cement and Formation (grey)

The corrosion resistant layer is assumed to be applied as a cladded layer or co-extruded layer on the carbon steel casing (K55) to protect the inner casings from corrosion. By using a cladded layer instead of having the first two layers combined and made of a corrosion resistant material, the cost of the sacrificial casing is planned to be decreased. In one of the previous work packages for the sacrificial casing project, three possible candidates for the cladding material were analyzed and it was seen that the material properties of the cladded material have no structural effect on external casings. It was also seen that, using a cladding layer material with similar mechanical properties to the base material will result in less stresses between the corrosion resistant layer and the base layer (Kaldal, Jónsson & Karlsdóttir, 2017).

On the outside of the carbon steel casing, a layer of insulation material is used. As a part of this project, the candidate insulation layer materials were analyzed at Gerosion during the summer of 2018. Thermogravitational (TGA) / differential thermal analysis (DTA), thermal conductivity measurements, three-point bending tests, furnace heating and microstructural analysis with scanning electron microscopy were conducted on the candidate materials. These materials will be called A, B, C and D in this paper. All of these materials were initially selected due to their high operation temperature values, and heat insulating properties and their base material, Aerogel. This base material is preferred due to its insulating properties and extremely low density. Materials A and D, are coating type insulation materials and materials B and C are blanket type insulation materials. The main difference between B and C is that B is a heavy duty and more industrial version of the material C.

After these tests, it was seen that A has the highest thermal conductivity value among all the candidate materials with excellent adhesion to steel. However at high temperatures (350℃), it was not able to pass the furnace heating test, the product was completely burnt after a week in the furnace. D was able to pass the furnace heating test, with no visible changes after a week, but due to its brittleness and adhesion problem it is not considered in this analysis. Materials B and C showed the best performance in the conducted tests. They both have the lowest thermal conductivity values and passed all of the conducted tests with acceptable results. The downside of these blankets is their attachment to the base material. If a convenient method of attachment can be found, they show the potential to be used in the sacrificial casing (Pekyavaş, Přikryl & Karlsdóttir, 2018).

3. THE 2D FINITE ELEMENT MODEL OF THE GEOTHERMAL WELL

3.1 Geothermal Well Dimensions

Multiple axisymmetric two-dimensional models are generated for comparison of each scenario. Table 1 shows the outer diameters, thicknesses, materials used and depth values for each casing in the geothermal well, that is modelled in this project. The sacrificial casing dimensions include the corrosion resistant, base and insulation layers. The insulation layer is assumed to fill the gap between the base layer and the production casing.

Table 1: Dimensions Used in the 2D Geothermal Well Model

Casing	Outer Diameter (in)	Thickness (mm)	Material	Depth
Sacrificial casing	7 5/8	3+7+14*	Cladding material + K55 + insulating layer	800m
Production casing	9 5/8	11.99	K55	800m
Anchor casing	13 3/8	12.2	K55	300m
Intermediate casing	18 5/8	12	K55	80m
Surface casing	22 1/2	12	K55	15m

**These dimensions are the assumed thicknesses of the cladding material, K55 and the insulation layer material, respectively.*

The meshed finite element model consists of two layers of elements per casing in the x direction within the geothermal well. These elements have a size of 250 mm in the y direction. Triangular elements are used for the formation and these elements have the same element size as in the geothermal well, where the geothermal well is in contact with the formation. Coarser elements are used in the formation as it gets further away from the well casings. Figure 3 shows a simple version of the mesh that is used in the finite element model.

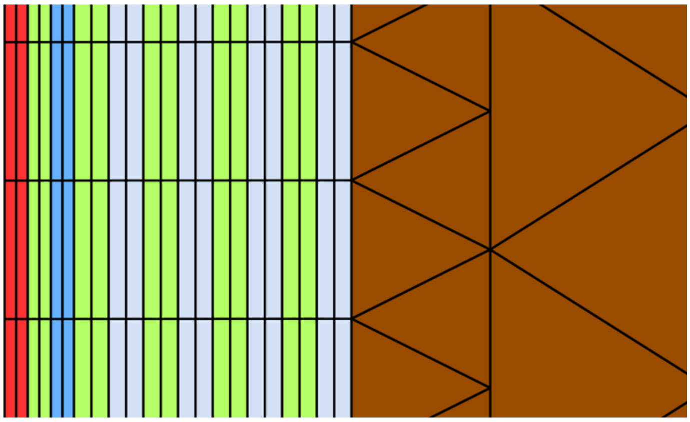

Figure 3: A Simplified Version of the Finite Element Mesh

3.2 Material Properties

Materials that are considered in this project and their properties will be discussed in this section. As a reference, candidate insulation layer materials and their properties can be seen in Table 2. As mentioned in the Sacrificial Casing section, material B was found to be the most compatible candidate for the insulation layer. Therefore, the only analyzed insulation material in this project is B. The materials that were analyzed for the corrosion resistant layer are titanium, 254 SMO and Sanicro 28. Sanicro 28 was selected in this analysis for the corrosion resistant layer, because it had the lowest maximum stress among the three candidate materials (Kaldal, Jónsson & Karlsdóttir, 2017).

Table 2: Insulation Layer Candidate Materials and their Properties

Material Name	Thermal Conductivity Range (W/m.K)	Maximum Operation Temperature (℃)	Type
A	0.06 - 0.1	420	Coating
B	0.02 - 0.069	650	Blanket
C	0.02 - 0.089	650	Blanket
D	0.05	500	Coating

Table 3 shows the material properties that are used for the corrosion resistant layer, casings (K55), insulation layer (B), cement and formation. Temperature dependent stress-strain data for K55 is also used for more accurate and realistic results.

Table 3: Properties of the Materials Used in the 2D Model

Variable	Corrosion Resistant Layer (Sanicro 28)	Casings (K55)	Insulation Layer	Cement	Formation
Thermal conductivity K (W m^{-1} $°C^{-1}$)	15.5	50	0.035	0.81	2
Specific heat C (J kg^{-1} $°C^{-1}$)	500	490	1000	880	840
Young's modulus E (GPa)	195	205	2.4*	2.4	80
Poisson's ratio γ	0.3	0.3	0.15*	0.15	0.31
Density ρ (kg m^{-3})	8000	7850	200	1600	2650
Thermal expansion α ($°C^{-1}$)	16e-6	13e-6	10e-6	10e-6	5.4e-6

**These values were not available and assumed to be equal to cement's properties. This assumption was made, because the structural effects of the insulation layer are not analyzed in this project.*

3.3 Scenarios and Boundary Conditions

The effects of different production scenarios on the temperature distribution are compared in this analysis. In all of the scenarios, drilling fluid at 15 ˚C at the top and 20˚C at the bottom of the well is assumed to be present for three weeks. This step is used to simulate temperature conditions in a geothermal well after drilling. In Scenario 1, there is discharge immediately after the drilling period followed by a week of production at 280 ˚C. In Scenario 2, instead of starting production immediately, the well is left to warm up by the formation for three weeks. This warm up process takes one week in Scenario 3, where hot water at 100 ˚C is present in the well to warm it up. All of the scenarios end after a week of production at 280 ˚C.

All of the casings are assumed to be bonded to each other and the right side and the bottom of the geometry the formation is fixed. Depending on the scenario and the process, the temperature on the innermost casing changes. The formation temperature is defined as an initial load step, then it is applied throughout the processes on the right edge of the model. The formation temperature is assumed to be 15˚C at the top and 220˚C at 800 m.

4. RESULTS

Temperature distribution in Scenario 1, 60 minutes after the discharge period at 400 meters in the geothermal well, can be seen in Figure 4. The first image without the sacrificial casing only includes the production casing, the cement outer to the production casing and the formation. The other two setups show, from left to right, the corrosion resistant layer, carbon steel base layer, insulation layer (cement in the second setup), production casing, the production casing cement and the formation. It can be seen that the sacrificial casing shows great insulation potential. Without the sacrificial casing, the temperature of the production casing reaches 280˚C almost immediately, whereas in the cemented casing setup the temperature is around 160˚C and finally the setup with the sacrificial casing protects the production casing. The temperature in the last casing setup with the sacrificial casing is around 80˚C.

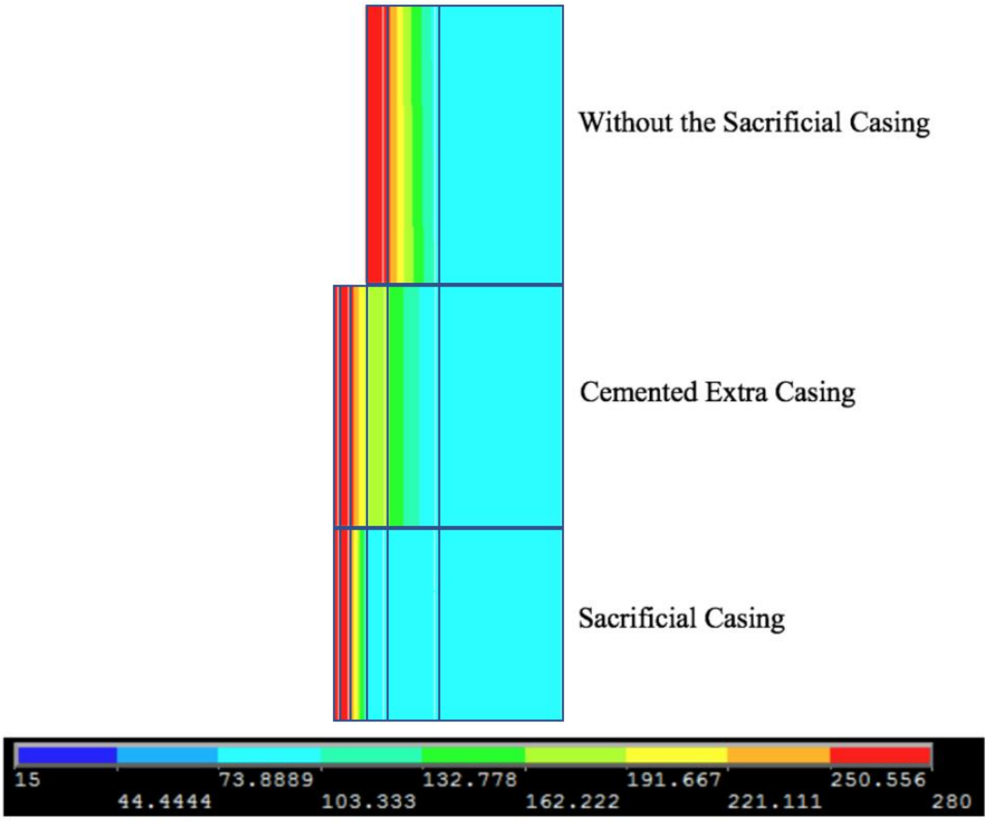

Figure 4: Temperature Distribution in the Geothermal Well 60 Minutes after Discharge in Scenario 1

The temperature in the middle of the cement layer outer to the production casing at 400 m is used to compare the different casing setups and scenarios. In Figures 5 – 7, WOSC represents the regular geothermal well setup, without the sacrificial casing. CEM represents the extra casing with the corrosion resistant layer and INS represents the conceptual sacrificial casing with material B as the insulation material.

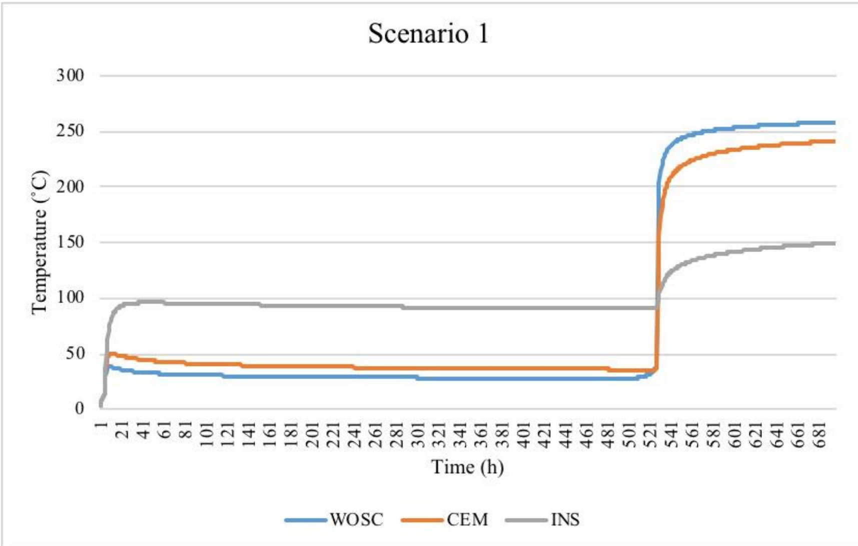

Figure 5: Temperature Distribution in Scenario 1

Figure 5 shows that in Scenario 1, the temperature in the middle of the cement layer outer to the production casing after a week of production without the sacrificial casing is 258˚C. The casing setup with an extra casing (CEM) has a final temperature of 241˚C and the setup with the sacrificial casing has the lowest final temperature of 149˚C. It can be seen that the sacrificial casing also decreases the effects of the cold water during the drilling period. The other two casing setups do not have this effect and as time passes, the temperature in the middle of the cement layer becomes closer to the drilling fluid temperature, which is 15˚C.

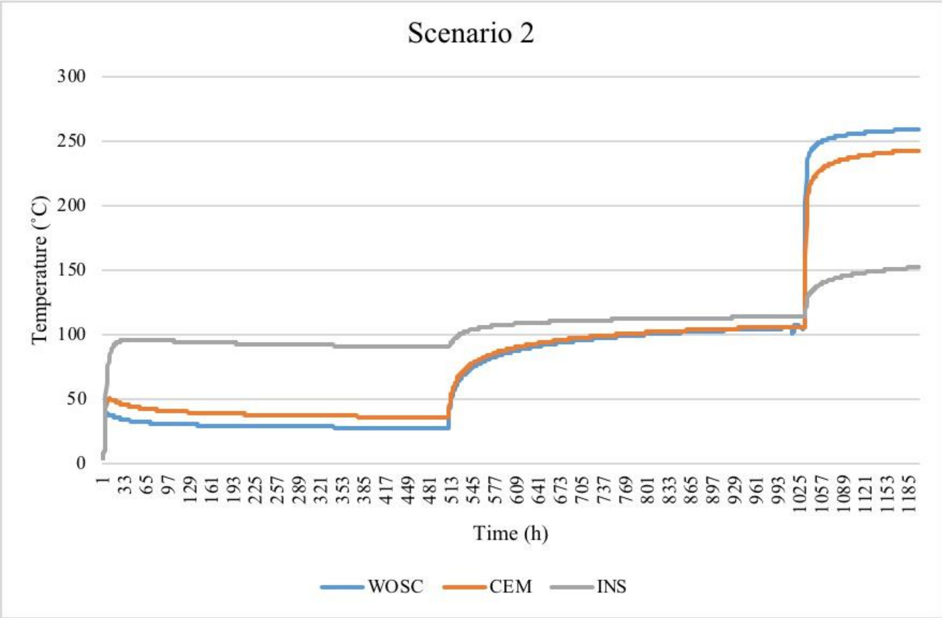

Figure 6: Temperature Distribution in Scenario 2

Figure 6 shows Scenario 2, where the casings are left to warm up for three weeks after the drilling period, all of the casing setups have a similar temperature value after the warm up period. Without the sacrificial casing the temperature reaches 101˚C, the cemented extra casing reaches 106˚C and the sacrificial casing reaches 113˚C. All of these temperature values are close to the temperature formation at 400 meters. After a week of production, the temperature values reach 259˚C, 243˚C and 152˚C respectively.

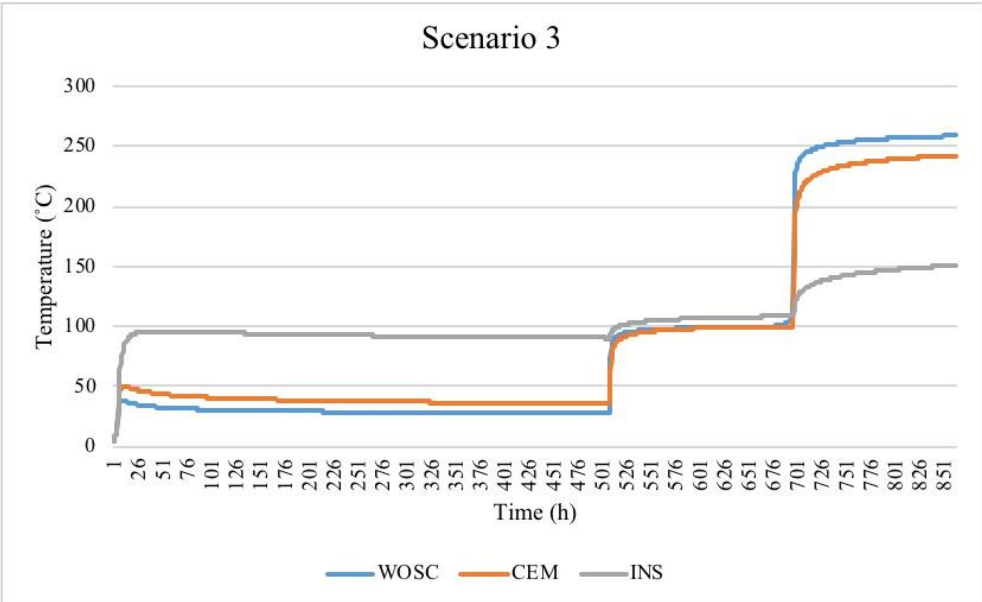

Figure 7: Temperature Distribution in Scenario 3

Scenario 3 (Figure 7) shows similar temperature values to Scenario 2, but instead of leaving the well to warm up for three weeks, hot water at 100˚C is used to warm up the casings. The three week period reduces down to a week, resulting with similar temperature values after warm up and production periods. Temperature values after the warm up period are 99˚C, 99˚C and 108˚C respectively and after the production period the temperature values are 258˚C, 242˚C and 150˚C, respectively.

5. CONCLUSION AND FUTURE WORK

In this paper, a finite element model of a two-dimensional axi-symmetric geothermal well is created for the purpose of analyzing the temperature distribution of an 800 m geothermal well's production casing with and without the sacrificial casing. The sacrificial casing is a novel solution for protecting the geothermal well from thermal and corrosive effects of high temperature geothermal fluids. The specification and installation of the sacrificial casing is within another work package in the project and therefore is not considered in this paper.

The thermal model is created to see the optimal insulation capabilities of the sacrificial casing compared to a regular geothermal well. It shows, that in all of the scenarios that the temperature in the cement layer outer to the production casing has decreased with the use of the sacrificial casing. Also, the cemented extra layer of casing has an impact on the temperature distribution, but not as much as the sacrificial casing. For example in Scenario 1, the temperature in the cement layer outer to the production casing after a week of production is 258˚C. The casing setup with an extra casing has a final temperature of 241˚C and the setup with the sacrificial casing has the lowest final temperature of 149˚C. It was also seen that the final temperature distribution does not depend on the different scenarios used in this project. For future work, a sensitivity analysis for various properties of the insulation layer, especially density, specific heat and thermal conductivity, should be done to find the optimum material that could be used in the insulation layer. A preliminary structural model was also created to check the structural effects of the sacrificial casing and it was seen that the sacrificial casing showed promising results. A more detailed structural model, including the couplings and connections will also be modelled to check the sacrificial casing's effect on the stresses and strains in the production casing.

6. ACKNOWLEDGEMENTS

The authors would like to thank Reykjavik Energy (Orkuveita Reykjavíkur) and ON Power (Orka Náttúrunnar) for providing the temperature and pressure data of the geothermal well HE-61. This project was funded by Gerosion and Rannís, the Technology Development Fund, under the contract number and name "176703-0611 - Fórnarfóðring fyrir háhita jarðhitaborholur, Sacrificial Casing for High Temperature Geothermal Wells".

REFERENCES

Hjartarson, S., Sævarsdóttir, G., Pálsson, H., Ingason, K., Pálsson, B., & Harvey, W. (2012). Utilization of High Enthalpy, Chloride Bearing Geothermal Fluid. Stanford. Retrieved from https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2012/Hjartarson.pdf

Karlsdóttir, S. (2012). Corrosion, Scaling and Material Selection in Geothermal Energy Production. In Comprehensive Renewable Energy (pp. 239-256). Elsevier (1st ed.).

Karlsdottir, S.N. , Thorbjornsson, I.O. (2013). Corrosion Testing Down- hole in Sour High Temperature Geothermal Well in Iceland," CORROSION 2013 Conference and Expo, 17-21st of March 2013 in Orlando, Florida, USA.

Pekyavaş, M., Přikryl J., Karlsdóttir, S. (2018). Technical Report for RANNÍS. Material Selection and Laboratory Testing, Reykjavík, Iceland.

Kaldal, G. S., Jónsson, M., & Karlsdóttir, S. (2017). Technical Report for RANNÍS. Thermal Stress and Strain Modeling, Reykjavík, Iceland.

Kaldal, G. S., Jónsson, M., Pálsson, H., & Karlsdóttir, S. N. (2013). Collapse Analysis of the Casing in a High Temperature Geothermal Wells. Stanford. Retrieved from https://pangea.stanford.edu/ERE/pdf/IGAstandard/SGW/2013/Kaldal.pdf

Kaldal, G. S., Jónsson, M., Pálsson, H., & Karlsdóttir, S. N. (2015). Structural modeling of the casings in high temperature geothermal wells. Geothermics, 55, 126-137. doi: 10.1016/j.geothermics.2015.02.003

Thorhallsson, S. (2017). Drilling Technology and Wells. Lecture, University of Iceland.

Thorhallsson, S. (2017). Geothermal Well Designs. Lecture, University of Iceland.