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Numerical and Experimental Evaluation of Liner Dual Barrier System in Geothermal Wells

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ABSTRACT

The drilling and completion of a production interval is a critical operation in geothermal wells. A liner dual barrier system consists of two barrier elements - a seal assembly and cement sheath between formation and liner. Any defects in the barrier system can transform into a potential well integrity risk. Limited research is available on the failures of these barriers for geothermal applications. The objective of this study is to investigate the performance and failure modes of a dual barrier system at high temperature and CO_2 conditions.

In geothermal CO_2 -rich reservoirs, well barriers usually experience severe degradation. For this study, a setup similar to the production casing/liner program of a geothermal well was fabricated using two concentric pipes with elastomer and cement sheath to seal off the annular space. The sealing performance of a commonly used elastomer material (ethylene propylene diene monomer) was investigated at 1000 psi and 180°F under CO_2 exposure. An autoclave was used for aging elastomer samples. Exposure to aging conditions caused cracks and blisters on elastomers. This resulted in failed sealability tests. A finite element model has been developed to simulate sealability tests. Simulation results have indicated the lack of sufficient sealability after CO_2 exposure, showing good agreement with experimental observation.

For the cement barrier, the experimental setup was used to investigate cement bonding with casing (steel pipe). Even at room temperature, cement sheath exhibited weak bonding at the inner pipe interface. This caused a failure in the sealability test. Material properties of cement cured at elevated temperatures of up to 350°F were used in the finite element model to examine the effect of temperature and wellbore pressure on cement integrity. The stress levels developed in cement were analyzed to identify modes of failure.

1. INTRODUCTION

1.1 Liner Hangers Systems in Geothermal Wells

A liner is a casing string that does not extend all the way to the surface. Liners are frequently used in the production intervals of geothermal wells. Technically, after installation, a liner is engaged to the previous casing using a device called "liner hanger" that incorporates seal assembly and setting components. Based on the setting mechanisms, the liner hangers can be classified into two versions, conventional and expandable (Mohamed and Al-Zurigi, 2013; Patel et al., 2019b; Patel and Salehi, 2019a). In the conventional version, slip-cone assembly is used to energize the seal assembly as shown in **Figure 1 (A)**. The compressive load transfers to the compression plates (i.e. cones) which then move to compress and energize the seal. The second version of the liner hanger is called an expandable liner hanger. In this technology, there are no mechanical moving parts to energize the seal. Instead, an expandable mandrel is usually run inside the liner using differential hydraulic pressure. The liner hanger is plastically deformed (expands) in the radial direction and the bonded seal assembly expands to fill the gap between the liner and the host casing as shown in **Figure 1 (B)**.

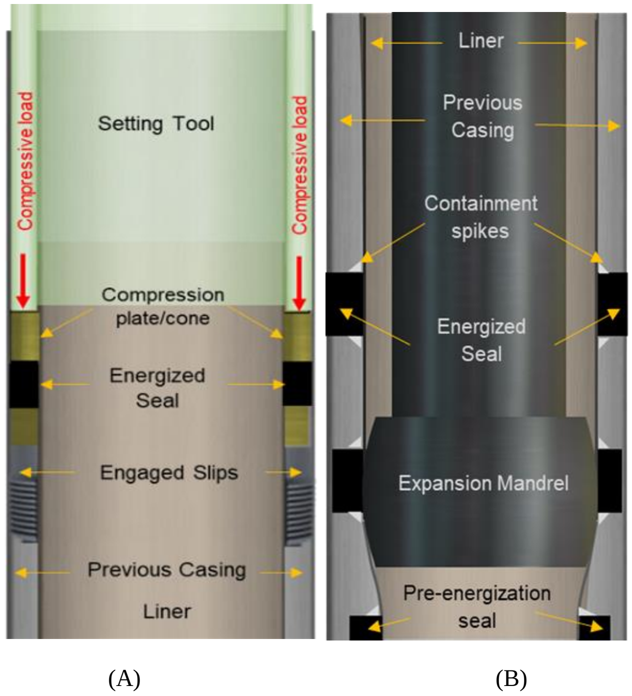


Figure 1. Schematic of (A) typical conventional and (B) expandable type liner hanger seal assemblies (Patel et al., 2019a)

Before setting a liner, it is typically partially cemented. The seal assembly and the cement sheath collectively establish a barrier system called dual barrier as shown in **Figure 2**. This barrier is very crucial for the well integrity and stability because it contains the produced fluids. Consequently, the elastomeric materials of the seal assembly and the cement sheath must be selected, designed and placed carefully. The produced fluids in geothermal wells are usually characterized by their corrosive nature since they are rich with acidic gases e.g. H_2S and CO_2 (Bihua et al., 2018). In the presence of water, CO_2 forms corrosive carbonic acid which usually attacks and compromises the integrity of the elastomers and the cement sheath. The failure of these elements occurs according to certain mechanisms that will be explained in the following subsections.

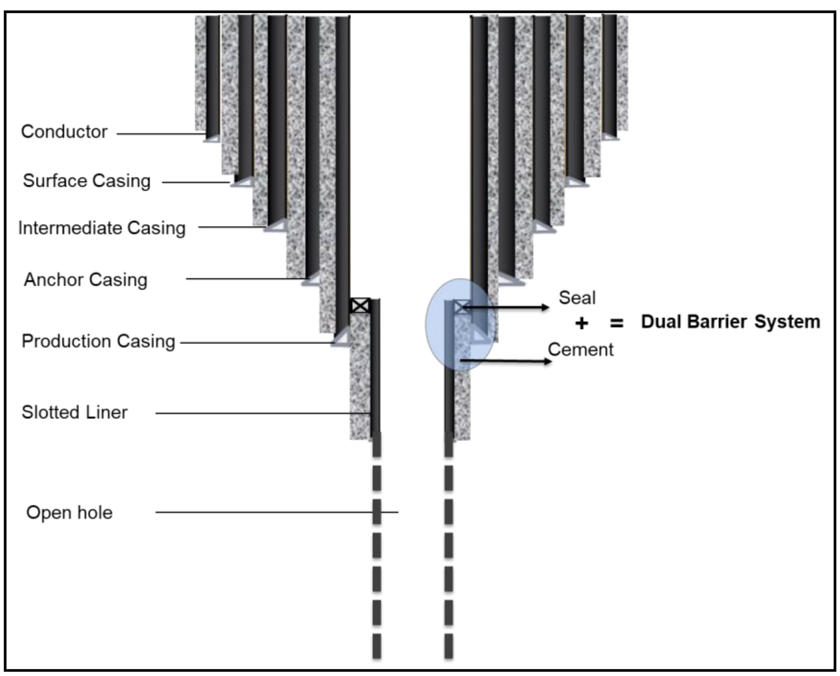


Figure 2. Liner hanger seal assembly and cement sheath establish dual barrier system in a geothermal well to confine the produced fluids

1.2 Failure Mechanisms of the Liner Hanger Seal Assemblies

Among the other types of elastomers that are used in downhole applications, ethylene propylene diene monomer (EPDM) was first introduced in geothermal wells application back in 1979 by Hirasuna et al. (1983). The authors invented a modified version of neoprene elastomers called Y267 EPDM to serve as a casing packer in extremely hostile geothermal environments. The elastomer can withstand downhole temperature up to 500^{o}F. In addition to serving in geothermal production wells, the authors claimed that the Y267 EPDM elastomer can also be used in different operations such as steam injection, geothermal hydraulic stimulation, geothermal hydraulic fracture, cement wiper plugs, float valve seals, and logging tool seals. The elastomer is inappropriate for environments in which there is the possibility of free access to air and oxygen at high temperatures. In addition to Y267 EPDM, special types of elastomers have recently been developed to withstand high-temperature downhole conditions such as FFKM. This elastomer can work at temperatures up to 617°F (PPE, 2019).

Generally, the wellbore elastomeric materials can suffer from various modes of failure. The main failure mechanisms can be classified into chemical, physical/mechanical, thermal, and fatigue from cyclic temperature and pressure (Ahmed et al., 2019a; Patel et al., 2019a; Salehi et al., 2019). In this paper, more emphasis was given to chemical and thermal failures since they are the dominants failure mechanisms for the elastomeric materials used in geothermal wells. The chemical, most common failure mechanism, includes attack of source gases, swelling and rapid gas decompression (RGD). The elastomer can be attacked by sour gases such as CO_2, H_2S, and mercaptans and its cross-linked structure may break down. This normally results in cracks and blisters on the elastomer surface as shown in **Figure 3 (A**). The elastomer is also prone to structural disintegration (See **Figure 3 (B)**) in case it is exposed to swelling agents such as oil, CO_2, H_2S, brine, surfactant, etc. The key properties that can be affected by the swelling process are the volume and hardness. After the swelling, the elastomer volume and hardness must not exceed +25/-5% and +10/-20% respectively as specified by NORSOK M-710 (2014). The third worst chemical failure mechanism is RGD. When the elastomer is in contact with corrosive gases such as CO_2 and H_2S at high pressure, the gases are absorbed by the elastomer and get entrapped in its molecules in the form of pockets. When the confining pressure decreases rapidly at a rate more than certain values specified in NORSOK M-710 (2014), the entrapped gases come out of the elastomer body and create blisters and cracks as shown in **Figure 3 (C)**.

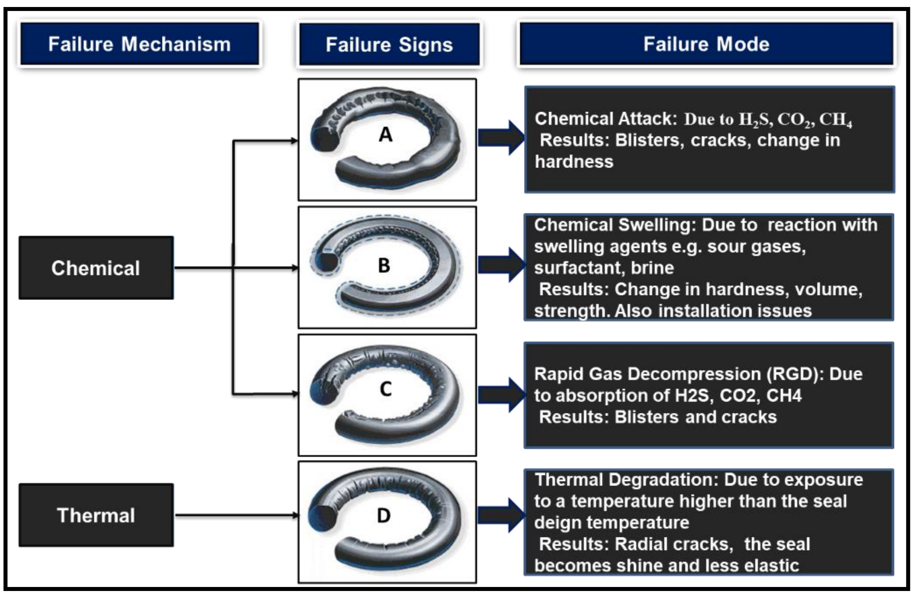


Figure 3. Elastomers failure modes (A) chemical attack, (B) swelling, (C) RGD, (D) thermal degradation (images source: Marco Rubber Inc. 2019; PPE 2019)

Thermal degradation is another major challenge that limits the use of elastomeric materials in the geothermal wells. Blizzard (1990) highlighted that the integrity of many elastomers can be compromised at a temperature greater than 400 °F. As shown in **Figure 3 (D)**, thermal failure can be diagnosed by radial cracks, softening, and shiny surfaces (Marco, 2019), and it is usually accompanied by compression set (PPE, 2019).

1.3 Failure in Liner Hangers Cement Sheath

Cement is an essential well barrier element because it is mechanically supporting the weight of the wellbore's structural components such as casings, liners, production string equipment, etc. The cement also hydraulically isolates fluids influx from formations into the wellbore and from the wellbore to its surroundings. Cement's mechanical and hydraulic integrity can be compromised by several mechanisms. Such mechanisms include but are not limited to chemical degradation, mechanical loads from stresses, in-situ stresses, thermal stresses, fatigue from cyclic loads, etc (Ahmed et al., 2018; Ahmed et al., 2019b; Al Ramadan et al., 2019a; Patel and Salehi, 2019b). Moreover, the inherent permeability of cement sheath can also be a concern (Kimanzi et al. 2019). In this paper, the failure mechanisms resulting from cement exposure to chemical degradation by acidic gases and the concentration of the mechanical loads were given more consideration.

Cement is prone to fail at environments containing H_2S and CO_2 according to the phenomena of carbonation and sulfidation respectively. H_2S and CO_2 attack cement by causing leaching, expansion, and dissolution effects (Ahmed et al., 2015). Therefore, cement recipes designed for zonal isolation of these types of formations must be acid resistant with a high density. Several research studies have been performed to develop slurries that meet the regulation requirements. Additives to the base cement is a common field practice, enhancing its acid resistance and improving the other cement tensile properties. Ahmed et al. (2015) demonstrated that Class H with hydroxyapatite and magnesium oxide are the best formulations for resisting acidic gases attack under HPHT environments. Cement resistance can be substantially improved by adding corrosion-resistant Fe_2O_3-amended cement (Bihua et al., 2018) and adding pozzolan-amended cement (Zhang et al., 2013).

Set cement mechanical strength can be lost in case the induced stresses exceed limiting values of the cement strength. Cement failure may occur according to three main mechanisms such as radial cracking, debonding, and plastic deformation (Lavrov and Torsæter, 2016; Ahmed et al., 2018: Patel and Salehi 2019b; Al Ramadan et al., 2019b). The cement may experience crushing and debonding in case the radial stress exceeds the cement compressive or tensile strengths respectively. Debonding can also happen if the shear stress exceeds the cement-pipe or cement-formation interfacial bonding strength. Radial cracks can be created if the hoop stress exceeds the cement tensile strength. All these failure criteria are utilized in this paper to characterize the cement failure modes that will be investigated in the dual barrier cement model section.

At temperature equal to or higher than 230^{o}F cement strength deteriorates according to a phenomenon called cement retrogression. In this phenomenon, the cement suffers from a rapid decrease in its strength properties and its resistance to chemical attack, whereas an increase in its permeability and porosity can occur. The cement retrogression phenomenon is prevalent at the early stage of cement heating that may take place just after few days or a month after cement displacement (Pernites and Santra, 2016; Al Ramadan et al., 2019c). According to API RP 65-1 (2018), cement retrogression can be controlled by the addition of approximately 35 % to 40 % crystalline silica by weight of cement.

2. EXPERIMENTAL WORK FOR EVALUATION DUAL BARRIER SYSTEM

2.1 Scope of the Experimental Work

The experimental scope covers testing the integrity of liner hanger elastomeric materials under aging conditions as well as testing the aged elastomer and cement as a dual barrier system. To perform the experiments, two EPDM elastomers (shown in **Figure 4 (A)**) having 8-in diameter were inserted in an autoclave cell and exposed to CO_2 at room temperature and 600 psi for three days. Then the pressure inside the cell was reduced suddenly in less than one minute to mimic the decompression rate specified by NORSOK M-710 (2014) for RGD test. The elastomers exhibited cracks and blisters (shown in **Figure 4 (B)**) after their removal from the aging cell. The elastomers were tested individually in the setup designed for this study. The elastomers sealing integrity was compromised and this can be observed in the pressure test results. In addition to O-rings, small elastomers samples (0.75-in diameter, Length of 0.33-in and 1-in) were also aged in an autoclave cell as shown in **Figure 4 (C)** for 7 days at 180°F and 1000 psi. The elastomer samples were kept under pressurized CO_2. As discussed in Section 3.1 of this paper, the objective of this test was to simulate elastomer aging under corrosive downhole conditions and to obtain elastic properties as input data for the numerical simulations.

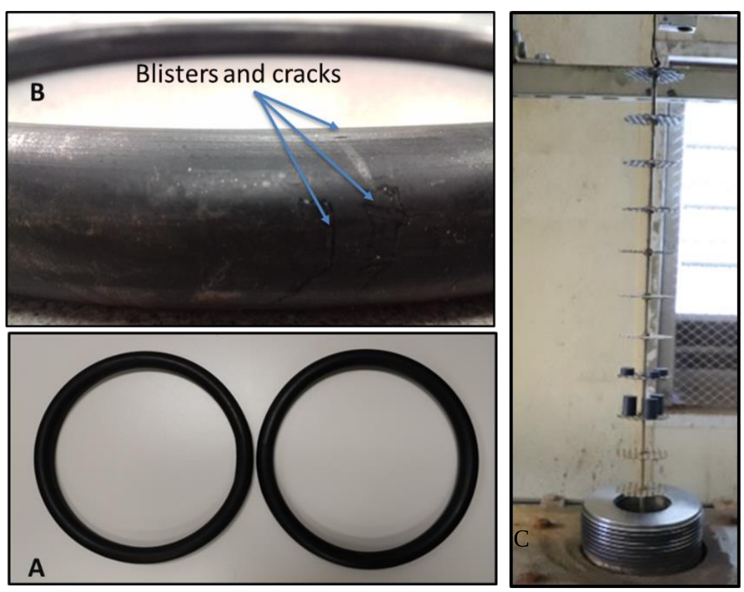
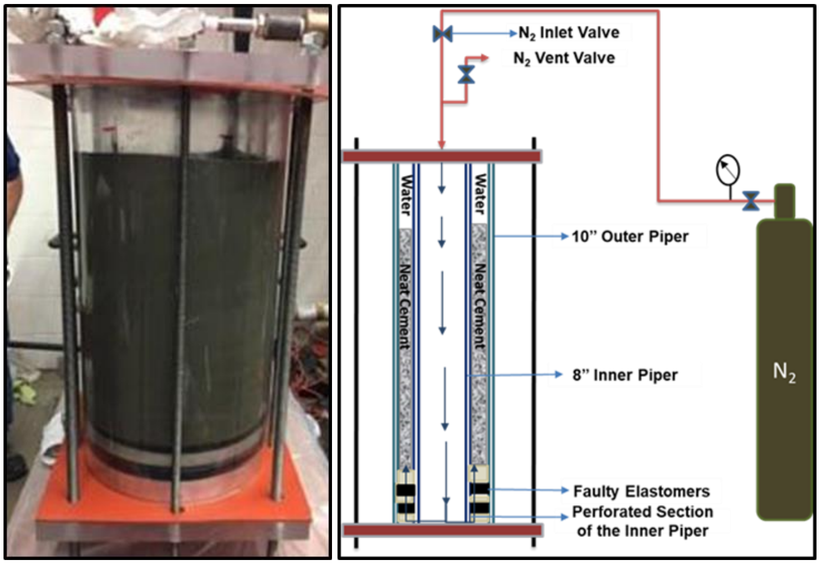


Figure 4. Elastomers before degradation with CO_2 (A), blisters and cracks on elastomers surface after CO_2 degradations (B), and small samples of elastomers being inserted into the aging cell

2.2 Experimental Setup and Tests Description

In this study, the setup was designed and constructed to replicate the actual final production liner of a geothermal well. The setup was fabricated using two acrylic pipes with inner and outer diameters of 8 and 10 inches. The annular space between the pipes is 0.75-in. The length of each pipe is 12- in (setup length). Two faulty EPDM elastomers degraded with CO_2 exposure were inserted in the annular space between the pipes and separated with aluminum rings to mimic the seal assembly configuration of the conventional type liner hanger. Neat Class H cement was poured on top of the elastomers to establish a dual barrier as shown in **Figure 5 (A)**. After 12 hours WOC, the nitrogen gas inlet valve (See **Figure 5 (B)**) was opened to inject the gas at 40 psi for 30 minutes, during which gas bubbles were monitored. The gas inlet valve was closed after 30 minutes and monitoring of gas bubbles continued for another 30-minutes as a holding time. This time was determined according to the requirements of the Code of Federal Regulations CFR (2016), Section 250.425. The test was repeated after 7 days to evaluate the effect of curing time or wait-on-cement (WOC) upon the cement sealability.



(A) (B)

Figure 5. Cement placement above the elastomers to establish a dual barrier system (A) and schematic showing the pressure test for elastomers and cement (B)

2.3 Results of Faulty Elastomer and Neat Class H Cement

After 12 hours from the cement placement (WOC), a 40 psi pressure test was conducted to evaluate the hydraulic integrity of the dual barrier. Nitrogen gas was injected underneath the faulty elastomers and it passed through the cement sheath. Bubbles were seen in the water column (**Figure 5 (B)**) above the cement sheath. The test inferred that the bonding between the cement and the acrylic pipe walls (inner and outer) was insufficient to hold the pressure. Leaks occurred at many locations between the bonded interfaces. Only a few leak points were seen within the cement sheath (micro-channels). Once, the gas injection was stopped, the pressure reduction was almost instantaneous with approximately 100% pressure depletion within 5 minutes. The test was repeated after 7 days to examine the effect of WOC on cement sealability. The sealability improved and this was reflected by the improvement in the pressure reduction profile as shown in **Figure 6**. This indicates that the WOC time improves cement sealability as a barrier. However, results also confirmed that the neat Class H cement cannot act as a primary barrier in case the elastomeric elements of the liner hanger is in a faulty mode.

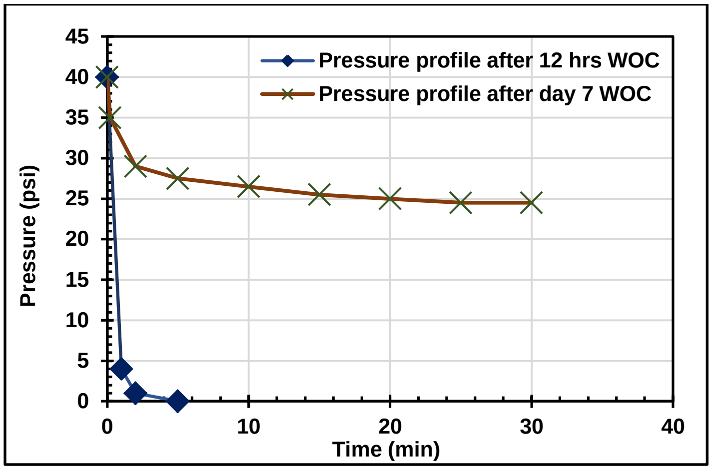


Figure 6. Faulty EPDM and neat Class H cement pressure decline at 40 psi after 12 hours and after 7 days WOC

3. FINITE ELEMENT MODEL FOR EVALUATION OF LINER HANGER DUAL BARRIER SYSTEM

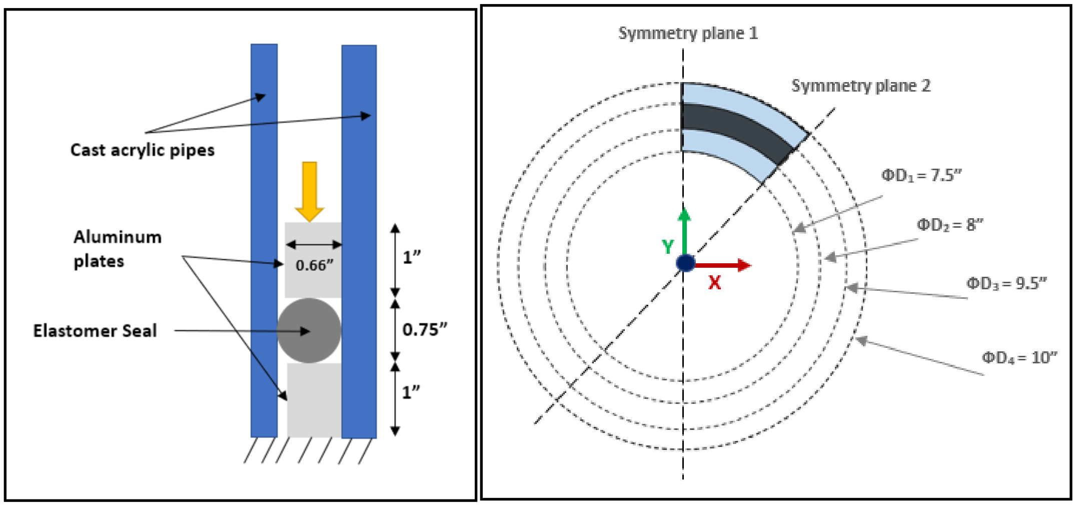
3.1 Finite Element Model of Seal Assembly

To confirm the experimental results and examine additional operating scenarios, a finite element model was developed. The schematic of the model with dimensions and boundary conditions is provided in **Figure 7**. The actual experimental setup has two elastomer ring seals and three aluminum plates. Modeling the exact configuration would have resulted in too many contact regions and led to convergence issues. To mitigate the convergence issues, only one seal between two plates was used in the FEA model. This also helped in reducing simulation time.

As shown in **Figure 7**, seal energization was performed by applying displacement boundary conditions to the top of the aluminum plate. The displacement values used in the simulation were obtained from the setup by measuring the axial compression of the seal using the measurement scales attached to the pipe. **Figure 8** shows the FEA before and after the seal energization process. Material properties used in the model are listed in **Table 1**.

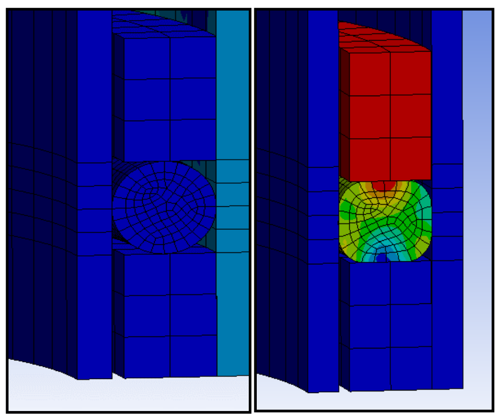
Table 1: Material properties used in the FEA model

Property	Cast Acrylic Pipes	Aluminum Alloy Plates	EPDM elastomer	EPDM elastomer – after aging in CO_2
Young's Modulus / Elastic modulus	0.4×10^6 psi	$10.29 \text{ X } 10^6$ psi	277 psi	194 psi
Poisson's ratio	0.37	0.33	0.49	0.49



(a) (b)

Figure 7: Schematic and dimension of FEA model of the experiment setup (a) 2D schematic in XZ plane. (b) top view of the model in XY plane



(A) (B)

Figure 8: Graphical representation of FEA model of the experiment setup before (A) and after (B) seal energization

For the EPDM elastomer seal, the elastic modulus was measured in the lab using a uniaxial compression test. Elastic modulus after exposure to CO_2 was also measured and used in the model. EPDM elastomer rings used in the setup were identified to have a diameter which is 1 mm greater than the annulus gap formed between the acrylic pipes. Hence, 1 mm of contact interference was simulated in the model. The target variable in the simulations was the maximum contact pressure value generated at the seal-pipe interface. The contact pressure generated as a function of axially applied compression is graphically presented in **Figure 9**. The presence of seal interference leads to pre-stress condition and results in contact pressure even at zero displacement. A leak-free gas-tight condition was observed with the unaged EPDM seal-ring system when a 40 psig pressure test was performed in the absence of an external displacement application via bolts. This is confirmed by the FEA model which predicts contact pressure of 48 psi for the EPDM seal with 1 mm interference and 0 mm displacement application (See **Figure 9**). However, after exposure to CO_2, the EPDM seal generated 30 psi contact pressure. This is in line with the experimental observation where the leak was observed at 40 psi. At 30 psi, a leak was observed from the setup which as per FEA prediction, contact pressure should not have happened. However, it should be noted here that the FEA model considers surfaces of seal and pipe to be perfectly smooth while the real seal surface, after exposure to CO_2, exhibited surface blistering. Such microscopic features can also impact contact pressure value and true sealability (Patel et al., 2018).

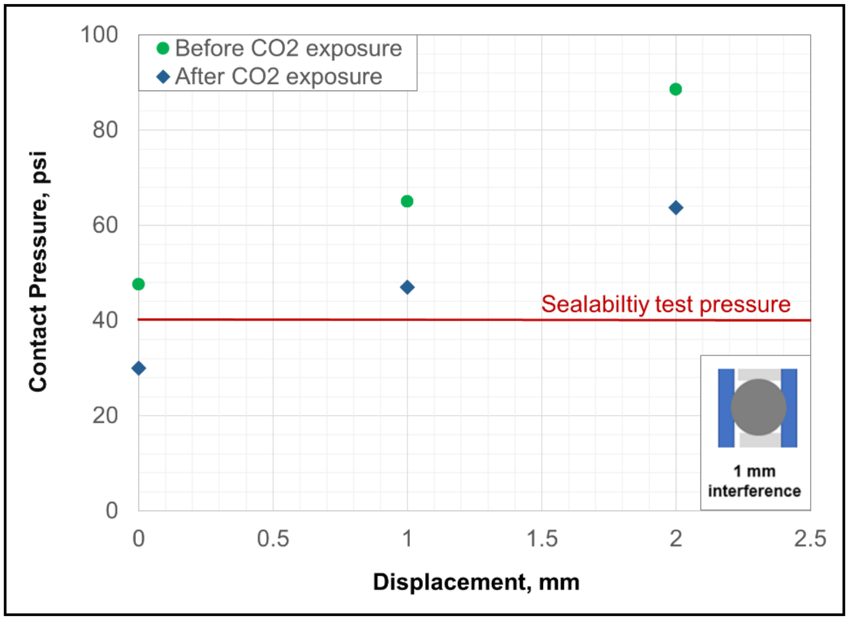


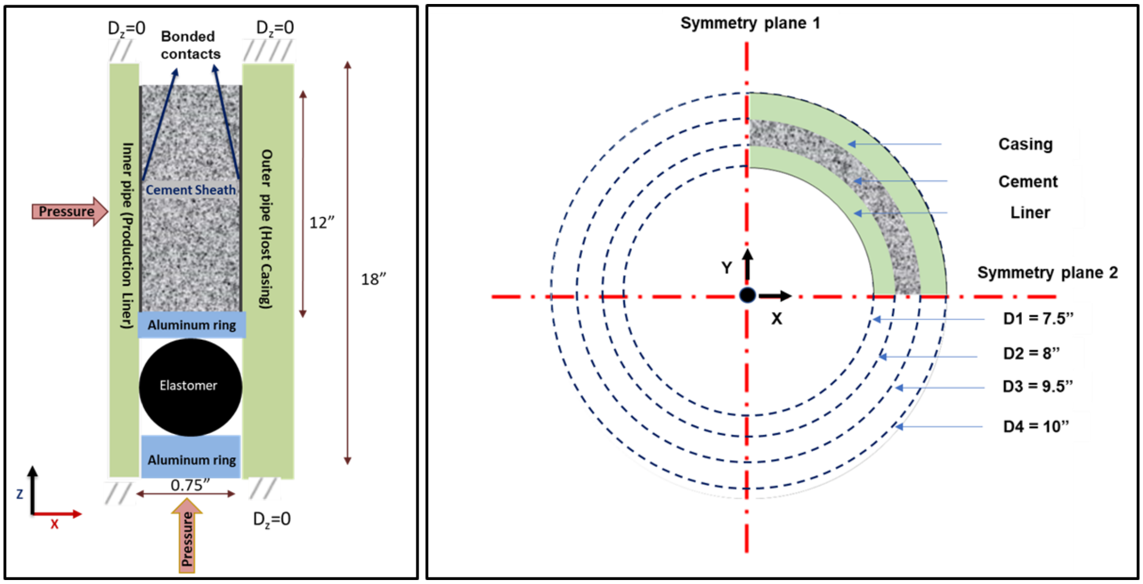
Figure 9: Contact pressure as a function of compression as simulated by finite element model

3.2 Finite Element Model of Seal Assembly and Cement Sheath as a Dual Barrier System

The objective of the FEA model developed in this study is to evaluate the cement sealability at 350°F. Mainly, to investigate the effect of curing time and pressure variations. The sealability was examined by comparing the stresses generated under these conditions with the strength of the cement and cement-liner interface. A model replicating the liner-cement-casing system is shown in **Figure 10**. The simulation input data are shown in **Table 2**. Steel properties were used for the liner and casing. The pressure was varied at 5000, 8000, 1000, and 15000 psi to simulate realistic pressure loading conditions of a geothermal well. The magnitudes of radial and hoop stresses obtained after running simulations under these pressures are plotted in **Figure 11** and **Figure 12** respectively. The results revealed that cement in a dual barrier system can withstand radial stresses up to 13000 psi; however, it is susceptible to failure by tensile hoop stresses generated from pressure loads of 2000 psi and upward.

Table 2. Cement properties used for modeling and simulation (Jimenez et al., 2017)

Cement properties / Curing Intervals	Young's Modulus (E), psi	Poisson's Ratio (ν)	UCS (psi)	Tensile Strength (psi)
Neat Class H +35% Crystalline silica ,7 days WOC. Cured at 350 °F and 3000 psi	1.64×10^6 psi	0.32	5412	307



(A) (B)

Figure 10. Production liner dual barrier FEA model, side view of annular cement (A), top view (B)

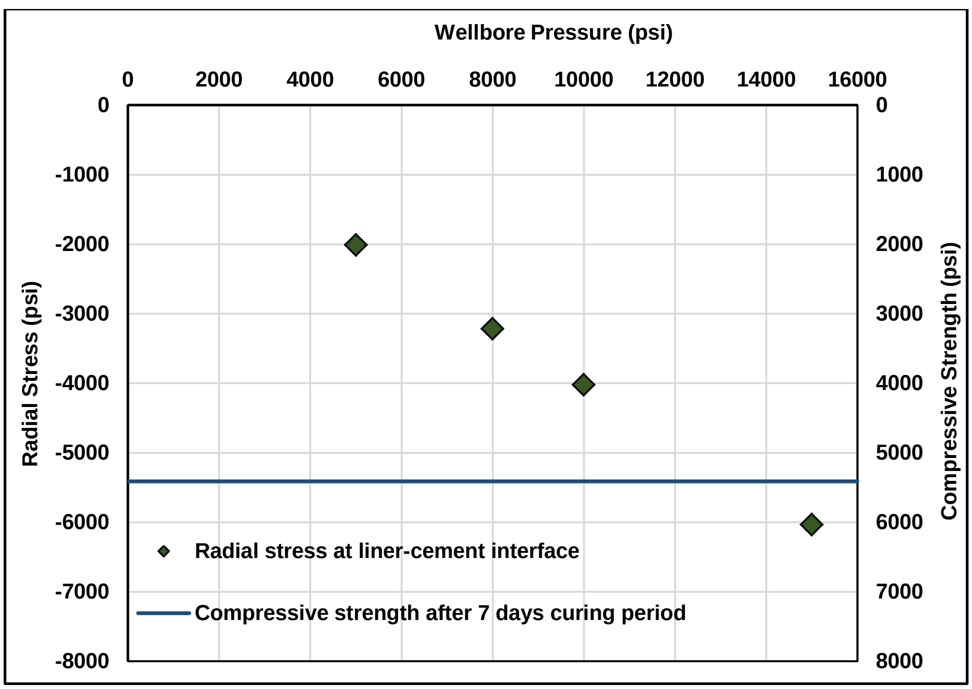


Figure 11. Radial stress act at cement-liner interfaces of dual barrier system at various wellbore pressure loads

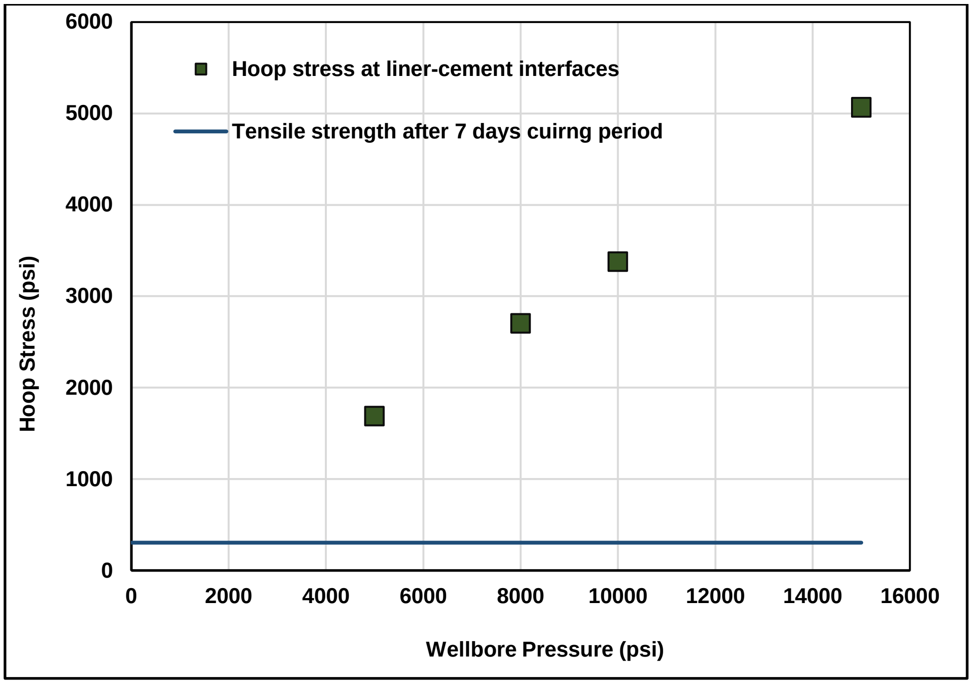


Figure 12. Hoop stress act at cement-liner interfaces of dual barrier system at various wellbore pressure loads

4. CONCLUSIONS

This paper shows the numerical and experimental work performed to understand the liner integrity in geothermal wells. The main findings of this paper are shown as follow:

Elastomeric materials of production liners in CO_2-rich geothermal wells are highly vulnerable to failure due to RGD phenomena.

Exposure to CO_2 can be determinant to the sealing performance of a liner hanger. Both experimental and FEA modeling results indicated that exposure to CO_2 can cause substantial (up to 40%) reduction in the sealing capabilities of EPDM elastomer.

The WOC time improves cement sealability as shown by the pressure decline trend plotted of the pressure tests conducted after WOC time of 12 hours and 7 days.

Neat Class H cement cannot act as a primary barrier in the case that the elastomeric elements of a liner hanger are defective.

The cement blended with 35% crystalline silica at 350°F used in this study demonstrated a low value of tensile strength, this was proved by cement failure under tension at pressures higher than 2000 psi. Therefore, for cement serves in a geothermal well, materials that assist in improving the tensile strength should be considered beside the use of crystalline silica.

5. ACKNOWLEDGMENT

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