PROCEEDINGS, 47th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 7-9, 2022
SGP-TR-223

# High Temperature, High Pressure Stability of Aqueous Foams for Potential Application in Enhanced Geothermal System (EGS)[1]

Viren Thakore[a, *], Fei Ren[a], Hong Wang[b], Jy-An John Wang[b], and Yarom Polsky[c]

[a]Temple University, 1947 North 12th Street, Philadelphia, PA 19122

[b] Materials Science & Technology Division, Oak Ridge National Laboratory, PO Box 2008, MS 6069, Oak Ridge, TN 37831

[c] Electrification & Energy Infrastructure Division, Oak Ridge National Laboratory, PO Box 2008, MS 6075, Oak Ridge, TN 37831

*Email: thakorev@temple.edu

**Keywords:** Enhanced geothermal system (EGS), aqueous foams, high temperature, high pressure, surfactant, stabilizing agent, exponential, half-life, stability.

## ABSTRACT

Enhanced Geothermal Systems (EGS) are typically constructed by injecting high-pressure water into deep hot dry rocks (HDR) under carefully controlled conditions to create new or re-open existing fractures, which usually uses an immense quantity of water. In lieu, a more sustainable technique is to utilize aqueous foams as fracturing fluid to reduce water consumption and waste-water treatments of conventional hydraulic fracturing. Although foam-based fracturing has shown promising results in oil and gas industries, its feasibility has not been demonstrated in EGS conditions that usually involve high temperature and high pressures. One potential barrier for utilizing foams in EGS applications is that foams are thermodynamically unstable and will become more unstable with increasing temperature due to liquid drainage, bubble coarsening, and coalescence.

This work focuses on evaluation of the stability of selected aqueous foams under high-temperature and high-pressure conditions. Specifically, foams generated with surfactant alfa olefin sulfonate (AOS) were studied at temperature up to 200°C, while the pressure ranged between 100 psi and 1000 psi. The effect of additional stabilizing agents was also examined, including guar gum, bentonite clay, borate salt crosslinker, silicon dioxide nanoparticles ($SiO_2$), and graphene oxide (GO) dispersion. Results showed that the stabilizing agents can enhance the foam thermal stability. Foams made with AOS and the borate salt crosslinker exhibited the longest half-life of 20 min at 200°C when the pressure was 1000 psi. An analysis of the data showed that foam stability decreased exponentially as temperature increased. On the other hand, pressure increased the foam half-life according to a power model. This study indicates that it may be possible to obtain highly stable foams at high-temperature and high-pressure conditions with appropriate stabilizing agents.

## 1. INTRODUCTION

Enhanced geothermal systems (EGS) are created by injecting high-pressure fracturing fluids under carefully controlled condition to create effective fracture networks in hot dry rocks (HDR), from which thermal energy can be harvested. The fracturing fluids are typically water based. It is estimated that the use of water in reservoir fracturing is about 2 million gallons per MW with more than 50% of water usage for well stimulation. As a result, approximately 120 billion gallons of water will be needed if water is used as the hydraulic fracturing fluid to meet the DOE's goal of 60 GW electricity generated from EGS in 2050 (Clark et al. 2010). In addition, excessive water usage may cause harm to the environment by contaminating surrounding water resources or damaging rock formations. Therefore, it is highly desired to develop water-free or waterless fracturing technologies for EGS applications.

Among various waterless fracturing technologies, foam-based fracturing is considered a good candidate due to its unique attributes: low water consumption, less chemical usage, higher proppant carrying capacity, and less environmental damage (Abdelaal 2021; Gandossi 2016; Hong Wang et al. 2019, 2020, 2021; Wanniarachchi, Ranjith, and Perera 2017). Foams are complex dispersions of liquidous and gaseous phases, where the liquid phase acts as the continuous phase and gas as the dispersed phase. The behavior and properties of foams, such as stability, viscosity, and bubble texture are highly influenced by external parameters such as temperature and pressure. One of the most important parameters for EGS related applications is the foam stability, which is affected by three mechanisms: drainage, coarsening, and coalescence. Foam drainage is induced by the downward flow of liquid through lamella borders due to gravity and capillary force (Georgieva, Cagna, and Langevin 2009). Bubble coarsening is similar to the Oswald ripening phenomenon, where gas diffuses from smaller to larger bubbles due to pressure difference (Thomas 2015). Coalescence refers to the merge of two or more bubbles when they are in contact due to drainage of liquid between the lamella borders. All three phenomena are inter-related, where controlling drainage can influence both the coarsening and the coalescence (Saint-Jalmes 2006; Weaire et al. 2003). Therefore, slowing down liquid drainage will result in increased stability performance.

The majority of literature studies (Frohne 1976; Gupta 2010; Oussoltsev et al. 2008; Riedel 1981) carried out to date concerned about the stability of foams under conditions relevant to the oil and gas industries, which normally involve low temperatures. For example, Wang

---

[1] This manuscript has been co-authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The publisher acknowledges the US government license to provide public access under the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

and coworkers (Hetang Wang et al. 2017) evaluated 10 different surfactants using a FoamScan® equipment to measure the foam half-life at a maximum temperature of 65°C, which showed that stability all the foams decreased with increase in temperature. Also, among all the surfactants, anionic surfactants performed better than cationic and non-ionic surfactants. In contrast, a smaller number of studies were carried out to evaluate foam stability under high temperature conditions. Study by Delahaije *et al.* showed that at elevated temperatures the poor foam stability correlated with foaming ability, i.e., foam stability depended on the surfactant ability to produce foam under certain condition such as temperature, pressure, and base solution composition (Delahaije, Lech, and Wierenga 2019). The previous study by the authors of this paper (Thakore et al. 2020) compared the stability of $N_2$-based foams and $CO_2$-based foams between room temperature and 180°C, and found that $N_2$-based foams were more stable due to the lower solubility of $N_2$ gas in water. An earlier work by Rand and Montoya (Rand and Montoya 1983) evaluated 50 different anionic surfactants in deionized water at downhole condition of 260°C to determine if foams could survive. Results showed that alfa olefin sulfonates (AOS) appeared to be the best surfactant for foam fracturing.

On the other hand, Szabries and coworkers investigated foam stability at high pressure of 35 MPa and temperature up to 120°C, where results indicated that at high pressure mean bubble size remain relatively small and foams were slightly more stable compared to low pressure (Szabries et al. 2019). This is explained by increase in the Marangoni effect which allows liquids to flow from areas with lower surface tension to areas with higher surface tension. Work performed by Wang et al. (Hetang Wang et al. 2017) on foam stability at high pressure (2000 psi) and high temperature (110°C) showed that the performance of foams at high temperatures was greatly dependent on the type of surfactant used. Their work also showed that pressure had a positive influence on the stability of foams but was also dependent on the type of surfactant used (Hetang Wang et al. 2017).

One of the strategies to enhance the high-temperature thermal stability of foams is by addition of gelling agents to the liquid phase. Surfactant based gelling agents, also known as viscoelastic surfactants, have been investigated for enhancement of foam stability. One of the early experiments investigated rheological properties of $N_2$-based foams with addition of gelling agent such as guar gum at temperatures as high as 150°C (P. C. Harris and Reidenbach 1987). It was observed that foam fluids did not thin rapidly with addition of guar gum. A gelling agent such as guar gum typically functions as a thickener which can increase the viscosity of a liquid without substantially changing its other properties. A recent study conducted by Zhang et al. (Zhang et al. 2019) showed that viscoelastic surfactants such as laurylamine dipropylenediamine had a high-temperature tolerance up to 160°C due to their high bulk viscosity that led to lower drainage velocity in the foam film.

Another way to increase viscosity of foam fluid is to introduce crosslinking agents such as borate salts in addition to guar gum. Borate ions can form a complex cross-link pair with the stabilizing agent guar gum, resulting in an increase in the viscosity of the base fluid and in turn more stable foams. For example, Harris et al. (Phillip C. Harris 1993) showed that addition of high-pH crosslinkers increased the foam stability at temperatures up to 300°F. In addition, bentonite clay, which was extensively used in oil and gas industries as a cross-linking agent, showed improvement in the foam viscosity and thus foam stability at temperatures as high as 100°C (Verma, Chauhan, and Ojha 2017).

Moreover, foam stability may be further improved with addition of nanoparticles as potential stabilizing agents. Several studies have reported foam stability at high temperature with presence of $SiO_2$ nanoparticles in the liquid phase. Lv and coworkers observed that stability of foams increased when $SiO_2$ nanoparticles were added to the base solution at temperatures up to 90°C (Lv et al. 2015). Microscopic analysis revealed that addition of nanoparticles slowed down the foam bubbles size change and in turn delayed their coalescence, which resulted in enhanced foam stability. It was proposed that the presence of nanoparticle aggregates could slow down the drainage of foams by blocking plateau border of foam bubbles (Al-muntasheri, Advanced, and Aramco 2017). Parameters, such as the concentration of nanoparticles, their size, and salinity of the solution are all important parameters that affect the rheological behavior of the foam fracturing fluids (Binks and Horozov 2005). Another lab scaled experiment was conducted to study foam stability of AOS foams with nanoparticles, guar gum and viscoelastic surfactant at high temperature (100°C) and pressure (800 psi). Results indicated that temperature and pressure showed negative effect on foam stability when only AOS was used, however addition of nanoparticle improved stability of foams made with AOS, AOS and guar gum, and AOS with Viscoelastic Surfactant (VES) (Emrani and Nasr-El-Din 2017). In addition to $SiO_2$ nanoparticles, graphene oxide (GO) dispersion has also been evaluated as a potential foam stabilizing additive. GO is considered to adhere to surface of water by a lower interfacial energy, which acts like a surfactant. Research showed that GO can be used as a surfactant to emulsify organic solvents with water and disperse insoluble materials in water. Also, GO sheets were found to be capable of stabilizing oil-water interface to form the particles-stabilized emulsions (Cote et al. 2011; Kim et al. 2010). Studies have also shown that GO has good hydrophilicity and the high interfacial activity that enabled stabilizing $CO_2$ based foams (Barrabino, Holt, and Lindeberg 2018).

Our previous work (Thakore et al., 2021) evaluated the foam stability of four different type of surfactants including AOS, sodium dodecyl sulfonate (SDS), TergitolTM (NP – 40), and cetyltrimethylammonium chloride (CTAC) between room temperature and 200°C, while the pressure was varied between ambient pressure and 400 psi. Results showed that foams generated with AOS as the surfactant had the best stability as indicated by the foam half-life (Figure 1). In this paper, we report the foam stability at high temperatures (up to 200°C) and high pressures (up to 1000 psi) for various AOS based foams with additional stabilizing agents. The new results indicated that the foam stability can be extended by adding stabilizing agent such as crosslinker, which led to the longest half-life of 20 min at 200°C and 1000 psi. Analytical models were developed to comprehend the effect of temperature (exponential dependence) and pressure (power-law dependence) on the foam half-life.

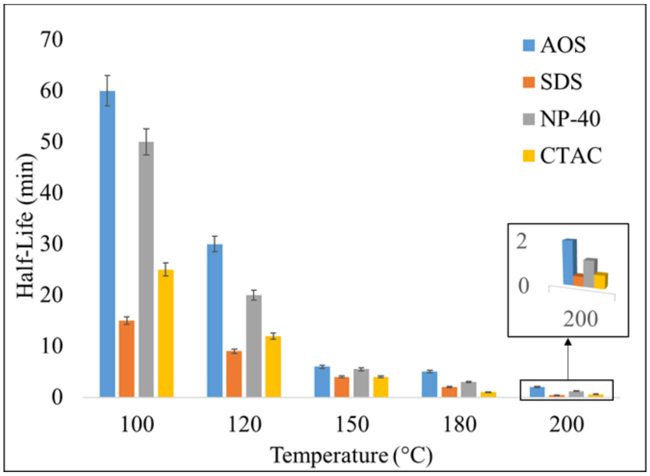

**Figure 1: Thermal stability of foams in terms of foam half-life with different surfactants as a function of temperature at 400 psi (Thakore et al. 2021).**

## 2. EXPERIMENTAL METHOD

### 2.1 Foam Study Apparatus

The laboratory apparatus used to evaluate the foam stability is shown in Figure 2. Details of this system were previously presented (Thakore et al., 2021). In the current setup, a new view cell was installed, which allowed for observation at temperature up to 200°C and pressures up to 2700 psi.

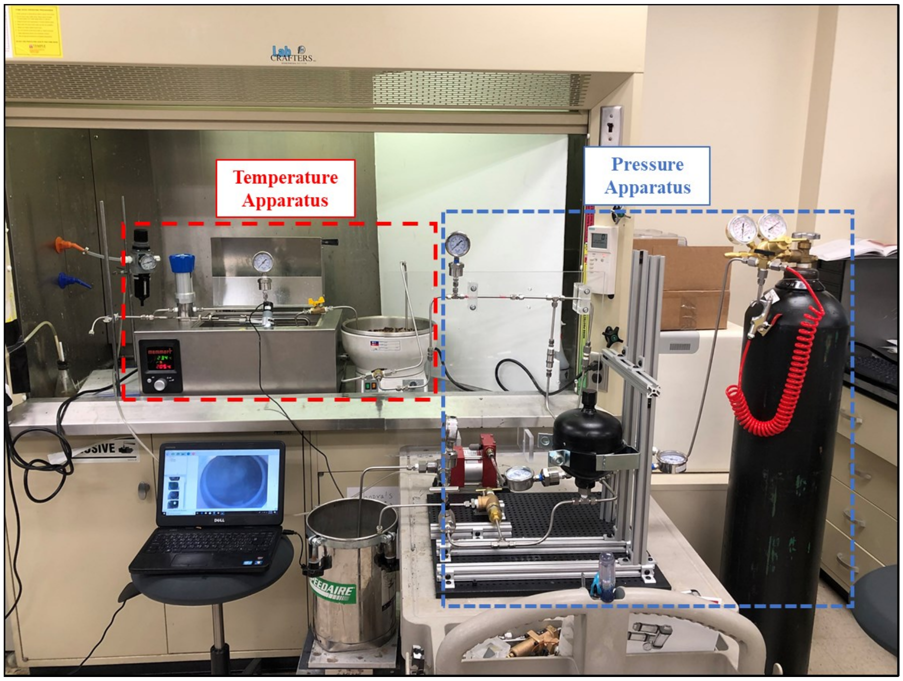

**Figure 2: Laboratory setup for foam study under high-temperature and high-pressure conditions.**

### 2.2 Foam Base Solution

The foam-based solutions were mixtures of deionized (DI) water with surfactant alfa olefin sulfonate (AOS) and additional stabilizing agents. Five stabilizing agents were investigated in this study: guar gum, bentonite clay, crosslinking agent (guar + borate salt), silicon dioxide ($SiO_2$) nanoparticles, and graphene oxide (GO) dispersion. These chemicals were previously studied to show stabilizing effects (Li, Al-Muntasheri, and Liang 2016; Ranka, Brown, and Hatton 2015; Verma, Chauhan, and Ojha 2017). All these chemicals were purchased from commercial sources and diluted to the specific concentrations based on literature results (Table 1).

**Table 1: Chemicals used to make the foam base solutions.**

| Chemical Name | Type | Vendor | Concentration (wt.%) | References for Concentration (wt. %) |
|---|---|---|---|---|
| AOS | Anionic Surfactant | Sigma-Aldrich | 1 | (Ahmed et al. 2017, 2018) |
| Guar gum | Gelling Agent | Sigma-Aldrich | 0.36 | (P. C. Harris and Reidenbach 1987) |
| Bentonite clay | Gelling Agent | Sigma-Aldrich | 0.36 | (Verma, Chauhan, and Ojha 2017) |
| Borate salt (crosslinker) | Gelling Agent | Sigma-Aldrich | 0.1 | (Phillip C. Harris 1993) |
| $SiO_2$ | Nanoparticles, 50-70 nm | US Nanomaterials | 0.1 | (Binks and Horozov 2005; Lv et al. 2015) |
| GO | Nanoparticle Dispersion, 4-30 µm (lateral size) | Graphenea | 0.05 | (Cote et al. 2011) |

To prepare AOS-containing base solution, an appropriate amount of AOS was added to 2500 ml of Deionized (DI) water and the solution was mixed with a mechanical stirrer at 1100 rpm for 5 min while avoiding the formation of bubbles. For the preparation of the guar/clay-containing solution, both were slowly added to the DI water which was constantly stirred at 800 rpm using a mechanical stirrer until all the powder was homogeneously dispersed without the formation of agglomeration. Then, surfactants were added to the guar suspension and mixed for about 5 min. Additional DI water was then added under constant stirring at 1100 rpm to avoid the formation of any foam. For the preparation of the crosslinker base solution, borate salt (crosslinker) was added into guar-containing solution with constant stirring at 1100 rpm to avoid thickening of base solution due to active cross-linking between guar polymer and borate ions. Then, the surfactant AOS was added to the crosslinked solution and mixed for 10 mins. Additional DI water was added to complete the solution with the required concentration. For the preparation of the suspension containing the $SiO_2$ nanoparticles, $SiO_2$ powder was ultrasonicated in DI water for 1 hour. This homogenized nanoparticle suspension was then added to the required surfactant solution under constant stirring. Graphene oxide base solution was prepared by simply adding the required amount of GO water dispersion to the DI water, followed by the addition of the surfactants, and stirring at 800 rpm to ensure homogenous mixing of the solution. Additional DI water was added to adjust the GO concentration to 0.05 wt.%. Pictures of the as-prepared base solutions are shown in Figure 3.

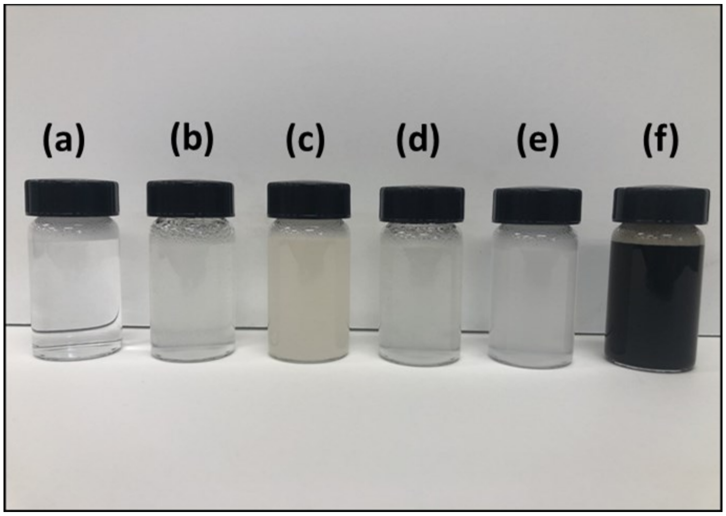

**Figure 3: Picture showing samples of foam base solutions containing a) AOS, b) AOS + guar gum, c) AOS + clay, d) AOS + crosslinker, e) AOS + $SiO_2$, and f) AOS + GO.**

### 2.3 Foam Half-Life Measurement

To study the foam stability, the foam life was measured inside the view cell at a given temperature and pressure condition. Before the foam was injected, the view cell was first heated to reach the oil bath temperature, which was confirmed with an IR camera. The foam quality is controlled by adjusting the flow rates of gaseous and liquid phases; and foam injection pressure was controlled by pressure regulators. It is important to note that the injection of foams into the view cell would slightly reduce the temperature of the view cell due to the lower temperature of the foams. This phenomenon may represent a potential temperature drop in the hot dry rocks because of the injection of ambient-temperature fluid. This "quenching" effect in the view cell was partially mitigated by preheating the foam using a water bath. After the foam was injected into the view cell, the height of the foam was monitored by a digital camera as shown in Figure 2. By measuring the foam height as a function of time, the half-life of the foam, i.e., the time needed to reduce to 50% of the original height, can be determined (Thakore et al. 2021). More than 800 data points were recorded, which were then used to develop analytical models to study the effect of temperature and pressure, respectively.

## 3. RESULTS

This section presents the foam stability data in terms of half-life between 100°C and 200°C while the pressure increased from 100 psi and 1000 psi. The results were grouped based on the stabilizing agents.

### 3.1 AOS Foams

Figure 4a shows the half-life of AOS foams at 100°C. A general increasing trend was observed as the pressure increased from 100 psi to 1000 psi. The half-life at 1000 psi reached 78 min. which was more than 4 times increase over the value measured at 100 psi (Figure 4a). A monotonic increase in half-life as a function of pressure was also observed at 200°C (Figure 4b). The half-life of AOS foams increased from 0.5 min at 100 psi to 10 min at 1000 psi (Figure 4b). At 100°C, a rapid increase of the half-life took place below 400 psi (Figure 4a), while the pressure induced stability increase was relatively slow below 400 psi at 200°C (Figure 4b). As will be seen in the following sections, similar trends were observed in other foams. However, this difference is not clearly understood and requires further study. When comparing the data points taken at the same pressure, half-lives recorded at 200°C were shorter than those taken at 100°C, as expected.

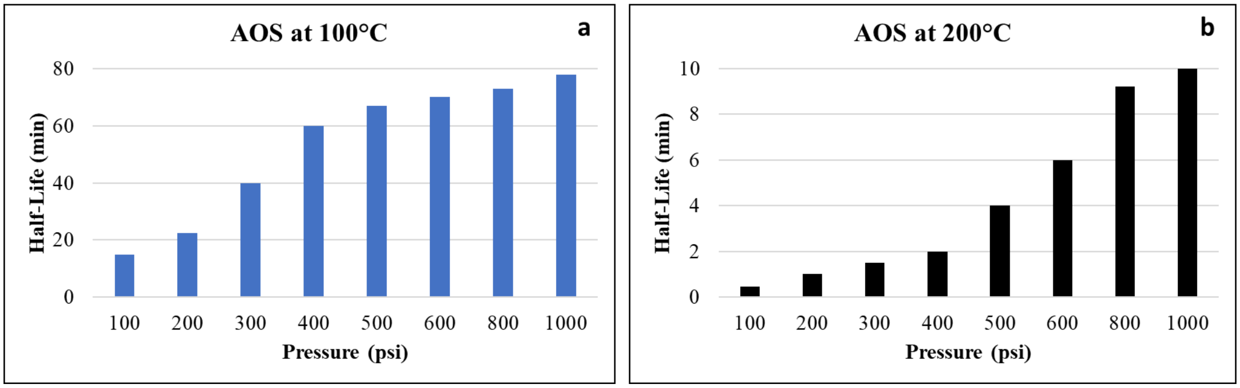

**Figure 4: Half-life of AOS foams as a function of pressure at (a) 100°C and (b) 200°C.**

### 3.2 AOS + Guar Foams

Gelling agent guar gum could enhance the thermal stability of AOS foams by increasing the viscosity of the foam base solution. Figure 5 compares thermal stability of AOS + Guar foams at 100°C and 200°C for pressures ranging from 100 psi to 1000 psi. The half-life of guar foams at 100°C and 100 psi was recorded at 30 min, and with increase in pressure to 1000 psi the half-life increased to 170 min (Figure 5a), which are 66% and 120% higher than the AOS-only foams at 100 psi and 1000 psi (Figure 4a), respectively. At 200°C, guar foams only lasted for a few minutes under 100 psi (Figure 5b). However, with increase in pressure to 1000 psi its half-life was increased by 20 times to 15 min (Figure 5b). When temperature increased from 100°C to 200°C, the half-life decreases by 90% at both pressure ranges of 100 psi and at 1000 psi, respectively.

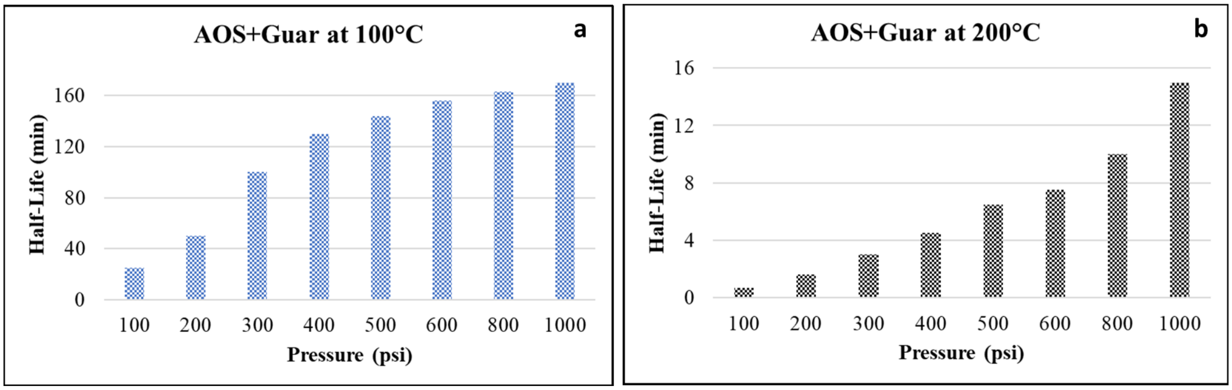

**Figure 5: Half-life of AOS + Guar foams as a function of pressure at (a) 100°C and (b) 200°C.**

### 3.3 AOS + Bentonite Clay Foams

Bentonite clay has a higher thermal capacity compared to guar gum as gelling agent. Clay as stabilizing agent also showed increase in AOS foam half-life. As shown in Figure 6a, the half-life of clay foams at 100°C increased by 450% from 20 min at 100 psi to 110 min at 1000 psi. At 100°C and 1000 psi, the half-life of clay foam was 40% longer than that of AOS-only foam (Figure 4a). At 200°C, half-life was also observed to increase from ~ 1 min at 100 psi to nearly 15 min at 1000 psi (Figure 6b). When compared to AOS-only foams, the half-life increased by 50% at 1000 psi (Figure 4b). Foam stability also decreased for clay foams with increase in temperature, at 100 psi a drastic decrease of 90% and at 1000 psi 80% decrease in half-life were recorded with increase in temperature from 100°C to 200°C.

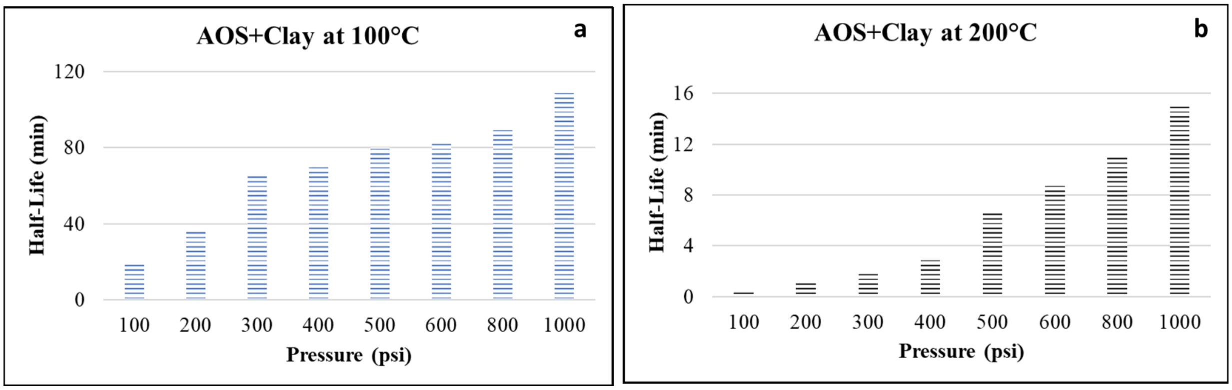

**Figure 6: Half-life of AOS + Clay foams as a function of pressure at (a) 100°C and (b) 200°C.**

### 3.4 AOS + Crosslinker Foams

Addition of crosslinker borate salt was observed to increase the base fluid's viscosity compared to other gelling agents. A steady increase in crosslinker foam's half-life was observed with increase in pressure at 100°C, as shown Figure 7(a). The half-life at 100°C and 100 psi was recorded at 60 min which increased to 190 min with increase in pressure to 1000 psi, which represents more than 200% increase. At 200°C and increase in pressure from 100 psi to 1000 psi crosslinker foams half-life was recorded to increase from 0.8 min to 20 min (Figure 7(B)), which is 2000% increase in half-life. AOS + crosslinker foams showed enhanced foam stability performance compared to guar gum and bentonite clay at high temperature of 200°C. At 200°C and 1000 psi crosslinker foam half-life increased by 150% when compared to only AOS foams. However, crosslinker foams also showed decreasing foam stability with increasing temperature from 100°C to 200°C. It is observed that crosslinker foam half-life decrease by 98% and 90% at injection pressures of 100 psi and 1000 psi, respectively, with increase in temperature to 200°C.

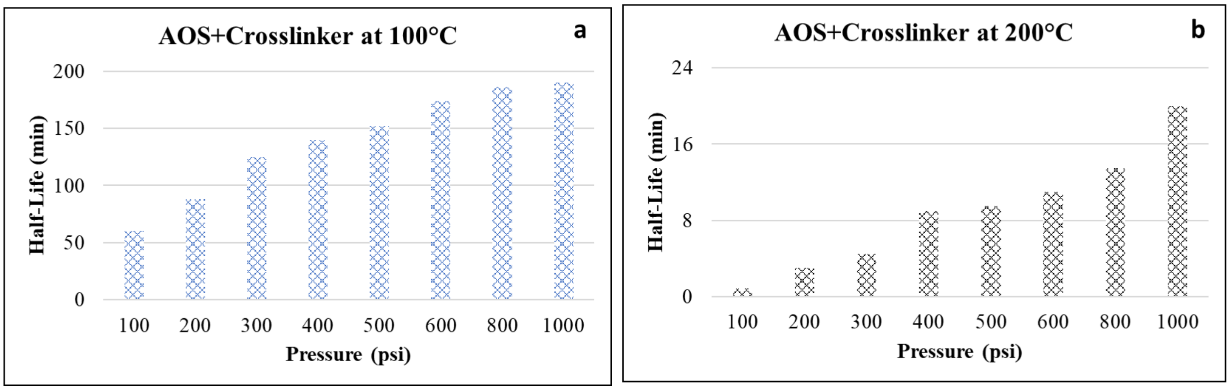

**Figure 7: Half-life of AOS + crosslinker foams as a function of pressure at (a) 100°C and (b) 200°C.**

### 3.5 AOS + $SiO_2$ Nanoparticles

Another stabilizing agent studied in this work was $SiO_2$ nanoparticles. Literature studies showed that nanoparticles tend to block the lamella border of foam structure which could result in decreased drainage rate and increased foam stability (Binks and Horozov 2005; Hunter et al. 2008). From Figure 8(a), at 100°C, the half-life recorded at 1000 psi was at 150 min, which showed an increase of 150% than the pressure was 100 psi. At high temperature of 200°C, $SiO_2$ also showed promising performance where foam half-life reached 17 min at 1000 psi, which was a 145% increase compared to 100 psi (Figure 8b). When compared to AOS-only foams at 200°C and 1000 psi (Figure 4b), the half-life was increased by 75% with addition of $SiO_2$ nanoparticles. However, half-life decreased with increase in temperature. From Figure 8, it is observed that half-life decreases by 90% and 85% at 100 psi and 1000 psi with increase in temperature from 100°C to 200°C, respectively.

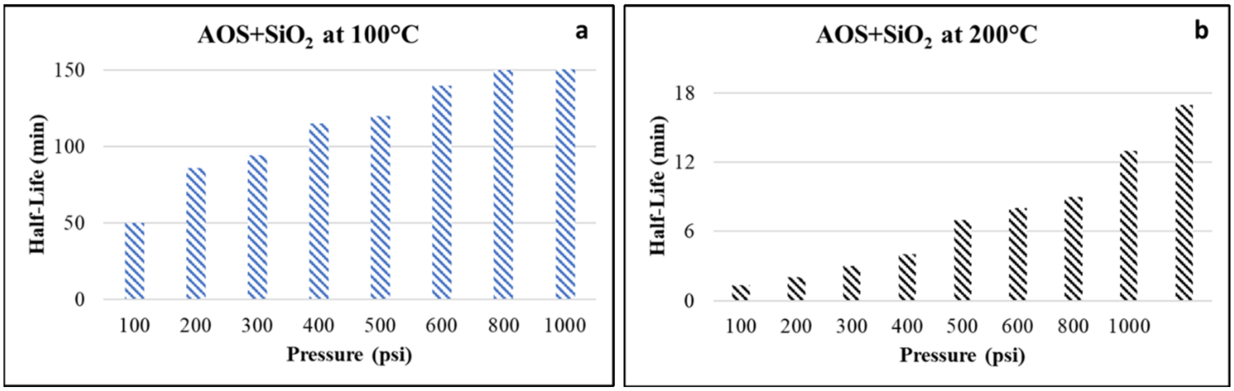

**Figure 8: Half-life of AOS + SiO$_2$ foams as a function of pressure at (a) 100°C and (b) 200°C.**

### 3.6 AOS + GO dispersion Foams

GO as stabilizing agent was recently studied for aqueous foams. GO dispersion itself can act as a surfactant besides AOS in the base fluid. GO has shown significant enhancement in thermal stability of AOS foams. As shown in Figure 9a, the half-life of GO foams at 100°C and 100 psi was recorded at 65 min, which increased to 190 min when the pressure increased to 1000 psi. When compared to AOS-only foams (Figure 4a), the half-life was observed to be increased by 150% and 220% at 100 psi and 1000 psi, respectively. At high temperature of 200°C, the half-life increased from ~ 1 min to 17 min when pressure increased from 100 psi to 1000 psi (Figure 9b). Again, at 200°C when compared to only AOS foams, half-life was increased by 80% and 150% at 100 psi and 1000 psi, respectively.

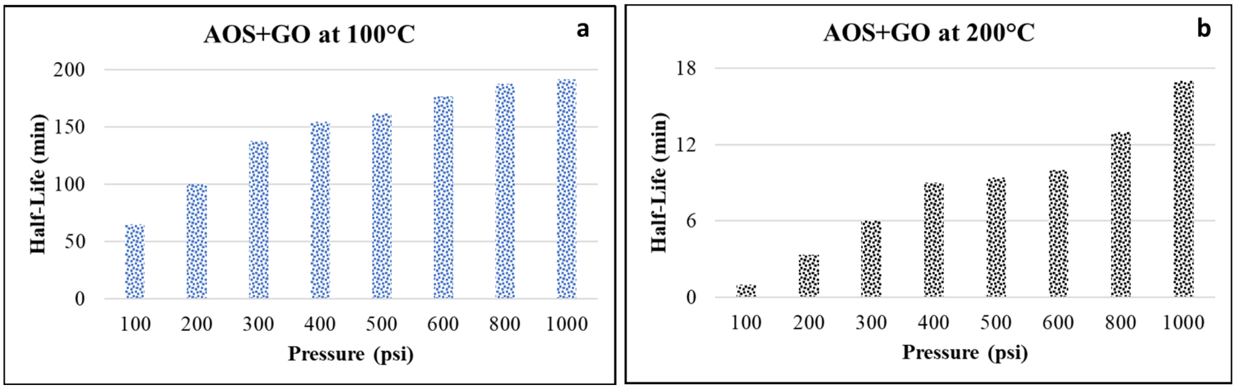

**Figure 9: Half-life of AOS + GO foams as a function of pressure at (a) 100°C and (b) 200°C.**

## 4. Discussion

### 4.1 Effect of Temperature

Good thermal stability is essential for foams to be utilized as a hydrofracturing fluid in EGS reservoir stimulation applications. Unfortunately, many studies showed that temperature exhibited a detrimental effect on foam stability. Jackman et al. argued that foams became unstable at temperatures above the critical temperature of the base solution due to increase in coalescence rate at high temperature (Jackman et al. 2018). Sharma and coworkers reported that with increase in temperature a significant increase in effective air mobility was observed which increased the rate of change in bubble size at high temperature leading to unstable foams (Sharma, Shah, and Brigham 1985). It was also shown that temperature had remarkable influence on microscopic structure of surfactant stabilized foams such that increasing temperature would decrease the surface tension and bubble size (Saint-James et al. 2005). Reduced foam stability may be also due to lower viscosity of the liquid phase at higher temperature, which resulted in more rapid liquid drainage and hence lower foam stability (Phillip C. Harris 1993). Wang et al. developed an analytical model which showed that foam stability decreased exponentially with increase in temperature for different types of surfactants between 20°C and 40°C at low pressures (Hetang Wang et al. 2017). Another literature study by Maini and Ma (Maini and Ma 1986) showed that drainage of liquid from foam generally followed first order kinetics, and the half-life for foam volume decay declined dramatically with increasing temperature.

In this study, the experimental data presented in Section 3 were found to follow an exponential decay function, according to the following equation.

$$\boldsymbol{t = t_0 + t_1 e^{\left(\frac{-T}{a}\right)}} \tag{1}$$

where $t$ is the half-life, $T$ is the temperature, $t_0$ represents an offset parameter in the exponential decay plot which is a coefficient added for finding the best fitting curve (least squares fit), $t_1$ and $a$ are fitting parameters. Figure 10 shows the fitting curves at 1000 psi when the temperature increased from 100°C to 200°C. Fitting results are listed in Table 2 for pressures at 600 psi, 800 psi and 1000 psi. As indicated by the $R^2$ values, the temperature dependent foam half-life can be well described by Eq. (1).

Fitting results in Table 2 show that, $t_1$ depends on the pressure such that an increase in the pressure will lead to decrease in $t_1$ and addition of stabilizing agents showed increased in $t_1$. In addition, $t_1$ seems to be a function of the foam composition as with different foam composition different value for $t_1$ is observed in Table 2. On the other hand, fitting parameter *a* is considered as a pressure dependent decay term, which is strongly influenced by the pressure and weakly related to the foam composition. It can be observed that parameter *a* increased with increase in pressure from 600 psi to 1000 psi, which in turn would increase the foam half-life. A lower value of *a* indicates a higher dependency of the foam stability on temperature. From Table 2, foam generated with stabilizing agents has larger *a* value compared to the AOS only foam, implying that the thermal stability of foams with stabilizing agents was less susceptible to temperature than AOS only foam. While the physical nature of the fitting parameters deserves further study, Eq. (2) may be used to provide some initial projection of foam half-life beyond the temperature range covered in this study.

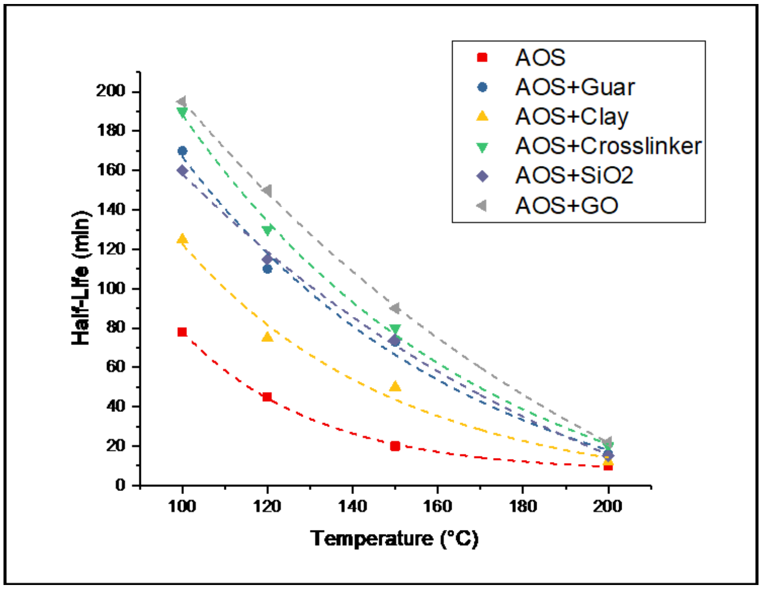

**Figure 10: Temperature dependent foam half-life at 1000 psi and the exponential fitting curves.**

**Table 2: Fitting results to Eq. (1) at 600 psi, 800 psi and 1000 psi.**

| **Foam Base Solution** | **Pressure** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **600 psi** | | | | **800 psi** | | | | **1000 psi** | | | |
| **Data set** | $t_0$ | $t_1$ **(min)** | *a* **(°C)** | $R^2$ | $t_0$ | $t_1$ **(min)** | *a* **(°C)** | $R^2$ | $t_0$ | $t_1$ **(min)** | *a* **(°C)** | $R^2$ |
| AOS | 3.5 | 1830 | 28.79 | 0.99 | 4.8 | 1598 | 31.65 | 0.99 | 6.7 | 1798 | 32 | 0.99 |
| AOS+Guar | 3.4 | 7230 | 25.93 | 0.99 | 5.2 | 3048 | 33.63 | 0.97 | -26.6 | 840 | 68 | 0.97 |
| AOS+Clay | 1.8 | 1254 | 36.56 | 0.96 | -0.4 | 786 | 48.33 | 0.98 | -3.5 | 902 | 50 | 0.96 |
| AOS+Crosslinker | 6.4 | 7506 | 26.31 | 0.99 | 9.6 | 3950 | 32.04 | 0.97 | -33.6 | 902 | 71 | 0.99 |
| AOS+GO | -0.5 | 1785 | 39.22 | 0.99 | -39.9 | 614 | 81.87 | 0.99 | -80.7 | 705 | 121. | 0.99 |
| AOS+$SiO_2$ | 9.6 | 4307 | 30.61 | 0.93 | -30.3 | 1025 | 64.10 | 0.97 | -114.7 | 593 | 110 | 0.99 |

### 4.2 Effect of Pressure

In contrast to the effect of temperature, pressure showed a positive effect on the foam stability. The density of the dispersed phase (gas) and the viscosity of the foam base fluid play important roles in thermal stability. With increase in pressure both the gas density and fluid viscosity increase, which in turn lead to more stable foams at high pressure (Holt 1996). Rand and coworkers (Rand and Kraynik 1983) experimentally studied the foam stability at high pressures and showed that the bubble size was significantly uniform at high pressure which led to low gas mobility between the bubbles, which causes the liquid to flow from areas with lower surface tension to areas of higher surface tension and stabilizes foam lamella border and reduces drainage rate. This phenomenon is termed as Marangoni effect, which accelerates under high pressure (Szabries et al. 2019). Moreover, foam bubbles become smaller with increasing pressure, which reduces coalescence and enhance foam stability (Firoze Akhtar et al. 2018). In this study, pressure effect on foam stability in terms of half-life is found to obey the following power-law equation,

$$\boldsymbol{t = p_0(1 + P)^{a'}} \qquad (2)$$

where t is half-life, P is pressure, $\boldsymbol{p_0}$ and *a'* are fitting parameters. Figure 11 shows examples of curve fitting to the power-law model on foam half-life at 200°C. Fitting results at 100°C, 150°C and 200°C to Eq. 2 are listed in Table 3. Fitting parameter $p_0$ is seen to decrease with increase in temperature, while increase with stable foam composition. Fitting parameter *a'* increases with addition of stabilizing agents compared to AOS only foams. On the other hand, *a'* considerably drops with increase in temperature to 200°C. Similar to Eq. (1), a deeper understanding of the physical meanings of the fitting parameters in Eq. (2) is needed. Meanwhile, this equation points towards a positive trend in foam stability as pressure increases.

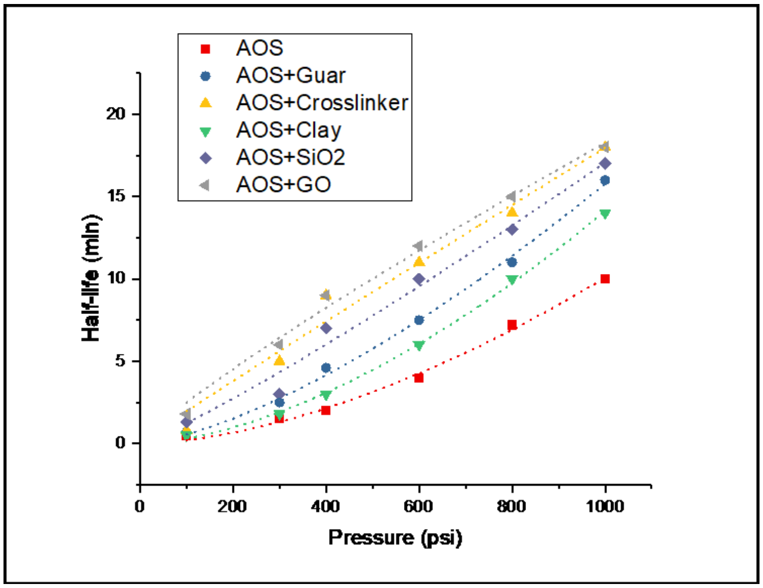

**Figure 11: Power-law model fitting curves showing the effect of pressure on foam half-life at 200°C.**

**Table 3: Fitting results to Eq. (2) at 100°C, 150°C and 200°C.**

| **Foam Base Solution** | **Temperature** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **100°C** | | | **150°C** | | | **200°C** | | |
| **Data set** | **$P_0$ (min)** | ***a'* (1/K)** | **$R^2$** | **$P_0$ (min)** | ***a'* (1/K)** | **$R^2$** | **$P_0$ (min)** | ***a'* (1/K)** | **$R^2$** |
| AOS | 1.86 | 0.55 | 0.90 | $3.9 \times 10^{-6}$ | 2.33 | 0.97 | $8.49 \times 10^{-5}$ | $4.77 \times 10^{-5}$ | 0.99 |
| AOS+Guar | 4.18 | 0.54 | 0.90 | $4.94 \times 10^{-4}$ | 1.72 | 0.99 | $6.71 \times 10^{-4}$ | $2.73 \times 10^{-4}$ | 0.99 |
| AOS+Clay | 2.13 | 0.57 | 0.95 | $5.34 \times 10^{-7}$ | 2.72 | 0.97 | $1.46 \times 10^{-4}$ | $4.1 \times 10^{-5}$ | 0.99 |
| AOS+Crosslinker | 7.97 | 0.43 | 0.94 | $2.34 \times 10^{-4}$ | 1.84 | 0.99 | 0.022 | 0.016 | 0.97 |
| AOS+GO | 13.99 | 0.38 | 0.90 | $1.4 \times 10^{-3}$ | 1.61 | 0.97 | 0.045 | 0.0159 | 0.99 |
| AOS+$SiO_2$ | 8.32 | 0.42 | 0.94 | $1.3 \times 10^{-3}$ | 1.62 | 0.97 | 0.006 | 0.004 | 0.97 |

In this paper, the independent effects of temperature and pressure on foam half-life were analyzed. In future work activities will be focused on providing guidelines for design of stable foams and predict the behavior of foams under given temperature and pressure. As part of these activities a comprehensive analytical model that simultaneously accounts for the effects of temperature and pressure on foam half-life will be pursued and its connection with physical phenomena will be explored. This could be achieved through non-linear surface fitting models with two independent variables (temperature and pressure) and one dependent variable (half-life) that could help to predict foam half-life at downhole condition of high temperature and high pressure for EGS application.

## 5. CONCLUSIONS

In this work, foam stability was evaluated in terms of half-life for foams made with surfactant AOS. Temperature ranged between 100°C and 200°C, while pressure increased from 100 psi to 1000 psi. Results showed that thermal stability of AOS foams was further enhanced by additional stabilizing agents. At a testing condition of 200°C and 1000 psi, the half-life was increased by 50%, 40%, 100%, 75%, and 80% when guar gum, bentonite clay, crosslinker, $SiO_2$ nanoparticles, and GO dispersion were used in AOS foams. AOS foams with crosslinking agent and GO dispersion showed the most stable foams with a half-life of 20 min and 17 min at 200°C and 1000 psi, respectively. At a fixed pressure, temperature showed a detrimental effect on foam stability, which could be described by an exponential decay model. On the other hand, pressure exhibited a positive influence on the foam stability, which followed a power-law model. This improvement is likely due to the smaller bubble size and the Marangoni effect at high pressure. These results imply that it would be possible to generate very stable aqueous foams (half-life of hours) at high-temperature and high-pressure conditions with appropriate surfactant and stabilizing agents, which may be suitable to conduct hydraulic fracturing in EGS applications.

**ACKNOWLEDGEMENT**

This research was sponsored by the US Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Geothermal Technologies Office, as part of the Enhanced Geothermal Systems Program under Contract No. DE-AC05-00OR22725 with the US Department of Energy.

## REFERENCES

Abdelaal, Ahmed et. al. 2021. "A Review of Foam-Based Fracturing Fluids Applications: From Lab Studies to Field Implementations." *Journal of Natural Gas Science and Engineering* 95: 104236.

Ahmed, Shehzad, Khaled Abdalla Elraies, Muhammad Rehan Hashmet, and Mohamad Sahban Alnarabiji. 2018. "Empirical Modeling of the Viscosity of Supercritical Carbon Dioxide Foam Fracturing Fluid under Different Downhole Conditions." *Energies* 11(4).

Ahmed, Shehzad, Khaled Abdalla Elraies, Muhammad Rehan Hashmet, and Alvinda Sri Hanamertani. 2017. "Viscosity Models for Polymer Free CO2 Foam Fracturing Fluid with the Effect of Surfactant Concentration, Salinity and Shear Rate." *Energies* 10(12): 12–17.

Al-muntasheri, Ghaithan A, Expec Advanced, and Saudi Aramco. 2017. "Nanoparticle-Enhanced Hydraulic-Fracturing Fluids : A Review." (May).

Barrabino, Albert, Torleif Holt, and Erik Lindeberg. 2018. "An Evaluation of Graphene Oxides as Possible Foam Stabilizing Agents for CO2 Based Enhanced Oil Recovery." *Nanomaterials* 8(8).

Binks, Bernard P., and Tommy S. Horozov. 2005. "Aqueous Foams Stabilized Solely by Silica Nanoparticles." *Angewandte Chemie* 117(24): 3788–91.

Clark, C.E., C.B. Harto, J.L. Sullivan, and M.Q. Wang. 2010. "Water Use in the Development and Operation of Geothermal Power Plants." *Energy System Division, Argonne National Laboratory* (January): 1–87. papers2://publication/uuid/6B6C1CF5-F7AE-45EB-8DDC-AAA0BC287B11.

Cote, Laura J. et al. 2011. "Graphene Oxide as Surfactant Sheets." *Pure and Applied Chemistry* 83(1): 95–110.

Delahaije, Roy J.B.M., Frederik J. Lech, and Peter A. Wierenga. 2019. "Investigating the Effect of Temperature on the Formation and Stabilization of Ovalbumin Foams." *Food Hydrocolloids* 91(November 2018): 263–74. https://doi.org/10.1016/j.foodhyd.2019.01.030.

Emrani, Arezoo S., and Hisham A. Nasr-El-Din. 2017. "Stabilizing CO2 Foam by Use of Nanoparticles." *SPE Journal* 22(2): 494–504.

Firoze Akhtar, Tarek et al. 2018. "Rheological Behavior of Aqueous Foams at High Pressure." *Journal of Petroleum Science and Engineering* 162(December 2017): 214–24.

Frohne, H. 1976. "Comparison of Conventional Hydrulic and Water/Nitrogen Foam Fracturing in Two Ohio Devonian Shale Gas Wells." *Paper Knowledge . Toward a Media History of Documents* (February): 12–26.

Gandossi, Luca. 2016. *State of the Art Report on Waterless Stimulation Techniques for Shale Formations*. http://publications.jrc.ec.europa.eu/repository/handle/JRC103643.

Georgieva, Daniela, Alain Cagna, and Dominique Langevin. 2009. "Link between Surface Elasticity and Foam Stability." *Soft Matter* 5(10): 2063–71.

Gupta, D V Satya. 2010. "Unconventional Fracturing Fluids : What , Where and Why." *Baker Hughes Incorporated*: 45.

Harris, P. C., and V. G. Reidenbach. 1987. "High-Temperature Rheological Study of Foam Fracturing Fluids." *JPT, Journal of Petroleum Technology* 39(5): 613–19.

Harris, Phillip C. 1993. "Chemistry and Rheology of Borate-Crosslinked Fluids at Temperatures to 300°F." *JPT, Journal of Petroleum Technology* 45(3): 264–69.

Holt, T. 1996. "Effects of Pressure on Foam Stability; Implications for Foam Screening." : 543–52.

Hunter, Timothy N., Robert J. Pugh, George V. Franks, and Graeme J. Jameson. 2008. "The Role of Particles in Stabilising Foams and Emulsions." *Advances in Colloid and Interface Science* 137(2): 57–81.

Jackman, Matthew et al. 2018. "Effect of Temperature on Foamability Using a Thermoresponsive Polymer." *AIP Advances* 8(7). http://dx.doi.org/10.1063/1.5017739.

Kim, Jaemyung et al. 2010. "Graphene Oxide Sheets at Interfaces." *Journal of the American Chemical Society* 132(23): 8180–86.

Li, Leiming, Ghaithan A. Al-Muntasheri, and Feng Liang. 2016. "A Review of Crosslinked Fracturing Fluids Prepared with Produced Water." *Petroleum* 2(4): 313–23. http://dx.doi.org/10.1016/j.petlm.2016.10.001.

Lv, Qichao et al. 2015. "Study of Nanoparticle-Surfactant-Stabilized Foam as a Fracturing Fluid." *Industrial and Engineering Chemistry Research* 54(38): 9456–77.

Maini, B. B., and V. Ma. 1986. "PRESSURES Laboratory Evaluation of Foaming Agents Elevated Temperatures and Pressures." *Journal of Canadian Petroleum Technology* (December).

Oussoltsev, D. et al. 2008. "Foam Fracturing: New Stimulation Edge in Western Siberia." *Society of Petroleum Engineers - SPE Russian Oil and Gas Technical Conference and Exhibition 2008* 1: 636–48.

Rand, Peter B., and Andrew M. Kraynik. 1983. "Drainage of Aqueous Foams: Generation-Pressure and Cell-Size Effects." *Society of Petroleum Engineers journal* 23(1): 152–54.

Ranka, Mikhil, Paul Brown, and T. Alan Hatton. 2015. "Responsive Stabilization of Nanoparticles for Extreme Salinity and High-Temperature Reservoir Applications." *ACS Applied Materials and Interfaces* 7(35): 19651–58.

Riedel, E. F. 1981. "An Assessment of Environmental Health and Safety Issues Associated with the Commercialization of Unconventional Gas Recovery: Devonian Shale." In *U. S. Department of Energy*, , 78.

Saint-Jalmes, Arnaud. 2006. "Physical Chemistry in Foam Drainage and Coarsening." *Soft Matter* 2(10): 836–49.

Saint-James, A., M. L. Peugeot, H. Ferraz, and D. Langevin. 2005. "Differences between Protein and Surfactant Foams: Microscopic Properties, Stability and Coarsening." *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 263(1-3 SPEC. ISS.): 219–25.

Sharma, M. K., D. O. Shah, and W. E. Brigham. 1985. "The Influence of Temperature on Surface and Microscopic Properties of Surfactant Solutions in Relation to Fluid Displacement Efficiency in Porous Media." *AIChE Journal* 31(2): 222–28.

Szabries, Martina, Svenja Sergelius, Arne Kordts, and Marlitt Jönsson. 2019. "Foam Stability and Foam Structure under High Pressure for Tertiary Oil Production." *Application Report*: 1–5.

Thakore, Viren et al. 2020. "High-Temperature Stability of Aqueous Foams as Potential Waterless Hydrofracking Fluid for Geothermal Reservoir Stimulation." *PROCEEDINGS, 44th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 10-12, 2020 SGP-TR-216*: 1–10.

Thakore, Viren et al. 2021. "High Temperature Stability of Aqueous Foams for Potential Application in Enhanced Geothermal System ( EGS )." *PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 10-12, 2021*: 336–47.

Thomas, Gilberto L. 2015. "Wet Foam Coarsening Evidence a Self Similar Growth Regime." *Physiology & behavior* 176(12): 139–48.

Verma, Amit, Geetanjali Chauhan, and Keka Ojha. 2017. "Synergistic Effects of Polymer and Bentonite Clay on Rheology and Thermal Stability of Foam Fluid Developed for Hydraulic Fracturing." *Asia-Pacific Journal of Chemical Engineering* 12(6): 872–83.

Wang, Hetang et al. 2017. "Effect of Temperature on Foaming Ability and Foam Stability of Typical Surfactants Used for Foaming Agent." *Journal of Surfactants and Detergents* 20(3): 615–22.

Wang, Hong et al. 2019. "Research Considerations for Foam Fracturing in Stimulation Development for Enhanced Geothermal Systems." *Proceedings*, 44th Workshop Geotherm. Reservoir Eng., Stanford University, Stanford, CA, SGP-TR-214, 617-627.

Wang, Hong et al. 2020. "Study of Foam Fracturing for Enhanced Geothermal Systems Using Model Material." *Proceedings,* 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, SGP-TR-216, 545-555.

Wang, Hong et al. 2021. "Study on Foam Fracturing of Granite for the Development of Enhanced Geothermal Systems." *Proceedings*, 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-218, 348-360.

Wanniarachchi, W. A.M., P. G. Ranjith, and M. S.A. Perera. 2017. "Shale Gas Fracturing Using Foam-Based Fracturing Fluid: A Review." *Environmental Earth Sciences* 76(2): 1–15.

Weaire, Denis et al. 2003. "The Fluid Dynamics of Foams." *Journal of Physics Condensed Matter* 15(1): 65–73.

Zhang, Panfeng et al. 2019. "Enhanced Stability and High Temperature-Tolerance of CO2 Foam Based on a Long-Chain Viscoelastic Surfactant for CO2 Foam Flooding." *RSC Advances* 9(15): 8672–83.