

## FLOW OF TEMPERATURE SENSITIVE POLYMER SOLUTIONS THROUGH POROUS MEDIA

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**Abstract.** *In this work we analyze experimentally the flow of polymer solutions through porous media, used as an attempt to improve water-flood efficiency by directing injection water to the desired oil zones. The polymer used, called BrightWater<sup>®</sup>, is a specially designed, long-chain and temperature-sensitive polymer, which is formulated to produce sub-micron size particles made up of tightly-bound tangles of polymer chains. As the injection water travels into a thief zone ahead of the main water-flood, it encounters hot reservoir rocks and warms up. When the temperature reaches a certain level, the BrightWater<sup>®</sup> is activated: its particles burst and expand irreversibly, blocking the pore throats of the rocks in the thief zone. Once a block is created, water is automatically diverted to the rest of the reservoir, pushing oil out of zones that were previously poorly swept. Bottle tests and slim tube sand packs tests were performed to simulate the injection, propagation and popping of the particles. The first test consists in rheological measurements to investigate the activation of the polymeric micro particles by heat. The slim tube sand packs tests are performed to determine the time between injection and activation of BrightWater<sup>®</sup> polymer.*

**Keywords:** *polymer solutions, waterflood, sweep efficiency, rheology*

### 1. INTRODUCTION

Oil recovery operations traditionally have been subdivided into three stages: primary, secondary and tertiary [Don W. Green(1998)]. Primary recovery results from the use of natural energy present in a reservoir as the main source of energy for the displacement of oil to producing wells. The second recovery stage is the injection of water or gas to extract oil of porous rocks [Furati(1998)]. Tertiary recovery procedures involve the use of surfactants and a range of other chemicals in order to improve the fraction of oil recovered from reservoirs.

At the end of the primary production period the recovery factor is low, and usually less than 30% of the original oil in place is recovered. Therefore, more than 70% of the initial oil in place is available to be produced with the aid of secondary and improved oil recovery techniques [Moghadasi et al.(2004)Moghadasi, Müller-Steinhagen, Jamialahmadi, and Sharif, Vossoughi(2000), Thomas(2001)].

Moghadasi et al. [Moghadasi et al.(2004)Moghadasi, Müller-Steinhagen, Jamialahmadi, and Sharif] observed that during secondary and enhanced recovery, reductions of permeability occur in many reservoirs. Moreover, during the secondary recovery stage, injected fluids tend to flow to the more permeable layers or zones, bypassing a large amount of oil [Moghadasi et al.(2004)Moghadasi, Müller-Steinhagen, Jamialahmadi, and Sharif, Vossoughi(2000)], according to Fig. 1. Consequently, there is a formation of a viscous fingering [Homsy(1987), Saffman and Taylor(1958)], which will create an early breakthrough of the injected fluid, implying in a low oil recovering and eventually, an uneconomical process.

In order to improve oil recovery, several techniques are used to maintain the reservoir pressure and to increase the oil displacement towards the production wells. Polymer solutions and foams are generally used for mobility control of secondary and tertiary floods. Recently, a new polymer, known as Bright Water [James Pritchett(2003), H. Frampton(2004)], was developed as an attempt to improve the sweep efficiency of water flood in oil recovery. The polymer is a time-delayed and highly expandable particulate material. The main idea is to inject the polymer particles with the water flood, through the pores of the reservoir. Then, it will propagate through the rock matrix and after a temperature change in the thief zones, and at a certain time, the particles would increase in volume, blocking the pore throats, and diverting chase water into poorly swept zones. In other words, the polymer encounters hot reservoir rocks and warms up. When the temperature reaches a certain level and after a certain time, the BrightWater<sup>®</sup> is activated: its particles burst, and expand irreversibly, drastically reducing the rock permeability in the thief zones. Therefore, water will flow through lower permeability regions, pushing oil out of zones that were previously poorly swept. This can be seen in Fig. 2.

In this work an experimental study is performed in order to evaluate the behavior of this new polymer in the flow through a reservoir. Two different tests were done to obtain the polymer rheology, and to simulate the injection, propagation and popping of the Bright Water<sup>®</sup> particles. The tests and the experimental procedure are described in the next section. Then, some rheological data are presented, as well as some preliminary permeability results. Finally, some final comments on the results and on works in progress are presented.

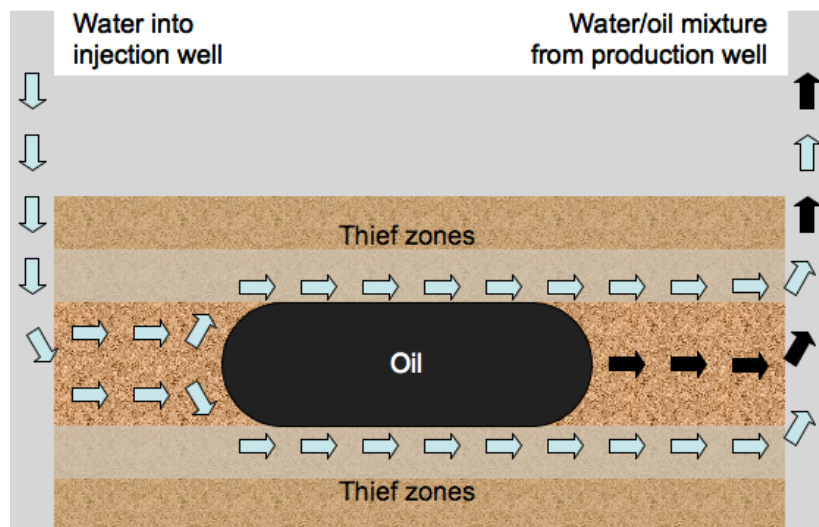


Figure 1. Poorly swept efficiency in reservoir.

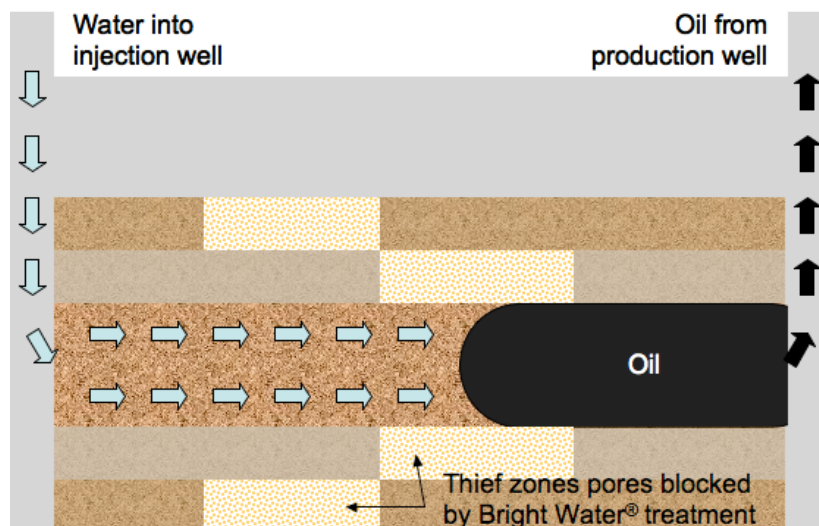


Figure 2. Reservoir after treatment.

## 2. EXPERIMENTS

Two different tests were performed to evaluate Bright Water<sup>®</sup> polymer performance. In the first one, namely Bottle Test, a careful rheological characterization is done, to investigate the polymer activation, by analyzing the effect of time and temperature on the viscosity. The second test, namely the Slim Tube Test, is performed to measure the permeability change due to the presence of the polymer.

### 2.1 Fluid preparation

This preliminary step corresponds to the preparation of the polymeric solution that will be used in the Bottle tests and in the Slim Tube tests. The Bright Water<sup>®</sup> material is supplied as a concentrated dispersion in hydrotreated light distillate (30% active). The dispersion is prepared by mixing a surfactant and the synthetic seawater in a magnetic mixer. In the beginning, we stir the mixture vigorously, so that a large vortex is created. After 30 minutes stirring, Bright Water<sup>®</sup> polymer is then added. We continue to stir the mixture for more 60 minutes and then 1000ppm sodium thiosulfate is added, as an oxygen scavenger. The mixture procedure should be performed carefully to avoid inhomogeneities that would result in uncontrolled rheological properties.

### 2.2 Bottle tests

The Bottle Tests consist on a long and careful investigation of the polymer solution viscosity, as a function of temperature and time. When the polymer is activated by the effect of the temperature and time, the kernel particles expand,

increasing the volume occupied by them. Consequently, the volume fraction of the continuous phase decreases, leading to an increase of the viscosity of the dispersion. Therefore, activation of the polymeric micro particles by heat can be detected and analyzed. Two dispersions were prepared to be used in the bottle test, following the procedure described above. Different concentrations of the constituents were investigated, as it can be seen in Table 1.

Table 1. Dispersions of Bright water

Bright Water Active concentration [ppm]	Bright Water as supplied concentration [%w/w]	Dispersant active concentration [ppm]	Dispersant as supplied concentration [%w/w]
5010	1.67	1500	0.5
1500	0.5	720	0.24

In the Bottle Test, each dispersion is stored in groups of 20 sealed bottles, and placed at a controlled temperature bath or oven during a certain period of time, to represent the process of aging in a reservoir. Then, at a predetermined time, one bottle is removed from the oven or water bath and cooled to 24°C. Two aging temperatures were investigated in this work: 30°C and 60°C. A water bath was used for the temperature of 30°C and an oven for the temperature of 60°C. The viscosity of the solution was measured at that temperature, using the rotational rheometer Paar Physica MCR 301. This procedure was repeated at different times, until the final time of around 100 days.

### 2.3 Slim tube sand pack tests

The polymer popping activation takes place after some period of exposition at a certain temperature. Therefore, the polymer is introduced at the injection well and propagates hundreds of feet through the reservoir until activation occurs. To investigate the behavior and performance of this procedure, the slim tube sand packs tests are performed to determine the time between injection and activation of the BrightWater® polymer. The slim tube is a simple (one-dimensional) model of the actual reservoir formation, designed to have equivalent sand permeability and temperature. A slim tube sand pack is a long stainless steel tube filled with a graded sand mixture (from a sandstone quarry), which is packed tightly into the tube. The filling process, together with the tube geometry, are designed to give the desired permeability. The tube is coiled to fit into the oven and to give a certain compressive stress that prevents sand movement or channeling. The slim tube is usually used as an experimental tool for testing both water and gas control technologies.

The polymer is injected through the slim tube sand pack with a inner diameter equal to 1/4" and a length equal to 40 ft, which is placed inside an oven with a controlled temperature. Pressure drop and flow rate measurements are performed through time. Pressure taps are positioned through the tube, at every 10 ft, so that we are able to measure the pressure drop through different regions of the tube. The flow rate is controlled by the Waters® 515 HPLC Pump, used to provide high precision, reliability and smooth eluent flow. Moreover, viscosity measurements are done at the same time with samples of the same polymer solution and at the same temperature of the slim tube. Figure 3 shows the experimental apparatus.



Figure 3. Slim tube test apparatus.

The experimental procedure is described as follows. Initially, the sand pack is filled with air, which is cleaned by pushing CO<sub>2</sub> through the slim tube. The next step is to inject synthetic seawater (SSW) until all the CO<sub>2</sub> is removed. This is checked by measuring the pH of remaining fluid, which should be around 8. After that, the tests of permeability of the sand pack with SSW are performed.

With the sandpack at 30°C, the BrightWater® solution (see Table 2) is injected, carefully at a determined flow rate, and for a certain period of time, so that the solution will be positioned at the required place, which corresponds to the central region of the slim tube (between 7ft and 33ft down the pack). Measurements of pressure drop are done periodically, to evaluate the permeability of the four different regions between the pressure taps. The permeability test lasts for a long period of time, usually around 100 days, or until activation and loss of permeability is observed. This result will indicate if there is some blocking action meaning that the BrightWater® was activated. Moreover, an indication of the blocking position can be estimated.

Table 2. Dispersion of Bright water

Bright Water Active concentration [ppm]	Bright Water as supplied concentration [%w/w]	Dispersant active concentration [ppm]	Dispersant as supplied concentration [%w/w]
2755	0.92	1000	0.34

For slow, unidirectional, and steady flow, the permeability  $K$  is defined using the Darcy's Law [Dullien(1992)]:

$$K = \frac{QL\mu}{A\Delta P} \quad (1)$$

where  $Q$  is the flow rate,  $\Delta P$  is the pressure drop through the length  $L$ ,  $\mu$  is the viscosity, and  $A$  is the cross section area. The mobility factor is defined as:

$$\lambda \equiv \frac{K}{\mu} \quad (2)$$

For each measurement, the Resistance Factor (RF) is calculated as the ratio of the initial mobility to the mobility after treatment, and is given by:

$$RF = \frac{\lambda_i}{\lambda_a} = \frac{\Delta P_a}{\Delta P_i} \quad (3)$$

### 3. RESULTS AND DISCUSSION

#### 3.1 Bottle tests

The results obtained with the Bottle Tests are presented below. Figure 4 shows the viscosity values as a function of the shear rate for the SSW and BrightWater® at 2755 ppm active concentration (0.92% as supplied), for different periods of heating at 88°C. It can be observed that the fluid presents a non-Newtonian behavior, since the viscosity decreases with the shear rate.

**SSW and BW at 2755ppm active concentration (0.92% as supplied) at 88°C**

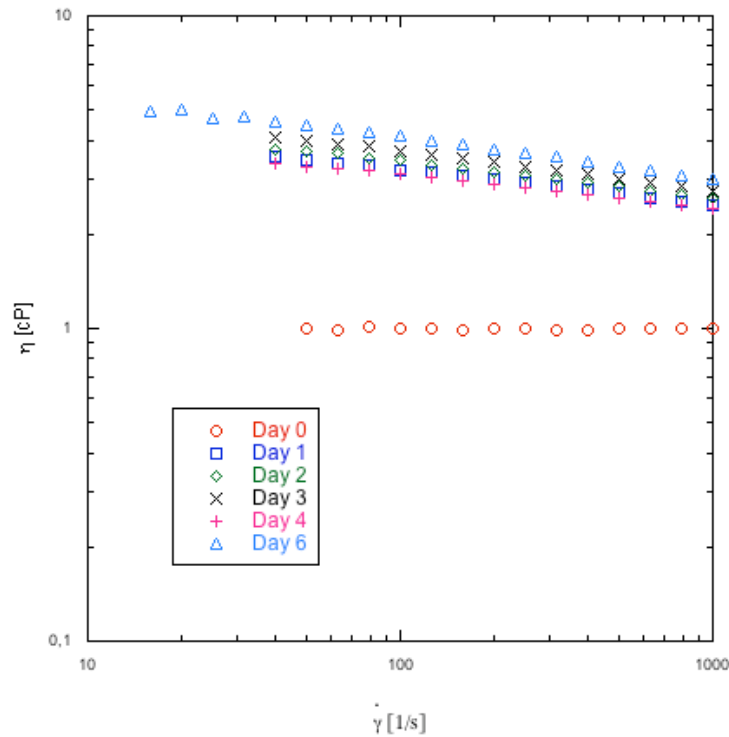


Figure 4. Non-Newtonian behavior of the polymer solution.

Moreover, the shear thinning behavior is more strength for larger times. The viscosity function can be modeled by a Power-law equation, given by:

$$\eta = k\dot{\gamma}^{n-1} \tag{4}$$

where  $k$  is the consistency index and  $n$  is the power-law index. The rheological parameters are obtained via least square fits, and are given by:

Table 3. Power-Law curve fitting

Time [Days]	$k [Pa.s^n]$	$n$
1	5.289	0.892
2	5.808	0.885
3	6.491	0.877
4	4.998	0.896
6	7.205	0.876

Figures 5-6 illustrate the polymeric microparticles activation by heat at a fixed shear rate, equal to  $200 \text{ s}^{-1}$ . This value was chosen based on the fact that the actual process occurs at low shear rates, and taking into account the rheometer accuracy range. For lower shear rates, the torque falls below the rheometer sensitivity, and for higher shear rates, secondary flows begin to appear.

Figure 5 shows the test for 0.5% Bright Water® active concentration and figure 6 shows the same test with a higher concentration, equal to 1.67%, both after aging at  $30^\circ\text{C}$  and  $60^\circ\text{C}$ .

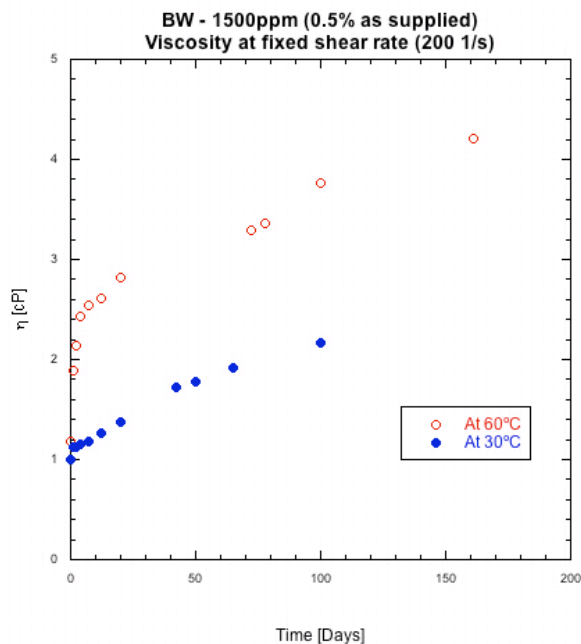


Figure 5. Evolution of viscosity with time for the 0.5% Bright Water Polymer

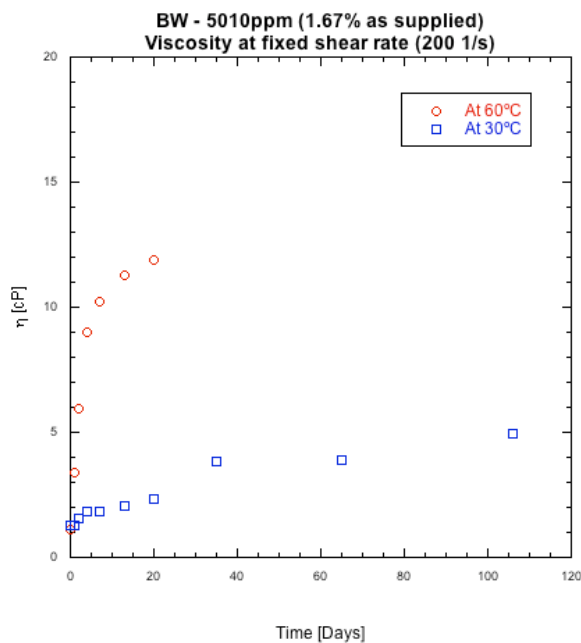


Figure 6. Evolution of viscosity with time for the 1.67% Bright Water Polymer

It can be noted that the qualitative behavior is similar for both tests, but the concentration of the particles affects the viscosity level. It is also observed that higher temperature leads to a higher increase in the viscosity. All results show that the viscosity increases with the time of heating and tends to an asymptote at larger times, indicating that the activation process has finished.

### 3.2 Slim tube sand pack tests

The permeability tests are still going on. Preliminary results are shown below. The permeability of SSW of each 10ft section is evaluated using Eq. 1, and considering the cross section area  $A$  equal to  $2.463 \cdot 10^{-5} \text{ m}^2$ . The results are presented in Table 4. It can be noted that the permeability is almost uniform over the tube. The average value is equal to 6.40D, and the standard deviation is equal to 0.39.

Table 4. Permeability through SSW injection.

Back-pressure	T [°C]	Section [ft]	Viscosity [Pa.s]	Flow rate [ml/min]	Valves	DP [psi]	DP [psi] - Section	Permeability [D]		
no	25	0-10	0,000957238	0,36	1-5	66,60	16,90	<b>6,18</b>		
		10-20			2-5	49,70	15,90	<b>6,57</b>		
		20-30			3-5	33,80	17,10	<b>6,11</b>		
		30-40			4-5	16,70	16,70	<b>6,25</b>		
yes	25	0-10		0,000957238	0,36	1-5	63,40	16,30	<b>6,41</b>	
		10-20				2-5	47,10	15,40	<b>6,78</b>	
		20-30				3-5	31,70	16,20	<b>6,45</b>	
		30-40				4-5	15,50	15,50	<b>6,74</b>	
no	88	0-10			0,00035693	0,36	1-5	24,00	5,60	<b>6,95</b>
		10-20					2-5	18,40	5,60	<b>6,95</b>
		20-30					3-5	12,80	6,30	<b>6,18</b>
		30-40					4-5	6,50	6,50	<b>5,99</b>
yes	88	0-10	0,00035693			0,36	1-5	23,40	6,10	<b>6,38</b>
		10-20					2-5	17,30	5,50	<b>7,08</b>
		20-30					3-5	11,80	6,30	<b>6,18</b>
		30-40					4-5	5,50	5,40	<b>7,21</b>
no	25	0-10		0,000957238		0,45	1-5	85,90	22,60	<b>5,78</b>
		10-20					2-5	63,30	20,70	<b>6,31</b>
		20-30					3-5	42,60	22,00	<b>5,93</b>
		30-40					4-5	20,60	20,60	<b>6,34</b>
yes	25	0-10			0,000957238	0,45	1-5	86,30	22,70	<b>5,75</b>
		10-20					2-5	63,60	21,10	<b>6,19</b>
		20-30					3-5	42,50	21,80	<b>5,99</b>
		30-40					4-5	20,70	20,70	<b>6,31</b>
no	88	0-10	0,00035693			0,45	1-5	30,30	8,00	<b>6,09</b>
		10-20					2-5	22,30	7,00	<b>6,95</b>
		20-30					3-5	15,30	7,80	<b>6,24</b>
		30-40					4-5	7,50	7,50	<b>6,49</b>
yes	88	0-10		0,00035693		0,45	1-5	30,00	7,00	<b>6,95</b>
		10-20					2-5	23,00	7,70	<b>6,32</b>
		20-30					3-5	15,30	8,10	<b>6,01</b>
		30-40					4-5	7,20	7,20	<b>6,76</b>

The Resistance Factor is obtained using Eqs. 2 and 3. The preliminary results for the Resistance Factor for the middle sections are presented in Fig. 7. It can be noted a large increase in the resistance factor in the first days of the experiment, indicating that the polymer activation begins to happen.



**SSW and BW at 2755ppm active concentration (0.92% as supplied) at 88°C**

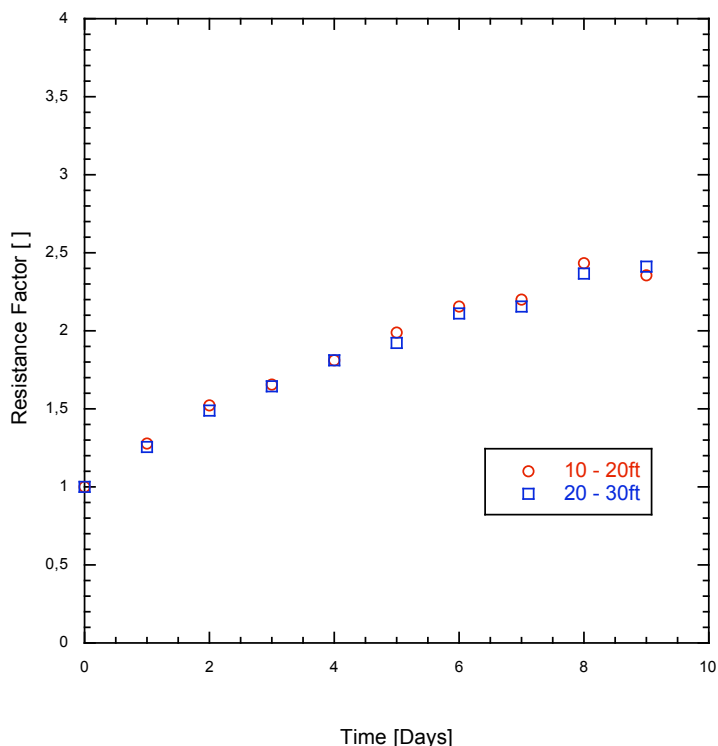


Figure 7. Resistance Factor

#### 4. FINAL REMARKS

A new polymer solution through ideal porous media is analyzed in this work. The BrightWater® polymer is designed in a way that its particles burst and expand irreversibly when submitted to high temperatures, during certain periods of time. When the polymer is activated, its volume increases, blocking the pore throats in the reservoir. In order to investigate the polymer behavior, bottle tests and slim tube sand packs tests are performed. The first one is used to obtain the polymer rheology during the aging process, and the last one is performed to determine the time between injection and activation, and the blocking efficiency. The results show that the viscosity increases with time and aging temperature, showing that the polymer activation is better for higher aging temperatures. The blocking efficiency is evaluated via the resistance factor results, which increases with the time of process, also indicating that the polymer activation process is in progress. The sand pack tests are still going on, in order to investigate how long is the activation process. Moreover, tests using an reservoir plug are also in progress, and will indicate how the actual blocking relates to the model blocking prediction.

#### 5. ACKNOWLEDGEMENTS

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