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Predicting Downhole Filter Cake Breaker Delay Time in Open Hole Completions

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Abstract

Delayed acid filter cake breakers have been effective in removing filter cakes within open hole completions. After placement, the delayed acid release provides sufficient time to safely 'pull out of hole' and avoid mud losses. However, in order to plan and execute the well completion effectively, it is crucial to have a reliable and accurate estimate of the acid release rate and subsequent filter cake breakthrough time.

This paper details the development and field validation of a model to predict the filter cake breakthrough time. The model is developed by coupling rate equations for the hydrolysis of the delayed acid generator with transient wellbore displacement simulations (particularly the fluid temperature profiles against time and depth). This allows the quantification of acid generated with respect to time, based on the specific pump schedule, well trajectory, and breaker solution for the job. The filter cake breakthrough time is calculated as the amount of time needed to generate sufficient acid to react with the estimated mass of filter cake in the open hole section.

The present breakthrough time model is validated with experimental results and an offshore open hole field case. The model can be carried out on standard engineering computers and allows optimization of the breaker fluid properties using far less laboratory efforts than conventional methods. Furthermore, this study developed a better understanding and a means to reliably estimate the impact of real-time changes to the pump schedule on the acid breaker's performance.

Introduction

When drilling through permeable reservoir sections, drill-in fluids deposit an acid-soluble filter cake. Delayed acid breakers are used to clean up drill-in fluid filter cakes in open hole completions to enable better production or injection capacity. The acid breakers are generally esters from organic acids, such as formic acid and lactic acid, which hydrolyze upon heating. Furthermore, in the presence of water, acid is released and dissolves the filter cake. The acid precursor is spotted using a base brine. The formulation is designed to allow acid to be generated and dissolve the filter cake within a targeted time window. The time taken for fluid loss to begin (breakthrough time) is a function of the ester type and concentration, type and density of brine, and fluid temperatures. The breakthrough time for the filter cake must be long enough to allow:

- The acid breaker to be placed over the entire open hole interval,
- The gravel-pack service tools and/or wash pipe to be completely removed, and
- Isolation of the open hole interval or installation of the upper completion.

The delay time is typically 6 to 8hrs. However, particular operations may require delay times in the order of days for a variety of reasons, such as:

- Horizontal sections that are very long (>10,000ft) → Potentially long pull out of hole (POOH) times.
- No isolation valve is present → Upper completion work must be completed prior to filter cake dissolution.
- Unplanned adverse conditions → Potential operation shut down may be required mid-displacement.

Given the importance of having filter cake breakdown happen within a given time window, it is key to have reliable means of accurately estimating acid release rate and subsequent filter cake breakthrough time. This is particularly relevant in the event of unexpected interruptions mid-operations.

Current Method to Determine Breakthrough Time

The filter cake breakthrough test simulates downhole conditions where no mixing occurs during soaking time. **Figure 1** shows the setup for the filter cake breakthrough test. To run the test, a filter cake is first built on a ceramic disk in the High-Pressure High-Temperature (HPHT) cell, which is then soaked with the breaker solution at reservoir temperature. The bottom valve of the cell is kept open. The weight of fluid coming out of the cell (through the filter cake and disk) is recorded over time. When breakthrough occurs, the fluid starts to come out quickly – all fluid typically exits within 20 minutes of breakthrough (Bradley *et al.*, 2006).

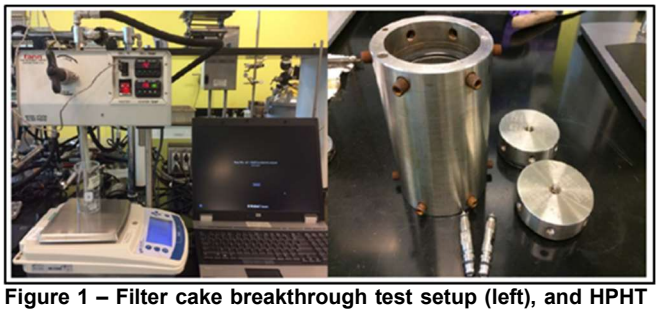


Figure 1 – Filter cake breakthrough test setup (left), and HPHT cell used for the test (right).

New Method to Determine Breakthrough Time

This work proposes an analytical methodology to predict

delayed acid breakthrough times within open hole completions. The proposed methodology combines acid breaker reaction rates with a robust transient temperature profile estimation from computational acid breaker displacement simulations. This methodology requires some experiments upfront to determine specific acid breaker reaction rate parameters. Once these values are known, precise computational estimates can be made with no further laboratory experiments.

Benefits of the New Methodology

The ability to design filter cake breaker jobs without the use of experiments is a first of its kind and has several benefits, including:

- Increased Speed of Engineering Design

The time saved from eliminating/minimizing breakthrough experiments can result in a direct cost saving of engineering hours. Furthermore, this methodology enables quicker design of service's sensitivity analysis, i.e. one can quickly determine how the breakthrough time would change based on varying the initial concentration and type of breaker, density, and type of brine, pump schedule, wellbore geometry configuration, or a number of other factors with minimum laboratory work.

- Increased Accuracy

The breakthrough test occurs at a fixed temperature. Using its result therefore assumes that the acid breaker solution is at the bottom hole temperature from the beginning of the job. In very long wells, this may be unnecessarily conservative. The ester hydrolysis' reaction rate is highly temperature dependent and the proposed methodology allows us to take this into consideration. In addition, this methodology does not suffer from the potential experimental errors to which each individual breakthrough test could be subjected.

- Improved HSE

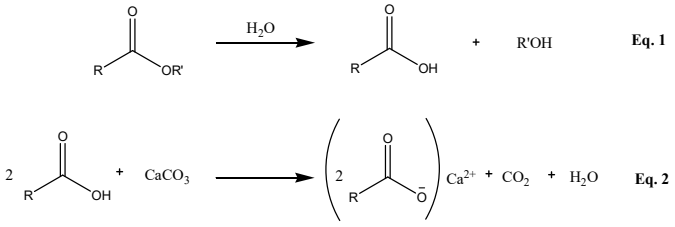
The breakthrough test can also create HSE hazards. The HPHT experiment involves pressuring up a cell to over 500psi and maintaining the cell at reservoir temperature (as high as 400ºF). Errors in de-pressuring, disassembling, or even moving the HPHT cells could result in severe injury or death. By removing / minimizing the number of breakthrough tests, we can lessen the exposure to these potential hazards.

- Reduced Risk

There are many factors that can cause a job not to be performed as originally designed. Many of these factors (e.g. weather, equipment failures, etc.) are unpredictable. If the delayed acid breaker spotting and wash pipe pull out of hole must occur within a 6 to 8hr window, then any delay could be detrimental to the performance of the job. This methodology allows investigation of the delay length that can be tolerated before the success of the job is compromised.

Reaction Rate Model

Delayed acid breakers are typically esters that hydrolyze in the presence of water to form acid and alcohol. The acid then reacts with the filter cake components (typically calcium carbonate and/or starches) to break the filter cake. The following equations show these reactions:



As can be seen in **Eq. 2**, the net reaction releases CO_2 (which will be a free gas if the experiment is done at atmospheric pressure). This fact allows us to use the CO_2 generation test (**Figure 2**) to measure the reaction rate constants.

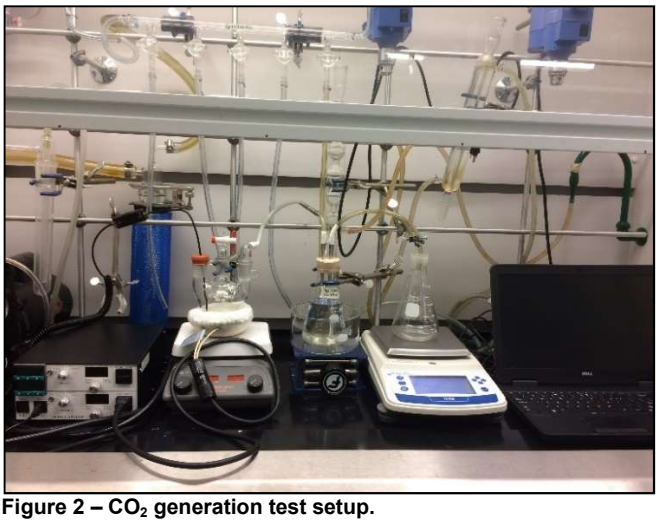


Figure 2 – CO_2 generation test setup.

The use of this test to determine the reaction rate constants is described in US Patent US7455112B2 (Moorehead *et al.*, 2006). In the test, ground calcium carbonate is stirred with a delayed acid breaker dissolved in a base brine and kept at a fixed temperature using a heating jacket. Evolved CO_2 gas is routed to a second flask full of water where it can displace water to a third flask. The weight of the water in the third flask is recorded with respect to time. Based on the assumption that the entire test is at atmospheric pressure, the volume of CO_2 evolved is equal to the volume of water displaced. If the reaction is allowed to be carried to completion, i.e. all of the delayed acid breaker product has reacted, then the half-life of the reaction, $t_{1/2}$, can be read from the graph and used to find the reaction rate constant, k, as per **Eq. 3**. The following equations are true assuming a first order or pseudo-first order kinetics.

$$t_{1/2} = \frac{ln2}{k} \qquad \textbf{Eq. 3}$$

It must be noted that, in the event that the formulation of the experiment generates more moles of organic acid than moles of $CaCO_3$ added, then **Eq. 3** cannot be used. Once the reaction rate constant is known at a minimum of two different temperatures, it is possible to determine the Arrhenius equation (**Eq. 4**) constants (A and E_a).

$$lnk = lnA - \frac{E_a}{RT} \qquad \textbf{Eq. 4}$$

Once the Arrhenius constants are determined, **Eq. 4** can be used to predict k at any other temperature. Once k is known for any given temperature, the amount of ester that has undergone hydrolysis can be determined using **Eq. 5**.

$$N = N_0 e^{-kt} \qquad \textbf{Eq. 5}$$

Transient temperature profile

As the breaker fluids are circulated and positioned to cover the entire open hole zone, a computational displacement simulator can accurately estimate the dynamic fluids' positions and subsequent experienced temperatures. Transient fluid temperature predictions in a wellbore can be achieved by using equations such as Ramey, H.J. (1962).

Once fluid stops being pumped, its temperature profile can be calculated by solving the thermal energy conservation equation. The solution for this equation depends on the specific assumptions, boundary conditions, and well completion. The following solution (**Eq. 6**) was obtained for a fluid that is only separated from the wellbore by a filter cake, based on the assumptions that the sand face on the reservoir side of the filter cake is constantly kept at the bottom hole temperature (Hill, 1990).

$$T(t) = \frac{(T_G - T_0)}{e_i\left(\frac{-r_2^2}{4\alpha t}\right)} e_i\left(\frac{-r_1^2}{4\alpha t}\right) + T_0 \qquad \textbf{Eq. 6}$$

Case Study

Finally, the proposed methodology is demonstrated on an actual field case. The studied well was situated offshore, about 19,000 feet MD (~10,500 feet TVD) and 130ºF BHT. The completion job was carried out with Formic Acid Precursor (FAP) delayed filter cake breaker in a sodium bromide carrier fluid. The well profile included high angle deviations, so the breaker fluid was split into a lighter pill and a heavier pill, such that buoyancy effects could assist in uniformly covering the open hole zone.

By design, the job would have taken approximately 6 hours for breaker spotting, wash pipe POOH and isolation valve closure. The treatment was designed to break down the filter cake after 8 hours.

During the displacement, an unplanned delay occurred due to clogging in the transfer lines, forcing circulation to be interrupted while the lighter pill was already in the wellbore. The hydrolysis reaction rate is accelerated by elevated temperatures. This unexpected disruption in fluid circulation could have been detrimental to the completion since the treatment could have prematurely produced acid and caused a well control incident.

The proposed methodology not only allows for an accurate initial design of the treatment, but, as further discussed, predicts how much interruption time can be tolerated without compromising the safety and success of the job. Fortunately, the lighter pill already in the wellbore was located above the seabed (lower temperatures) when the flow was stopped. As discussed later, this actually increased the delay in the final breakthrough time.

Step 1: Perform CO_2 generation test

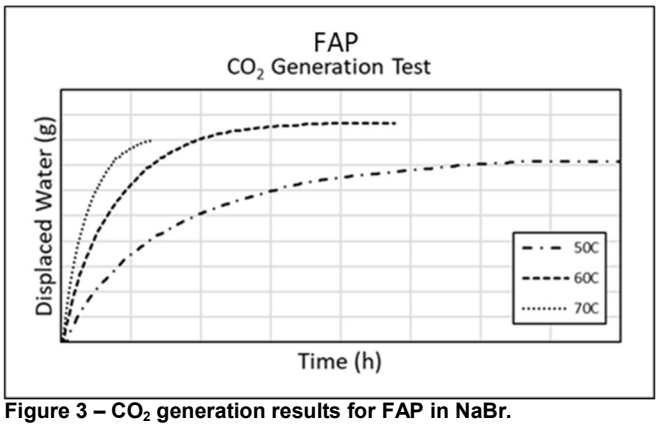


Figure 3 – CO_2 generation results for FAP in NaBr.

Step 2: Determine Arrhenius constants

The half-lives from **Figure 3** are used with **Eq. 3** to find the reaction rate constants, k, at each temperature, T. By plotting the ln(k) vs. 1/T (**Figure 4**), it is possible to determine the Arrhenius constants using **Eq. 4.**

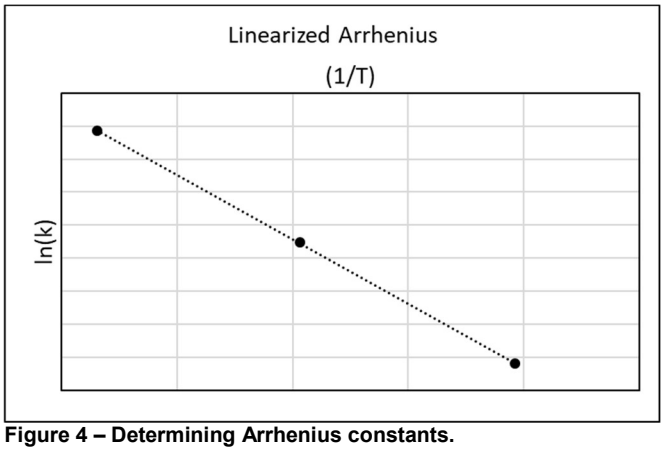


Figure 4 – Determining Arrhenius constants.

Using **Eq. 4**, it is possible to determine the reaction rate

constants at any temperature. By extension, **Eq. 5** can determine the remaining concentration of ester, N, at any given time, t.

Once all constants are determined, this model can be validated using experimental results as a comparative baseline (**Figure 5**). When the intercept is fixed at 0, the gradient of a linear trend line is very close to 1.0, indicating agreement between predicted and measured breakthrough times at different tests conditions.

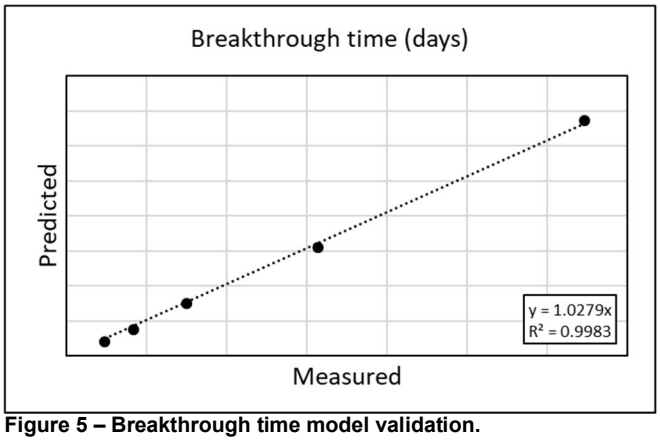


Figure 5 – Breakthrough time model validation.

Step 3: Transient Temperature Profile Estimation

Figure 6 illustrates the studied well geothermal profile and the fluid's transient temperature profile predicted within the wash pipe at a given time past displacement commencement. Temperatures are predicted using the design wellbore geometry and pump schedule information.

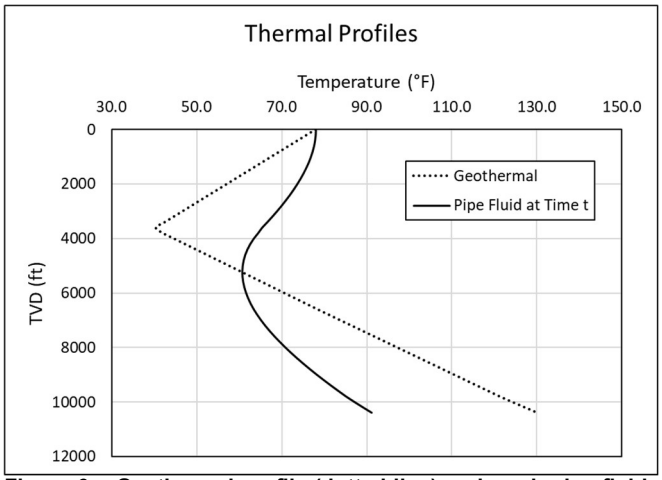


Figure 6 – Geothermal profile (dotted line) and wash pipe fluid transient temperature profile at a given time t.

As the different fluids are pumped down the wash pipe, a displacement simulator (Lopes Pereira *et al.,* 2019) predicts the positions of all fluids at any given time, as well as the associated transient temperatures. This allows for the determination of the treatment temperatures as a function of time (**Figure 7**).

As per designed pump schedules, in the initial minutes, both pills exhibit a decrease in temperature due to the cold water temperature effects. At around 55 minutes, the lighter pill is entirely positioned in the annulus. Circulation is then interrupted for 20 minutes to allow for the buoyancy effects to take place and assist the lighter pill to treat the top portion of the open hole section with the released acid.

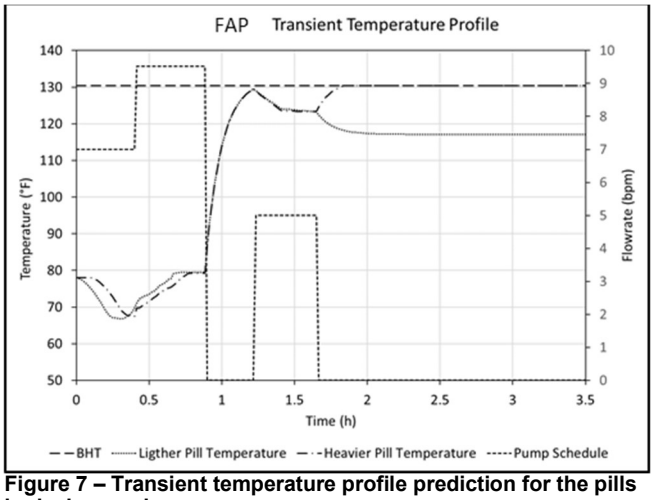


Figure 7 – Transient temperature profile prediction for the pills in design mode.

At around 75 minutes, circulation is resumed until the entire heavier pill is positioned in the annulus. This results in a small drop in the pills' temperature as "hotter" fluids are being displaced by "colder" fluids. At around 100 minutes, circulation is interrupted again. At this point, the lighter pill has gone higher up the annulus and reaches a temperature equilibrium at temperatures lower than BHT. As for the heavier pill, as intended, it is spotted to treat the lower portions of the open hole section with the generated acid.

Step 4: Combine the transient temperature profile with the reaction rate model to estimate breakthrough time

By predicting the fluids' temperatures as a function of time, also knowing the initial concentration of the breaker and the amount of acid required to disrupt the filter cake (estimated based on filter cake thickness and fluid composition correlations), it is possible to model the consumption of the breaker over time (consequently, the amount of acid released), and thus locate when breakthrough should occur (**Figure 8**).

Based on this calculation, the filter cake is expected to break through at around 9 hours after the displacement start, whereas experiments performed at the laboratory indicated 8 hours breakthrough time. This behavior suggests that breakthrough time estimation through traditional laboratory experiments (performed at constant BHT) are not far from predictions using the "actual" transient temperatures, provided that the designed pump schedules allow the fluids to reach (and maintain) BHT relatively soon.

Furthermore, it is possible to use this methodology to assess the impact of different displacement design configurations without further laboratory experiments.

Alternately, experiments are required when changes in design would modify the reaction rate constants (ex: a change in carrier fluid, delayed acid breaker type…), and the "new" constants have not yet been identified through experiments.

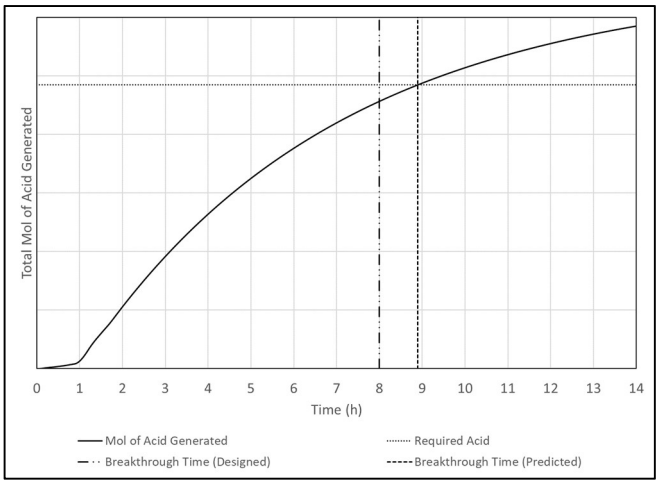


Figure 8 – Predicted acid generation profile and breakthrough time. Comparison to laboratory design results.

Another relevant aspect of the methodology proposed is the ability to assess, real-time, the impacts of design deviations. For the example mentioned previously, had the job been executed according to plans, the spotting of breaker, POOH, and isolation valve closing should have taken 6 hours. During the actual execution of the job, delays occurred caused by the need for troubleshooting mechanical problems. Unfortunately, the breaker had already been mixed in the brine and a portion of the product had already been pumped downhole. The total time between the breaker first being injected and the closing of the isolation valve was 8 hours and 25 minutes (**Table 1**).

Table 1 – Pump sequence and time record (elapsed hours).

Start time	End Time	Event Description
0:00	0:10	Pumped the lighter pill into the wellbore.
0:10	0:24	Minimum delay to change pump line-up.
0:24	0:26	Pumped brine into wellbore to displace the lighter pill.
0:26	1:34	Started mixing the heavier pill into slug tank for pumping. **One of the mixing lines became clogged. This interrupted the schedule to fix the clogged lines.**
1:34	1:49	Pumped the heavier pill into the wellbore.
1:49	2:26	Pumped brine to displace the pills.
2:26	2:39	Stopped mud pumps and left well static. Waited on diffusion of the low-density pill.
2:39	2:49	Pumped brine to position the high-density pill.
2:49	8:25	Stopped mud pumps and left well static. Waited on diffusion of the high-density pill. Wash pipe withdrawn. Isolation valve closed. No backflow observed.

Breakthrough experiments using HPHT cells are unable to discern how the breakers will behave during the actual treatment, in real-time, in case of delays after the fluid has already been mixed and pumped. **Figure 9** shows the actual thermal behavior of the pills based on the schedule discussed in **Table 1**.

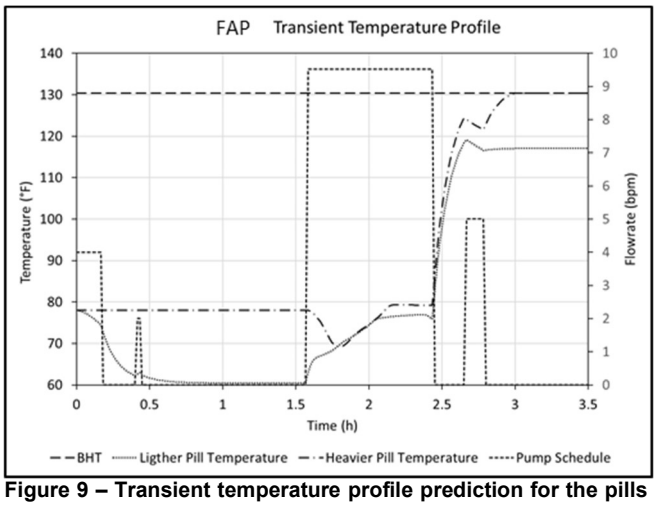


Figure 9 – Transient temperature profile prediction for the pills in real time.

As can be seen in both **Table 1** and **Figure 9**, there is a significant delay in between pumping the low- and the high-density pills. In this scenario, the proposed methodology estimated that the true breakthrough time would have increased to almost 12 hours (**Figure 10**).

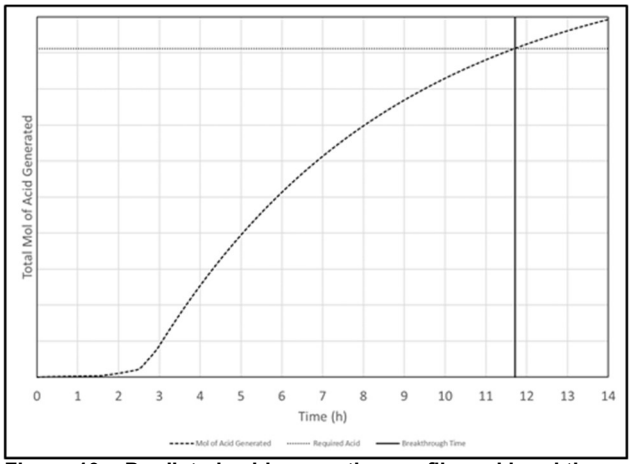


Figure 10 – Predicted acid generation profile and breakthrough time in real time.

Both unexpected interruptions happened while the lighter pill was positioned inside the wash pipe within the sea bed level (cooler temperatures), causing the pill to cool (**Figure 9**), consequently leading to a reduction in the kinetic reaction for acid release, justifying the increase in breakthrough time predictions as compared to design simulations.

Because operations were concluded successfully within 8.5 hours (i.e. POOH with no back flow and effective isolation valve closure), it was not possible to determine if the breakthrough time was close to 12 hours. However, it was longer than the original value of 8 hours obtained in the laboratory.

Finally, had the interruptions happened while the breaker pill was positioned in hotter zones, the reaction rates would have otherwise accelerated, potentially releasing the necessary amounts of acid for filter cake breakthrough prior to the desired time, likely leading to a well control issue. In this case, the presented methodology could be used in real time to assess the most appropriate way to react safely.

Conclusions

This work presents a new methodology to estimate the breakthrough time for a delayed acid filter cake breaker. The procedure was demonstrated and verified with laboratory results, as well as exemplified on a field case. The following conclusions can be drawn:

- The hydrolysis reaction of an ester-based delayed acid filter cake breaker can be fully characterized and modeled using CO_2 generation tests; this was verified experimentally using the HPHT filter cake test.
- The hydrolysis reaction model can be coupled with a transient temperature model and a displacement simulator to predict filter cake breakthrough time.
- The proposed methodology can be used to quickly perform sensitivity analysis on several filter cake treatment design parameters. Additionally, it can predict the real-time impact of unplanned modifications during execution.
- Compared to conventional techniques of estimating breakthrough time via HPHT cell experiments, the proposed method can increase speed of engineering design and accuracy, improve HSE, and reduce risk.

Acknowledgments

The authors would like to thank the many peers within Halliburton who collaborated in developing this work, as well as the support from management and Texas A&M University for presenting it.

Nomenclature

^oF	=	*Degree Fahrenheit*
α	=	*Thermal diffusivity*
A	=	*Frequency factor*
BHT	=	*Bottom hole temperature*
E_a	=	*Activation energy*
e_i	=	*Exponential integral (error function)*
FAP	=	*Formic acid precursor*
g	=	*grams*
gpm	=	*Gallons per minute*
h	=	*Hours*
$HPHT$	=	*High-pressure high-temperature*
HSE	=	*Health, safety and environment*
k	=	*Reaction rate constant*
lbm/gal	=	*Pounds per gallon*
MD	=	*Measured depth*
N	=	*Concentration*
N_0	=	*Initial Concentration*
ppb	=	*Pound per barrel*
$POOH$	=	*Pull out of hole*
R	=	*Universal gas constant*
r_1	=	*Inner radius of the filter cake*
r_2	=	*Outer radius of the filter cake*
T	=	*Absolute temperature*
t	=	*Time*
$T(t)$	=	*Temperature after time t*
T_0	=	*Fluid spotting temperature*
$t_{1/2}$	=	*Half life*
T_G	=	*Bottom hole temperature*
TVD	=	*True vertical depth*

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