

Off-Bottom Plug and Abandonment Operations in Deepwater Caribbean: Challenges and Solutions

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Abstract

Plug and abandonment (P&A) constitutes to as much as 50 % of the cementing operations in deepwater exploration, as per Bogaerts^[1]. Generally the P&A process require setting of an off-bottom cement plug (OBCP), which is a well-recognized problem in the industry. There are several challenges associated with setting an OBCP; Studies show that a common reason for failure of an OBCP is the lack of a stable base to sustain the weight of cement. The base for an OBCP is usually a viscous mud pill. A poorly designed viscous pill could lead to instability which can cause the fall-through of cement especially in the vertical wells. After several field applications, it was determined that using a mechanical base to support the slurry considerably increases the chances of success of an OBCP. There are mechanical base options that can be applied reducing the rig's critical path time and savings can be over 24 hours of rig time if successful plug placement is achieved in the first attempt. The challenges for an OBCP are accentuated in the deepwater environment. In deeper wells, plug placement is prone to cement contamination, which can be minimized by using engineered spacers, mechanical separators, and fluid modeling software. The temperature at seabed of deepwater wells has low temperature. After plug placement, the evaluation process may involve tagging of top of cement with weight; thus, the slurry design needs to have early compressive strength while still respecting the cooling down effect caused by deepwater. Wells in the deepwater Caribbean served as case studies to investigate the challenges and solutions and formulate lessons learned while setting OBCP.

Introduction

Abandonment plugs provide well integrity, which is required for safe abandonment. Abandonment of a well may require cement plugs at several depths and setting an OBCP is beset with challenges. There is a natural tendency for a heavy fluid to fall through a lighter fluid placed below it and it is only by resisting this tendency that cement plugs, set off-bottom, are able to remain static until the cement hardens. A lot of work in the industry has been done to develop chemical bases with optimum rheology that resist the falling through of the heavier cement slurry. With the recent increase in exploration activity in Caribbean deepwater, particularly in Trinidad and Tobago, French Guiana, Suriname and Guyana,

more and more exploration wells are abandoned with cement plugs. The costs of exploration in deepwater fields are very high and proper planning and engineering design are required to minimize failure of any operation. In this paper, the challenges and lessons learned pertaining to the cementing design and operations of OBCP in the deepwater Caribbean are outlined.

Challenges

Challenges, such as falling of cement through a weak base, inclined well geometry, and incomplete mud removal are common issues when placing OBCP. However, these become more complex and difficult to manage in deepwater. Low temperatures at seabed and high cost of repeating the job are the problems that are most commonly associated with deepwater cement plugs.

Temperature Profile: The correct prediction of BHCT is critical aspect for laboratory testing as it directly affects the cement parameters such as thickening time, compressive strength development time and behavior of cement during static time. The API models (API 10B-2) for BHCT prediction do not apply for deepwater cement jobs since they do not take into consideration the complex heat transfer that takes place between cement, riser, sea water and more. The cooling effect caused by sea water increases with increasing water depth. The correct prediction of temperature profile is important in determining the additives applicable for the specific cementing operation. The correct prediction of temperature profile is important in selecting the additives, which are applicable for the specific cementing operation.

Base for Off-Bottom Plug: The biggest challenge for setting an OBCP is that it does not have solid base to support its weight. The slurry for a cement plug is generally heavier than the mud that is in the well. As per Fosso^[2], there is a natural tendency for a heavy fluid to fall through the lighter fluid on which it is being placed. The larger the difference in the density, the more difficult it is to set an OBCP and the lower the probability of success. This success depends upon the resistance of the cement slurry to swap with the mud below. The mud-cement interface instability can lead to an incompetent plug and in many cases the plug has to be

repeated. **Fig. 1** shows the swapping of fluids that can place when an OBCP placed in vertical holes without solid base. **Fig. 2** shows how the challenge is attenuated with the deviated wells but the effective length of good cement in deviated wells is reduced due to the presence of slump angle. It is common to achieve successful placement in the second attempt, using the remaining cement from the first attempt as a base, but the second attempt uses the critical path time and generates non-productive time (NPT) for the operator.

Cement Contamination and Mud Removal: The primary objective of a cement plug is to achieve well integrity. The cement plug has higher probability of success if cement contamination is minimized. The contamination of cement is defined as any undesirable contact or mixing of cement slurry with fluids such as spacer, mud, and formation fluid. Any contamination of cement can affect the cement setting properties such as thickening time and compressive strength development. Determining the optimum plug length is critical. If the plug is too short, the plug has an increased risk of contamination. If the plug length is too long, there are increased risks of stuck pipe. Another typical cause for cement contamination is not using a mechanical separator before and after cement slurry. The absence of the mechanical separator causes the slurry contamination with spacer and/or mud. The effect of contamination is typically more severe when oil-based mud (OBM) or synthetic-based mud (SBM) is used. As per Gupta ^[3], some surfactants in spacer tend to have a retarding effect, thus spacer with these surfactants causes more severe contamination than spacer without surfactants. A last cause for contamination is incorrect placement of the cement plug. Typically a cement plug is to be underdisplaced and the fluids will balance out while pulling the drill pipe out of the cement plug.

Generally, slurry contamination dilutes the cement, which tends to increase the setting time, decrease the final compressive strength and delay compressive strength development. These phenomena increase the waiting on cement (WOC) and in worst cases may even require the cement job being repeated using the critical path time. The mud filter cake on the walls caused by improper mud removal can lead to channeling and micro annuli and can directly compromise the well integrity. As per API RP 65-Part 2, the parameters that effect the mud removal and which must be optimized before drilling and cementing the section include hole quality, dogleg severity, wellbore preparation, fluid properties such as rheology and density, the use of spacers and more.

Solutions

Proper design, planning and execution are required for successful placement of OBCP in any environment. Because of the increased complexity in deepwater environments, computer placement simulations are used to optimize the plug design and minimize cement contamination while placing plugs. A reliable base to support the weight of cement slurry

increases the probability of success of an OBCP.

Slurry Properties: The success of a cementing operation is heavily dependent on the quality of the laboratory testing, which makes the determination of slurry properties a key parameter for cement plugs. Many modern laboratory pieces of testing equipment are now available to conduct this slurry testing such that the slurry meets the required parameters. For plugs across a permeable zone an API fluid loss of less than 50 ml/(30 min) is recommended and for the plugs in non-permeable zones a fluid loss of less than 200 ml/(30 min) is required (Nelson ^[6]). The BHCT temperature profile and deepwater pressure profile is provided by the computer-aided model that simulates the slurry as it flows downhole. These profiles are used to conduct laboratory testing to determine the slurry properties such as thickening time, compressive strength, rheologies, and fluid loss control.

The cement plug recipes are unique in testing as compared to slurries for primary cementing. The testing needs to include post-job activity such as pulling pipe out of hole and circulating out excess cement at the top of the plug. The pull-out time can be simulated in the consistometer by stopping the motor. The time for which the motor is stopped is dictated by the length of plug and the time it would take to pull out of the plug. For instance, a plug could require 45 min of motor shutdown time and the maximum spike observed after starting the motor indicates if the slurry remains fluid and pumpable after this static period. The retarder concentration must be carefully optimized to ensure the thickening time requirements are met without compromising the compressive strength development.

In the intervals incorporating OBM or SBM, water wetting is also important to achieve a good formation-to-cement and cement-to-casing bond. Laboratory tests are conducted to adjust the spacer designs to incorporate surfactants and solvents to flip the water-in-oil emulsion to oil-in-water emulsion thus water wetting the formation and the casing to achieve a good bond and thus well integrity while at the same time, the spacer should have a minimum effect on the slurry properties in case of contamination.

Base for Off-Bottom Plug: A stable base is an important criterion when designing a plug cementing operation. For an OBCP, it is very important that a stable base is designed and used. For an OBCP, the first option is to use the set tagged top of cement from the previous plug as a base. In the absence of any base, an OBCP has a high probability of a failure as the cement falls through the mud, which has lower density and lower viscosity than the cement slurry. Some cement from the first attempt mixes with the mud to create a partially or fully set cement base. In case of failure of the first attempt, it is recommended not to circulate out but to leave the contaminated cement in the wellbore and use it as base for the second attempt.

The other common option is the use of a viscous pill base. The viscous pill is defined as relatively high-viscosity mud pill or a reactive pill that is placed right below the designed base of the cement plug. The rule of thumb is to design the viscous pill 1.5 times the length of the cement plug. The rheology of the viscous pill should be higher than that of slurry and generally a yield point of 70 lb/100 ft² is recommended (Bogaerts^[1]). For high viscosity pills, Nelson^[6] recommends a density difference of 1 lb/gal or a density hierarchy of 10 % compared to the mud in the well. The viscous pills are placed using a balanced plug placement technique. The cement plug can be placed right after the pill is spotted.

The final option for the base of an OBCP is a mechanical device. A mechanical base if placed properly provides the most technically effective base for an OBCP. Traditionally, some operators use a bridge plug as a first barrier for abandonment which acts as a mechanical base for the cement plug above. It is placed at the required depth using a dedicated run in hole with either wireline or drill pipe. The other option is to use tools, which are engineered to provide support for OBCP, as the ones shown in **Fig. 3**. These tools are generally launched through the drill pipe. Once this tool exits the drill pipe, it opens up like an umbrella and provides a mechanical base for the slurry that follows the tool. Apart from providing a mechanical base for the cement plug, these engineered tools do not require any dedicated run and help save the rig critical path time. **Table 1** summarizes the results for OBCP plugs placed in the Caribbean deepwater using viscous pill and mechanical type base.

Mud Removal and Separation: The first step for adequate hole cleaning is to have hole in good condition. It is essential to follow the good drilling practices to plan the delivery of a high-quality hole. It is a general practice to use viscosified water based spacers for mud removal. Computer-based simulations done by fluid modeling software allow the design engineer to use the well data and tailor the cement plug to meet the job objectives. Incorporating additional information such as the actual hole caliper, directional survey, casing data and formation data, to name a few, allows the engineer to adjust the fluid properties to achieve the rheological and density hierarchies between the displaced and displacing fluids. It is recommended to have 20 % frictional hierarchy and 10 % density hierarchy between the displaced and displacing fluid (Nelson^[6]). The use of actual fluid properties, such as density and rheology, for mud, spacer, and slurry with the correct placement schedule, can indicate potential final cement coverage. The computer aided design (CAD) software use fluid dynamics theory to verify the friction hierarchy, which is a combination of the parameters that are earlier defined and provides the extent of intermixing of slurry with other fluids when placed in the well. This “intermixing” of slurry with other fluids is translated to contamination. The software also simulates pulling out of the drill pipe (after the plug placement) and its effect on cement contamination. The software generates a map using three

colors as shown in **Fig. 4**. The green color is cement contamination of less than 20% by volume, yellow color is cement contamination of 20 % to 50% by volume and the red color is cement contamination of over 50% by volume. The map also takes into consideration the channeling of cement, as a result of which the red area on the map can be extended beyond the designed top of cement (TOC). The higher the density and rheology of the spacer, the better will be the movement of mud in the annulus. For the plugs set in the Caribbean deepwater wells, the WOC time was used based on the recommendations from Harder^[7], which states that the compressive strength of uncontaminated cement is reduced to 25% with 20-50% contamination.

Cement contamination caused by absence of a mechanical separator generally takes place at the top of the plug and reduces the effective length of good plug. This can be avoided by using mechanical separators such as foam balls and mechanical darts. Mechanical separators can be launched before and/or after the cement slurry to isolate the cement while it travels downhole. This prevents the slurry from coming in contact with the spacer or mud that are being pumped ahead and behind the slurry. Thus, the slurry contamination is reduced until the slurry reaches the open end of the stinger. From field experience, the darts have proved to be more effective than foam balls as the darts maintain integrity until they reach the final depth whereas foam balls can disintegrate while travelling downhole. In addition, dart catcher can be used, which allows to achieve positive indication of displacement and also allows recovery of darts.

Plug Length and Under-displacement: The recommended plug length for a balanced cement plug is generally from 150 m (500 ft) to 250 m (800 ft) (Nelson^[6]). However, as explained by Gupta^[3], plug lengths longer than 350 m (1,155 ft) are possible to achieve. Long plugs have their challenges associated with placement such as possibility of stuck pipe. However, at the same time the long cement plugs have increased volume of cement and consequentially have increased probability of a successful tag. On the other hand, the shorter cement plugs have higher probability of cement contamination but generally have reduced risks for placement. The OBCP placed closer to the seabed are generally shorter than 250 m (800 ft) due to the large cement volume owing to the surface hole size.

Another important factor that contributes to the success of a cement plug is the underdisplacement volume. Incorrect underdisplacement may lead to cement contamination during the pull out and consequentially unsuccessful tag. CAD helps in determining the underdisplacement volume by taking into consideration several factors including drill pipe configuration, the fluid properties, plug length, hole configuration and more. Underdisplacement, if done correctly, increases probability of correctly balancing the plug and minimizing cement contamination during pull out.

Case Study 1: Trinidad and Tobago

The abandonment of vertical exploration wells in deepwater off the coast of Trinidad and Tobago was done by a series of cement plugs. The cement plugs in the deeper section of the wells were placed in sequence with one plug on top of the previous one. The first plug was placed at the TMD in open hole and then the cement plugs were placed consecutively until the TOC was above the last casing shoe. After the open hole abandonment, an OBCP was required closer to the well-head before pulling out the BOP. A 15.80 lbm/gal slurry was used with engineered accelerator and dispersant to provide higher and faster compressive strength development. For mud removal, a viscosified spacer was used with surfactant and mutual solvent to inverse the emulsion of the oil film of SBM in the well and to make the surface water-wet for good cement placement.

The selection of the base for the OBCP was varied. In one of the cases, a bridge plug was used as a mechanical base. It was set at 663 m (2,175 ft) in intermediate casing using wireline. A cement plug of 111.3 m (365 ft) was set using the bridge plug as a base and the cement was later tagged successfully at 552.4 m (1,812 ft), which was only 0.6 m (2 ft) below the target depth. Although, the OBCP was successfully placed, more than 12 hours of critical rig time were used to place the bridge plug using wireline equipment.

In another well, the lessons learned from the previous well were used to place the OBCP in the intermediate string. **Fig. 4** shows how computer-aided modeling software was used to optimize the cement placement and mud removal. In this case, an engineered tool, as shown in **Fig. 3** was used as a base for the plug. The tool was set at 375 m (1,230 ft) and 107 m (350 ft) cement plug was placed on top of it. The placement, including under displacement and mechanical separators, was optimized using simulations. The plug was tagged successfully at 274 m (899 ft), which was 6 m (19 ft) below the target depth which was within the allowable tolerance. The OBCP was thus successfully placed. In addition, critical path time of rig was not used to set the bridge plug, which saved about 12 hours of rig time in comparison to the previous well. The time savings would have been reduced if the bridge plug set on drill pipe was used as base for the OBCP.

Case Study 2: Guyana Basin

The exploration wells in Guyana Basin were drilled vertical in water depths of over 1,800 m (5,904 ft). The wells were abandoned to comply with local and operator's regulations. The OBCP were placed closer to the well-head as a part of abandonment process. Due to the low BHCT profile of the OBCP close to the well-head, as shown in **Fig. 5**, a 16.24 lbm /gal conventional class G slurry was used with engineered accelerator and dispersant for faster compressive strength development and high final strength as shown in **Fig. 6**. The mud removal was optimized using polymer viscosified spacer with surfactant and mutual solvent to inverse the emulsion of the film of SBM for effective cement placement.

A mechanical separator was used behind the cement slurry to minimize the probability of contamination while the cement travelled in the drill pipe.

In one of the cases, an OBCP of 150 m (492 ft) was to be placed at 2,035 m (6,675 ft). The SBM in the well was 13.1 lb/gal. The plug was placed with same slurry and spacer recipes and same design parameters as explained earlier. The set cement from previous plug was used as the base. The plug was successfully tagged 7 m (23 ft) below the theoretical depth with 15 Kip and pressure tested with 2000 psi.

In another case, a 200 m (656 ft) OBCP was planned to be placed at 2,139 m (7,016 ft). In this case all other best practices were used as mentioned above. **Fig. 7** shows how computer modeling was used to optimize the coverage of uncontaminated cement. To support the cement plug, the diaphragm tool as shown in **Fig. 3** was used to provide mechanical base. The plug was successfully tagged with 15 Kips in the first attempt, 43 m (141 ft) below the target depth and was pressure tested with 1000 psi. This was just as predicted by the computer simulations and was accepted by the operator as it complied with the regulations.

Conclusions

- A mechanical base increases the probability of success of an OBCP in first attempt. The mechanical base can be a bridge plug or other engineered downhole tools as discussed in paper.
- It is important to follow all other good cementing practices to achieve good plug placement in the wellbore including slurry design, mud removal and to minimize contamination in the drill pipe by using mechanical separators.
- OBCP were placed successfully in the Caribbean deepwater exploration projects by using all the best practices and lessons learned.

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Table 1- OBCP as designed, predicted and tagged in Caribbean deepwater. The percent difference is calculated using the predicted vs. actual length.

Type of Base	Depth (m)	Designed Length (m)	Predicted Length (using actual pump data and 20-50% contamination) (m)	Actual Length (m)	Difference (Predicted – Actual) (%)
Set cement	2035	150	130	143	10
Viscous Pill	2857	250	205	180	-12.1
Diaphragm base	2850	100	100	90	-10
Diaphragm base	4471	361	358	324	-9.4
Diaphragm base	3170	270	239	250	4.6
Diaphragm base	2700	200	171	174	1.7
Diaphragm base	2139	200	171	157	-8.2
Bridge Plug	663	111.3	111.3	110.6	-0.6
Diaphragm base	375	106.7	106.7	101	-5.6

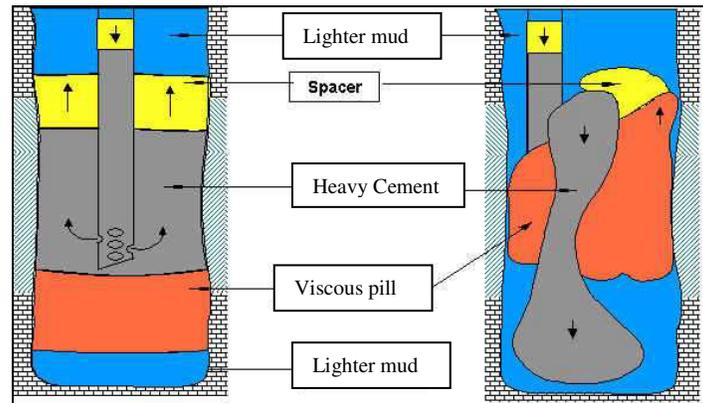


Fig. 1- (Left) ideal case of OBCP placed on a stable base shows no swapping of fluids; (right) fluid swapping as cement swaps with the instable viscous pill base and lighter mud underneath.

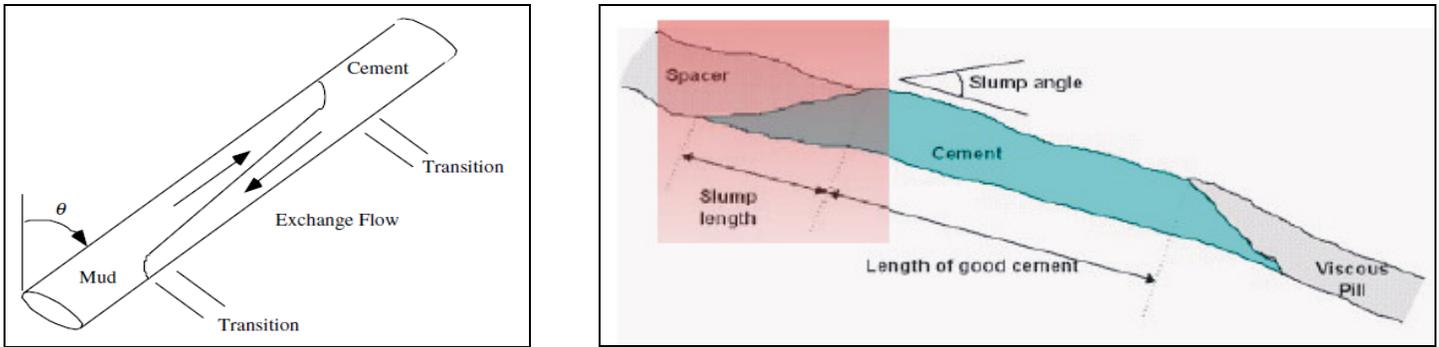


Fig. 2- (Left) diagram of how fluid cement falls through lighter mud in a deviated well; (right) schematic of the slump angle and the reduced effective length of good cement. (Drawing courtesy of Fosso ^[2])

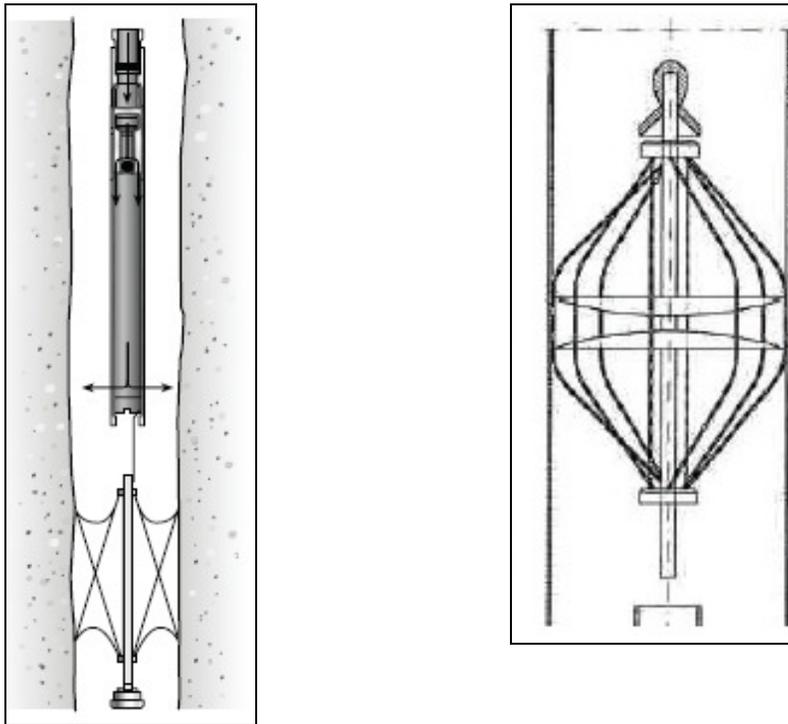


Fig. 3- Downhole tools engineered to provide mechanical base for OBCP; (left) umbrella tool; (right) diaphragm tool. (Drawing courtesy of Nelson ^[6])

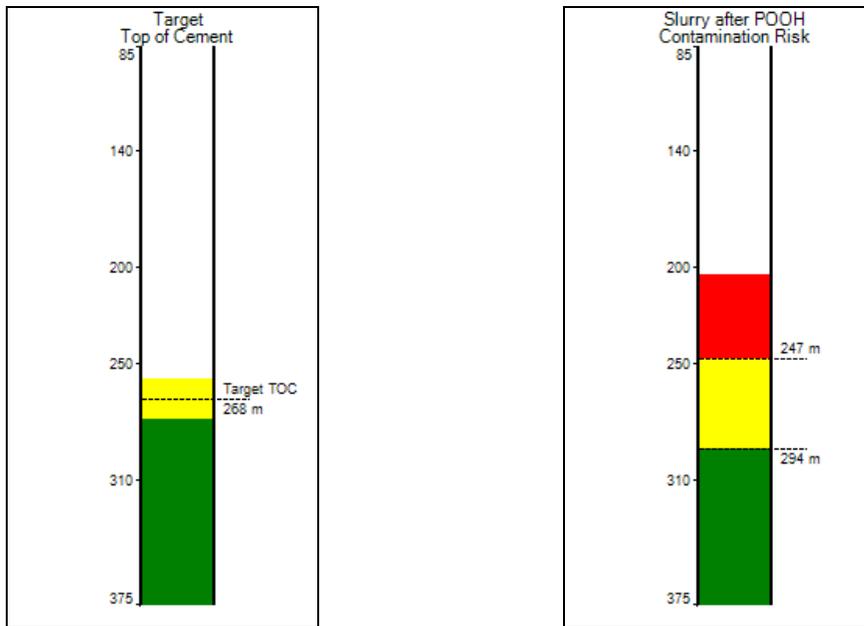


Fig. 4- Schematic showing one of the OBCP placed in Trinidad and Tobago, tagged at 274 m; (left) objective of the cement plug; (right) cement contamination predicted by CAD

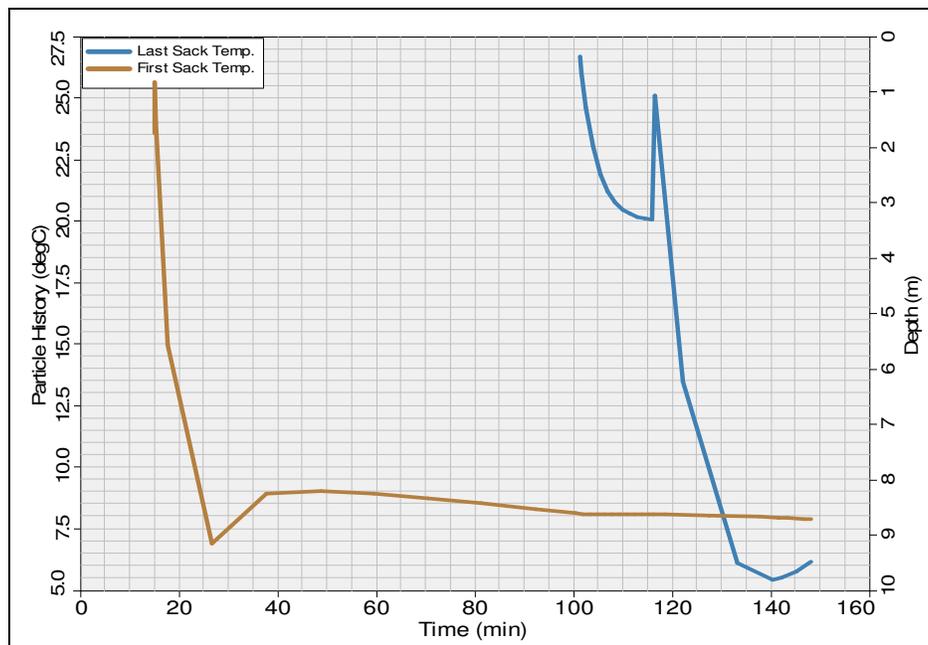


Fig. 5- BHCT profile for the OBCP placed close to the wellhead in Guyana Basin

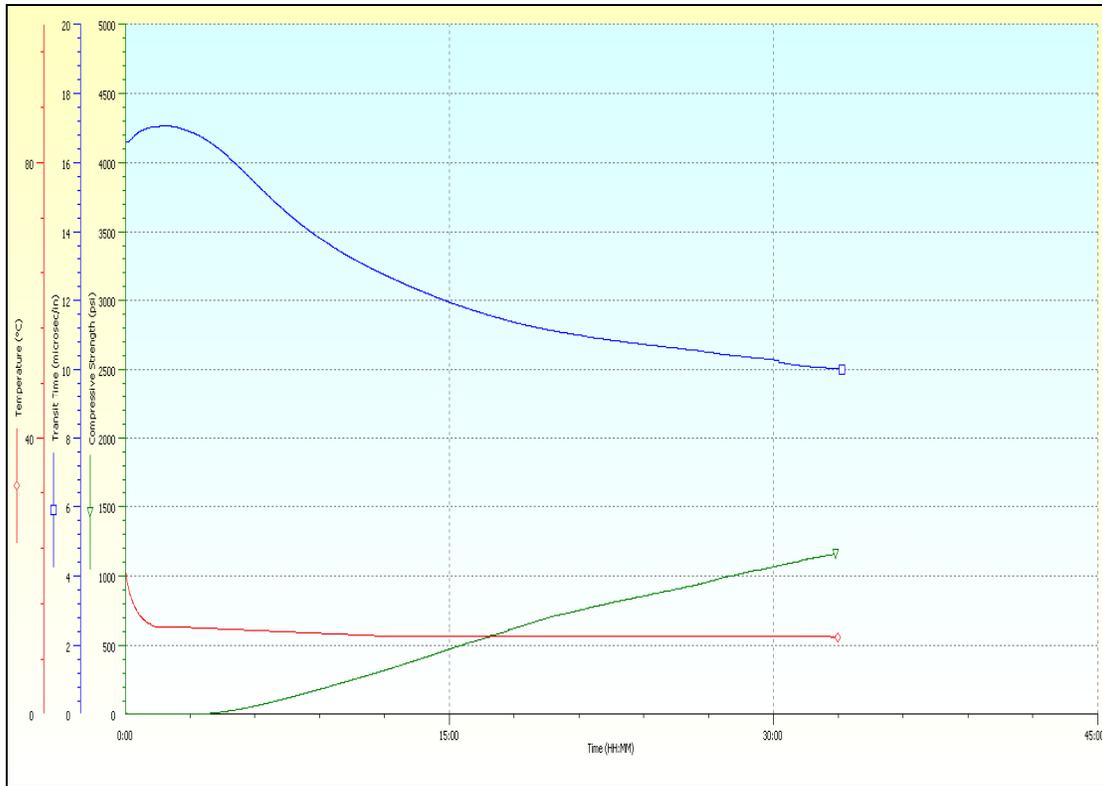


Fig. 6- Compressive strength development for the 16.24 lb/gal slurry for OBCP in Guyana Basin

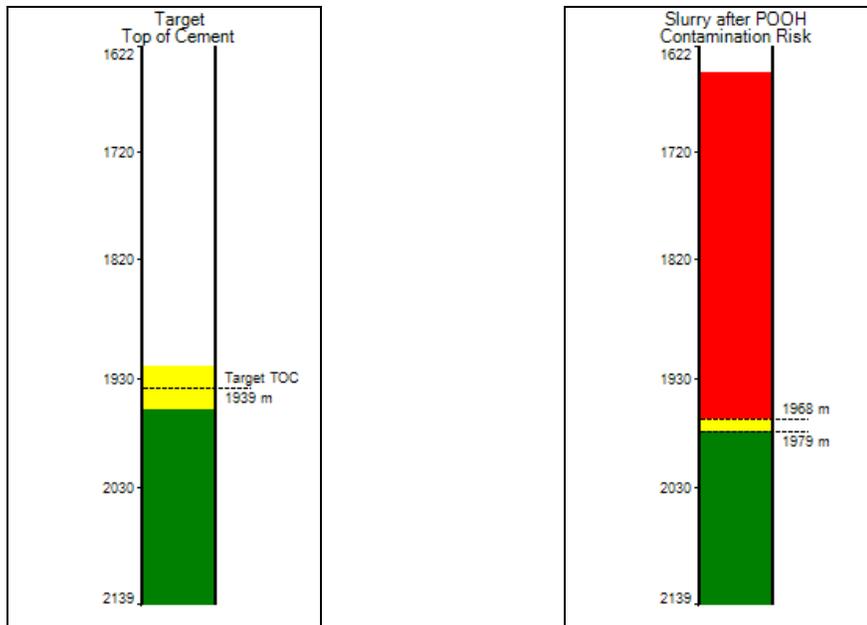


Fig. 7- Schematic showing one of the OBCP placed in Guyana Basin, tagged at 1982 m; (left) objective of the cement plug; (right) cement contamination predicted by CAD