Development and Application of a New Drillable Openhole Bridge Plug

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Abstract. The basement reservoir is distributed predominantly in Northern Slope Belt of Bongor basin in Chad and adopts openhole completion. Layered well testing is performed in basement reservoir to acquire fluid property, find water-oil interface, confirm oil production rate, etc. Sometimes more than two layers will be tested one by one from the bottom up in the openhole interval. Cementing plug technology is often applied to seal the tested zone and the cement plug also makes a new bottom hole for the MFE testing string to reduce the tail pipe length. But the fractures of basement openhole interval are well developed, so cement slurry leakage often occurs and makes it difficult to control the top of the cement plug, which makes a low success rate while cementing plug. Repeatedly cementing plug operations for one layer makes testing period and cost increased. In order to solve the aforementioned problems and through investigating and analyzing the basement reservoir lithology, a new type of tool, drillable openhole bridge plug, is developed after many laboratory experiments. It is combined with cementing plug to seal the tested zone and successfully used in six (6) wells, simplifying the plugging technology for basement openhole well, raising the success rate of plugging operation and making the plugging position more accurate.

1. Introduction
In Chad, basement reservoirs are dominated by granite with development of fractures. Key reservoir spaces include structural fractures, structure-dissolution fractures, intergranular pores and dissolution pores, with porosity of 3%-5% and permeability of 0.01-5 mD. Basement reservoirs are mostly completed in openhole. In addition to commingled well test in the entire openhole interval, layered well test is performed in some basement openhole intervals, and cement plug is used during well test.

Cementing plug has some problems. First, since openhole intervals contain fractures, it is very difficult to control the top of cement plug. Second, during cementing plug, some wells may encounter both leakage and kick. Such downhole complexities lead to low one-trip success rate of setting cement plug [8-9]. Third, some openhole intervals with layered well test may involve interlayers with thicknesses below 10 m. Under such circumstances, heights of cement plugs can hardly meet the operation requirement. To complete layered test, tested layers below have to be sealed for several meters in some cases [11-12]. Fourth, when perform straddle test, cement cap may serve as a new bottom-hole
supporting point for MFE openhole testing tools. Since the testing string has such a high suspension weight that may drive cement plug to go downward, tests may fail eventually [13-15].

To enhance success rates of cement plug setting in basement reservoirs with fractures, the testing engineers tried some innovative techniques, such as gravel-packing and cementing. However, the gravel-packing and cementing technique can only raise the bottom hole to short the length of supporting liner for MFE testing tool, but not truly avoid the problem of cement slurry leakage. Analysis results show that basement granite reservoirs are dominated by formations with medium to high hardness with high brittleness and high compressive strengths. Rough sidewalls in open hole intervals may facilitate anchoring of cast iron slips. With consideration of experiences in application of traditional casing bridge plugs, a new drillable openhole bridge plug for basement granite formations is developed [1,4-6,10]. Lab tests and field applications show that this tool has satisfactory performance to fully meet well testing demands in openhole intervals.

2. Technical difficulties and solutions for design of openhole bridge plug
Openhole intervals are characterized by irregular sidewalls, significant differences in hardness and strong heterogeneity and other problems. Under such circumstances, some solutions have been worked out. (1) Since basement granite formations have medium to high hardness, slips can be effectively anchored to meet the load-bearing demands. (2) Openhole intervals have irregular sidewalls with variable diameters and strong heterogeneity. Accordingly, longer rubber sleeves can be deployed to seal off such irregular sidewalls. (3) Since sidewalls have significant differences in hardness, it is necessary to enhance requirements for thermal treatment of slips and improve the hardness of slip teeth to meet demands of anchoring operations.

Specific optimizations are made. (1) Sizes of slips. Due to bore-hole expansion rate (1%–5%), it is necessary to optimize thicknesses of slips to enlarge radial displacement to satisfy the demand of radial expansion. In this way, the tool can be safely secured in expanded wellbore. (2) Axial anchoring area of slips. By enhance axial size of slip, it is possible to enlarge axial anchoring area and promote anchoring performance. (3) Size of rubber sleeve. By enlarging radial and axial sizes of rubber sleeves, it is possible to meet setting requirements in heterogeneous sidewalls.

3. Working mechanism and components of openhole bridge plug

3.1. Structural components
Figure 1 shows the structure of the openhole bridge plug, including 11 components, such as the central tube, slips, rubber sleeve, and release bolts.

Release bolt connecting hydraulic setting tools can be released after properly setting openhole bridge plug, which makes hydraulic setting tool release from openhole bridge plugs. The central tube carries and supports rubber sleeve, slips and other components, and transfer the setting pressure. Ratchet screws of the clamping ring drives the slip in one direction. After completion of setting operations, slips should be locked with setting loads maintained. The retaining ring protects slips while RIH. Slips can be bi-directionally anchored on the sidewalls in openhole intervals and, during RIH, subject to significant differential pressures. Cones provide necessary internal supports for slips radial expansion and anchoring. Shear pin is used during setting openhole bridge plug to prevent possibility of axial displacements of retaining rings and cones, and avoid openhole bridge plug setting in advance while RIH. Rubber sleeves are used to seal and separate fluids below and above the openhole bridge plug and bear differential pressure. Nut bolts prevent the lower sub threading off from the central tube. Lower sub serves as stopper and the guide shoe.
1. Release bolts, 2. Central tube, 3. Clamping ring, 4. Retaining ring, 5. Slips, 6. Cone
7. Shear pin, 8. Protection bowl, 9. Rubber sleeve, 10. Nut bolt, 11. Lower sub

Figure 1. Structure of the open-hole bridge plug

3.2. Working mechanism

3.2.1. Connecting setting tool. The hydraulic setting tool is connected with the setting sleeve through clockwise rotating screw. Nut bolts should be secured properly. Hydraulic setting tool is connected with the bridge plug through clockwise rotating screw. Until the contact surfaces approach each other, space the nut bolt hole position to correspond to the groove on retaining ring, and tighten the screw.

3.2.2. Setting. It is recommended to set the openhole bridge plug at 25 joints / h. Once the drillable openhole bridge plug is landed to the designed position, steel ball (Ø32 mm) is dropped into the pipe string. As soon as the steel ball reaches the sealing surface of diverter switch above the hydraulic setting tool, apply hydraulic pressure by cement truck into the tubing. Pressure shall be maintained for 3–5 mins at 4 MPa, 8 MPa and 12 MPa, respectively. During the pressurizing process, setting sleeve withstands external components of the openhole bridge plug and the pull rod uplifts the central tube in the bridge plug, which makes the slips set and rubber sleeves expand, and the openhole bridge plug is compressed and positioned as expected. When pressurizing to 17–22 MPa, the pressure drops to 0 suddenly, which means the release stud is broken, and the setting tool and setting sleeve can be POOH.

3.2.3. Verification of sealing performance. After properly setting the bridge plug, it is necessary to uplift the setting tool for 3–5 m and then lower to the original position gently. During lowering, a load of ≤50 kN shall be applied to check whether the bridge plug has been positioned properly or not. The weight indicator may fluctuate twice during the process of setting operation. One indicates that the shear pin is broken, and the other indicates that the nut bolt is burst. After properly setting the bridge plug, cover the plug with sands with total height of 3 m to protect the bridge plug from damages caused by shocks. If it is necessary to set cement plug on the bridge plug, the original setting string can be used directly for cementing.

3.2.4. Unsetting openhole bridge plug. A milling / drilling tool can be RIH to mill out the openhole bridge plug.

4. Lab tests
After multiple lab tests and modifications, the drillable openhole bridge plug suitable for openhole intervals with the diameter of Ø215.9 mm was developed. Table 1 shows its specifications.
Table 1. Specifications

| Specifications                      | KZQS-208 |
|-------------------------------------|----------|
| Total length /mm                    | 1207     |
| Max. OD /mm                         | Φ208     |
| Length of rubber sleeve /mm         | 300      |
| Suitable size of openhole /mm       | 216-227  |
| Setting pressure /MPa               | 12-15    |
| Releasing pressure /MPa             | 17-22    |
| Operating pressure differential /MPa| 35       |
| Working temperature /℃              | 120      |
| Load bearing /kN                    | 200      |
| Connecting thread                   | M28×3    |

Compared with conventional casing bridge plug, this new tool has following features:

1. It can be used for layered well test, fracturing, water plugging, cementing and other operations in openhole formations with medium to high hardness. It is set by hydraulic pressure.

2. It can temporarily or permanently seal-off layers with high-pressure oil, gas and layers with blowout or leakage, with the characteristics of easy operation, high safety, reliability and high pressure-bearing capacity.

3. After setting, the openhole bridge plug can be cemented by using original pipe string and setting tool.

4. It can set at designated positions accurately. If the length of the interlayer above the intervals to be plugged is small, the plugging effect of openhole bridge plug can be more obvious.

5. Slips and rubber sleeves with sizes optimized may ensure bridge plug with outstanding anchoring and sealing performance in openhole intervals.

6. The ratchet clamping ring maintains the setting load, ensuring reliable sealing after releasing pressure.

7. The setting pressure is moderate, ensuring the openhole sidewall suffer little impact from excessive setting stress.

8. Cast iron structures makes the openhole bridge plug removed easily.

5. Field applications

With massive preparations in advance, the drillable openhole bridge plug was successfully applied in wells BC1-5, BC2-1, RaSW02, LaE-3, LaE-4 and Ph1-B2 in Chad.

5.1. Well BC1-5 is taken as an example to illustrate the well test in openhole intervals of basement formations

On January 29, 2016, well test was performed in openhole interval (1400–1455.94 mm) of basement formation in Well BC1-5. Test results showed that the formation contained both oil and water. It was necessary to plug the water formation for purpose of well test in upper formations. It was decided to use Φ215.9 mm drillable openhole bridge plug combined with cement plug. After the openhole bridge plug was set at the depth of 1421 m, 1 m3 cement slurry was injected to make long-term plugging. Another purpose of the operation is to test the supporting capacity of openhole bridge plug + cement plug, so as to provide necessary data for bottom-hole supporting test with MFE.
dropped and set to the seat. Hydraulically pressurized into tubing to 5 MPa, 10 MPa, and 15 MPa, and held for 5 mins respectively, so that rubber sleeves of the openhole bridge plug could fully expanded and the slips stretched. Further pressurized to 22 MPa and the pressure dropped abruptly to 0 MPa, which shows that the release stud was broken and the setting tool was released. Picked up the string and then lowered gently. Loaded 30 kN weight on top of the bridge plug. Tag bridge plug position at 1421.48 m. The openhole bridge plug was set successfully.

5.1.2. Test for supporting capacity of the openhole bridge plug + cement plug. The bridge plug setting tool was used to normally circulate freshwater with total volume of 3.3 m³, inject cement slurry with total volume of 1.0 m³ (density: 1.85–1.90 g/cm³) and then pump in 6.32 m³ freshwater. POOH 6 joints of tubing. Reverse circulated the well with freshwater till the fluid at outlet was fresh water. Shut the well in and WOC. POOH the bridge plug setting string. Run in hole pipe string used for load bearing test. Tag TOC at 1399.52 m. The pipe string with suspension weight of 220 kN was lowered gently onto the top of the cement plug till the 220 kN suspension weight was fully transferred. The TOC was not changed when suffered the weight, which indicated that the loading test was successful.

5.1.3. Plugging performance. After plugged by openhole bridge plug combined cementing plug, the upper basement interval (1319.5–1399.52 m) was tested and shown to be oil zone with production rate of 54 m³, which indicated that plugging was successful. 21.95 m cement plug was set above the bridge plug with no leakage. In the past, at least 50 m cement cap was set; any leakage would lead to difficult control over cement cap or even failure of plugging in extreme cases. The successful plugging operation showed the bridge plug can also be used to prevent cement slurry loss. With lengths reduced significantly, the cement plug displayed no movement under the load of 220 kN, indicating that the drillable openhole bridge plug+ cement plug can fully satisfy demands for MFE test with liner supporting in the bottom hole.

5.2. Well BC2-1 is taken as an example to illustrate the well test in openhole intervals of basement formations.
On December 8, 2016, well test was performed in openhole interval (797.2-813.3m) of basement formation in Well BC2-1. Test results showed that the formation contained water. It was planned to plug the water interval and test upper formations. Ø215.9 mm drillable openhole bridge plug combined cement plug will be used. After the openhole bridge plug was set at the depth of 745 m, cement slurry with total height of 5 m was injected to achieve long-term plugging.

5.2.1. Plugging process of openhole bridge plug. Hydraulic setting tool and bridge plug were connected. The openhole bridge plug was RIH to the designed depth at 745 m. Freshwater with volume of 6 m³ was circulated to clean the ball seat in order to prevent impurities impacting steel ball setting and ensure the plugging performance. All surface pipelines were pressure tested. The ball was dropped and set to the seat. Hydraulically Pressurized into tubing as per setting procedures for drillable openhole bridge plug. After setting bridge plug, tag the openhole bridge plug at 745.08 m. In accordance with the operation procedures for cement plug, the setting pipe string was used to inject cement slurry with volume of 0.33 m³ and then WOC. Tag TOC at 740.13 m.

5.2.2. Plugging performance. After plugged by openhole bridge plug combined cementing plug, the upper basement interval (628.5-740.13 m) was tested and shown to be oil zone with production rate of 91.8 m³/d, which showed the layer plugging was successful. 4.95 m cement plug was set above the bridge plug. If cement cap was used, at least 50 m was required. With lengths of cement plugs reduced significantly, reservoir contamination, cement volumes, together with operation costs, were reduced significantly.
6. Conclusion

(1) With supports of slips in two directions and optimized slips and rubber sleeve, the drillable openhole bridge plug was applied successfully in six (6) wells. The new tool, jointly with the cement plug in upper part, can make the plug setting position more accurate and resolve the difficulties in operations related to setting cement plug in granite openhole interval with severe leakage.

(2) The drillable openhole bridge plug and cement plug can be set properly with only one trip. With length (previously at least 50 m, but now 21.96 m in Well BC1-5 and 4.95m in BC2-1) of cement plug significantly reduced, the cement plug displayed no movement under load of 220 kN. The drillable openhole bridge plug + cement plug can fully satisfy the demands for MFE test with liner supporting in the bottom hole.

(3) The drillable openhole bridge plug can be set at the interlayer with shorter thickness during layered test in openhole interval.

(4) The applications in six (6) wells proved that the openhole bridge plug was applicable for plugging granite formations with medium to high hardness.

(5) It was necessary to thoroughly flush the openhole interval before the bridge plug was set. Bridge plug shall be set at tight intervals with regular open hole diameter, hard and smooth surfaces. The openhole bridge plug shall be RIH steadily at an even speed of no higher than 20–25 m/min.

Acknowledgements

The work was financially supported by the National Utility Model Patent of China (Patent number: ZL 2015 2 0876614.6).

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