Lost Circulation Solutions for Severe Sub-Salt Thief Zones

M. Ferras, Sonatrach; M. Galal and D. Power, M-I L.L.C.

Abstract

Significant challenges exist when drilling through and below salt formations. The thief zone at the base of the salt can introduce severe lost circulation and well control problems, often resulting in loss of the interval or the entire well. In many cases, operators choose to drill the salt section with water-based mud systems rather than risk costly losses of oil- or synthetic-based fluids. The slower drilling rates and poor hole quality obtained by drilling with water-based mud are offset by the potential losses of the invert emulsion drilling fluid. The thief zone immediately below the salt formation is typically a thin zone of highly fractured rock, usually shale. Controlling losses in this zone has proved to be extremely difficult. Very few effective lost circulation remedies have been successful, especially when drilling with invert emulsion fluids.

The producing formations of the Hassi Messaoud field are located below a 900-meter (3000-ft) zone of mixed salt, which introduces a severe thief zone into the well construction process. The severe losses encountered drilling these wells result in significant non-productive time, massive fluid loss, borehole instability and loss of the drillstring. A severe pressure inversion also contributes to the lost circulation problems, with pore pressure reductions from ± 2.01 sg (16.8 lb/gal) in the salt to ± 0.93 sg (7.8 lb/gal) in the thief zone. Over 800 wells have been drilled in the Hassi Messaoud field, with more than half of these wells encountering total loss of circulation once the salt section is drilled. The degree of severity of the losses varies between sub blocks as a function of local stresses, which provide additional forces for rock destabilization.

Through the application of specialized lost-circulation materials, these wells can now be drilled without significant fluid losses. The drilling time for the troublesome intervals has been reduced by 50% in most cases. This paper reviews the methods applied to avoid lost circulation in the sub-salt thief zone and discusses the time and cost savings obtained.

Introduction

The drilling performance curve for the Hassi Messaoud field had reached a point of optimized performance leaving a very narrow window for further improvement, with the exception of the recurring sub-salt lost circulation. Loss of circulation typically occurs while penetrating the Trias Argileux Gresex (TAG) formation in the lower section of the 8½-in. interval (Fig. 1). Vertical well profiles indicate the thief zone is below a high-pressure interval, which is commonly drilled using salt-saturated water-based fluid with a density in the range of 1.98 – 2.1 sg (16.5 to 17.5 lb/gal). The losses are thought to be induced due to a severe pressure transition once the Trias Salifere (the main salt section) has been drilled, exposing the TAG formation to an excessive annular hydrostatic pressure (>9000 psi). This over-pressure induces fractures, causing severe formation losses.

The shape and structure of induced formation fractures is always subject to the nature of the formation, drilling and mechanical effects, as well as geological influences over time. It is believed the HMD field is divided into 25 separate blocks, and subsequently each block appears to exhibit unique geological characteristics. The field can best be described as unified single units referencing specific geology and stratigraphy.

With the experience gained developing the HMD field, the operator was able to predict the depth and severity of the losses with a relatively high degree of accuracy. Typical historical offset data are given in Table 1. The challenge remained to develop an effective solution to prevent or cure the severe losses encountered below the salt formation. Extensive investigations were carried out, involving modification of drilling practices and testing of a wide range of lost circulation materials (LCM). According to operational data, squeezed cement slurries across the thief zone were successful at sealing off the losses, but always involved a negative effect on performance due to the non-productive time associated with repetitive trips involved with the squeeze job.

A new chemically activated crosslinking pill (CACP) was proposed to the operator to shut-off losses, should they occur, below the salt zone. Strict operational procedures were also developed, giving clear directions as to the timing and method of applying the CACP.

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A new chemically activated crosslinking pill (CACP) was proposed to the operator to shut-off losses, should they occur, below the salt zone. Strict operational procedures were also developed, giving clear directions as to the timing and method of applying the CACP.
Performance improvement was the target of this proposal to the operator, with the performance improvements being directed not at the drilling fluid, but the large gap existing between conventional LCM and cement squeezes for severe loss of circulation. The CACP proposed to the operator had the following properties.

1. A simple fluid that can be pumped through the bit and bottomhole assembly (BHA).
2. Adjustable particle-size distribution to fit formation specific requirements (squeezeable into micro-size fractures).
3. Forms a semi-ridged gel structure as a filling material for the loss zone.

A time breakdown was conducted on a number of offset wells in the HMD field. The results of this analysis suggested that if the sub-salt lost circulation problems could be eliminated, a drastic enhancement of the drilling performance was possible. The following example illustrates the time and cost benefits available through eliminating the non-productive time (NPT) associated with the sub-salt losses.

If HMD field developed with an average of 25 wells per year, the following savings would be realized.

- Average 49 days per well
- Average 3 cement plugs per well
- 2.0 days lost per plug
- Total NPT = 150 days
- 3.06 additional wells could be drilled
- Over all performance could be improved by, 3.06 / 25 = 12.2 %
- 12.2 % possible additional production.

The CACP technique was proposed as a lost circulation solution in the TAG formation with the specific requirements to cure losses with maximum possible sealing efficiency and increase formation integrity across the weak sections. Additionally, the process of applying the CACP was to involve less time than that currently associated with applying the cement squeezes. The new technique was applied successfully, sealing the TAG formation without any lost tripping time, and allowing drilling to continue with no further losses.

Sub-Salt Lost Circulation

Drilling through salt formations can be troublesome for a number of reasons. Typically, the formations immediately below the salt are either mechanically weaker or fractured, introducing a greater risk for loss of returns. The lost time treating severe sub-salt losses can be up to several weeks, with obvious cost implications, especially for deepwater drilling operations. Though not the case in the extensively developed HMD field, often on exploration wells, little information regarding pore pressure and fracture gradient is available. Gulf of Mexico sub-salt wells often encounter higher pore pressures below the salt, creating challenging well control issues. In this instance, the higher mud weights required to balance the pore pressure place even greater stress on the weakened sub-salt formations. In the case of the HMD field, the pore pressure, and subsequent required mud weight, was significantly lower than that required in the actual salt formation. As such, the formations directly below the salt are drilled in a high over-balance environment.

Losses in the formations directly below the thick salt zones are typically severe, ranging from 16 \text{m}^3/\text{hr} (100 \text{bbl/hr}) up to total loss of returns and the inability to maintain a full annulus. A wide variety of lost circulation materials (LCM) have been applied in sub-salt thief zones, in an effort to control losses. Pills containing sized solids, gunk squeezes, conventional cement squeezes, and foamed cement have all been proposed as solutions to sub-salt lost circulation. While the cement
squeezes were able to reduce losses in the HMD field, the associated non-productive time remained a costly factor.

**Chemically Activated Crosslinking Pill**

The CACP proposed for the sub-salt lost circulation problem in the HMD field is a blend of crosslinking polymers and fibrous material. The material was designed to plug deep fractures, faults and vugular formations. The material can be blended with a biopolymer to enhance the viscosity of the material to suspend barite while pumping. The crosslinking process is chemically activated. After setting, the material forms a firm, rubbery, ductile plug in the fractures and voids that it has been squeezed into, preventing further loss of fluid.

The CACP can be mixed in freshwater, seawater and saltwater and applied in wells drilled with water-based, oil-based and synthetic-based mud systems. One major advantage of the CACP is that it can be pre-mixed ahead of time. This allowed for significant time savings on the HMD field. The anticipated volume of CACP required was pre-mixed and kept on standby. When drilling below the salt formation, once severe losses were encountered, the crosslinking agent was added to the pill and the CACP was immediately pumped into the thief zone. Though not necessary, the CACP can be used to cure losses and at the same time shut off zones producing water or gas. This would suggest that the CACP might be an ideal material for attacking Gulf of Mexico sub-salt thief zones.

Variations of the CACP are available that can be tailored to specific applications. Depending on the formation properties and the characteristics of the loss zone, higher polymer loadings can be selected, higher fiber loading, or a CACP with coarse calcium carbonate can be used. The CACP is not recommended for producing zones as the material does not degrade and is not acid soluble.

**Risk Assessment**

The proposal developed to counter the chronic lost circulation problems in the HMD field had not previously been proven in this type of situation. As such, the potential risks were identified and reviewed in the context of applying the CACP once losses occurred.

Since the pressure profile for the open-hole section is very complicated with a large pressure reduction and weak formations, there is always potential for wellbore instability to develop once formation losses occur. The massive losses that occur can reduce the annular hydrostatic pressure to levels that cannot support the upper sections of the wellbore, introducing the potential for borehole collapse. Once loss of returns has occurred, any delay in curing the losses introduces the risk of losing the well. For this reason, it was imperative to develop a lost circulation solution that could be deployed rapidly and become effective as soon as possible. The CACP involved minimal downtime between the onset of the losses and placement of the pill across the loss zone.

In order to minimize the potential for stuck pipe, the safest practice after pumping the pill required pulling the drillstring above the high-pressure formation (TS#2) immediately after placing the pill across the loss zone. If the borehole did collapse due to reduced annular pressure being insufficient to support the borehole, any potential for stuck pipe would be reduced. Typically, 9000-psi equivalent fluid density is required to stabilize the formation. Once the string is located above the loss zone, the CACP is squeezed into the induced fractures to reconsolidate the section and allow drilling to continue. The operation can be repeated to seal additional weak zones that may be encountered drilling to interval TD.

**Pill Design and Planning**

The well that was selected to apply the first CACP lost circulation pill was located in one of the most challenging blocks in HMD field. This scenario provided an opportunity to aggressively test the approach against severe loss conditions and a high level of borehole instability.

The section to be drilled would require a 2.02 sg (16.9 lb/gal) salt-saturated mud system. It would be necessary for the CACP to be designed with consideration for the following surface and downhole conditions:

- The effect of high concentrations of barite on both the slurry rheology and thickening time
- The compatibility of the CACP with the mud system when drilling through the plug
- The effect of formation salt contamination while pumping and squeezing the pill
- Mixing time and temperature effects

The slurry design was based on 90 minutes pumping time and a total of 5 hours setting time, which would be sufficient to allow for mixing, pumping, squeezing and pulling the drillstring above the pill to 3000-meters (9834-ft) measured depth. Fig. 3 illustrates the rapid increase in the viscosity of the material 90 minutes after crosslinking has been initiated.

**Spotting Procedure**

Based on the potential risks and the pill design criteria, a spotting and squeeze procedure was designed that would minimize any operational risks. For the initial trial, 8 m³ (50 bbl) of the CACP was mixed prior to drilling into the trouble zone. Once the thief zone had been drilled into and only if losses occurred, the following procedure was utilized. Fig. 4 provides an illustration of the stages involved with spotting and squeezing the CACP.
1. Pull out of hole to the top of TS#2.
2. Add the chemical activator and immediately pump the CACP, displacing all of the CACP from the drillstring.
3. Two options available,
   a. If only partial returns are observed while spotting the pill, pull up 10 stands to ensure the drillstring is completely above the top of the pill.
   b. If no returns are observed it is not necessary to pull 10 stands.
4. Close annular preventer and squeeze the pill 8 m³ (50 bbl) into the formation at no more than 320 L/min (2 bbl/min).
5. Hold pressure on the pill until 5 hours have passed since initial pumping.
6. Ream through plug and continue drilling ahead. If losses are again encountered, an additional pill can be mixed and the procedure repeated.

Proven Advantages
After the initial and highly successful trial, the procedure described in this paper was continued to ensure the procedure was in fact a feasible solution to the sub-salt thief zone problems. The procedure has since been adopted as standard practice for the HDM field. Some of the definitive advantages of the CACP procedure include:

- Reduced non-productive time by eliminating tripping time associated with cement squeezes, resulting in fewer days to TD with production brought on line faster. Average time saving of 7.5 days per well.
- NPT minimized with mixing and storage of CACP slurry prior to drilling into loss zone.
- The procedure does not require water-based spacers ahead of and behind the pill. Thus reduced washout across the salt sections and less cement volume required for casing.
- Reduced risk of borehole instability in the TS-2 and LD-2 formations due to the reduced exposure time and under-balanced static periods.
- CACP is more effective at increasing formation integrity. The drilling progress after each CACP has been better than previously recorded.
- The CACP is easy to mix and pump. A cement pump is not required (on the initial trial a cement pump was used).
- No mud treatment is required after each plug. Previously, after each cement squeeze, mud treatment was necessary.
- The CACP is compatible with the drilling fluids typically utilized on the HMD field.

Conclusions
Based on the highly successful application of the CACP in the sub-salt thief zone of HMD field, several conclusions can be drawn.

- A well-defined and engineered strategy for managing the onset of lost circulation below the salt formations was critical to improving the drilling efficiency in the HMD field.
- Strict adherence to the agreed upon decision tree ensured the successful implementation of the CACP methodology.
- Significant reductions in non-productive time were possible through elimination of trips associated with cement squeezes and the resulting in production coming online earlier than planned.
- Application of the CACP technology eliminated the lost time associated with preparation of alternative pills. The CACP slurry is prepared prior to the onset of lost circulation.
- A higher quality wellbore was available for cementing due to reduced washouts typically associated with placing cement plugs.
- After spotting and squeezing the CACP, fluid losses were eliminated and full circulation was maintained while drilling to TD.

The CACP approach has been adopted as standard practice on the HMD field when encountering severe losses in the sub-salt thief zone.

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References
Table 1 - Hassi Messaoud Historical Offset Well Data (Examples)

<table>
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<tr>
<th>Well, date</th>
<th>Offset 1</th>
<th>Offset 2</th>
<th>Offset 3</th>
<th>Offset 4</th>
<th>Offset 5</th>
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<tbody>
<tr>
<td>Depth of Losses (ft)</td>
<td>11000-11056</td>
<td>10997</td>
<td>10991</td>
<td>11171</td>
<td>11037-11043</td>
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<tr>
<td>Fluid density (lb/gal)</td>
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<td>17.2</td>
<td>16.9</td>
<td>17.0</td>
<td>16.9</td>
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<tr>
<td>Top of G 35</td>
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<td>10974</td>
<td>10968</td>
<td>10984</td>
<td>10925</td>
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<tr>
<td>Top of Camberien Ri</td>
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<td>11207</td>
<td>11158</td>
<td>11280</td>
<td>11211</td>
</tr>
<tr>
<td>Top of Cambrien Ra</td>
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<td>11289</td>
<td>11230</td>
<td>11414</td>
<td>11293</td>
</tr>
<tr>
<td>Cement Plugs pumped</td>
<td>6 + 2 LCM</td>
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<td>1</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>7-in. Casing Depth</td>
<td>11155</td>
<td>11217</td>
<td>11165</td>
<td>11273</td>
<td>11224</td>
</tr>
</tbody>
</table>

Figure 1: Risk Assessment Chart for HMD wells.
<table>
<thead>
<tr>
<th>S/ET</th>
<th>Ref</th>
<th>LITHOLOGY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIAS SALIFERE</td>
<td>Salt</td>
<td>L L L L</td>
<td>Massive Salt</td>
</tr>
<tr>
<td></td>
<td>G1</td>
<td>L L L L</td>
<td>Reddish Bowen Shale</td>
</tr>
<tr>
<td></td>
<td>G20</td>
<td>L L L L</td>
<td>SALIFERE</td>
</tr>
<tr>
<td>TRIAS ARGILEUX</td>
<td>Upper</td>
<td>L L L L</td>
<td>Shale (colored)</td>
</tr>
<tr>
<td></td>
<td>G30</td>
<td>L L L L</td>
<td>SALIFERE</td>
</tr>
<tr>
<td></td>
<td>G35</td>
<td>L L L L</td>
<td>Anhydride, Dolomitic Shale</td>
</tr>
<tr>
<td></td>
<td>G40</td>
<td>L L L L</td>
<td>Sandstone Dolomitic Shale, Marl</td>
</tr>
<tr>
<td>TRIAS GRESEEUX</td>
<td>Medium</td>
<td>L L L L</td>
<td>BRUN Shale</td>
</tr>
<tr>
<td></td>
<td>G50</td>
<td>L L L L</td>
<td>VF SandStone</td>
</tr>
<tr>
<td></td>
<td>G60</td>
<td>L L L L</td>
<td>Black Shale Lime Stone (Colored)</td>
</tr>
<tr>
<td></td>
<td>G70</td>
<td>B A</td>
<td>A - Cambrian, B - Andesite</td>
</tr>
</tbody>
</table>

G10 = Top of Trias Argileux  
G20 = Seismic marker  
G35 = Last salt marker  
G40 = first sand marker

Figure 2: Lithology Chart for Hassi Messaoud Field, Algeria  
T.A.G.I - Detailed
Fig 3 - Comparative rheology profile for CACP after crosslinker has been added and while hot rolling at 86°C. After 3 hr, the samples were too thick to be measured.

Fig 4 - Spotting and Squeezing Procedure for CACP in TAG formation. When the bit is below the salt and in the TAG formation, if and only if there is a loss of returns, the bit is picked up to a position above the thief zone (above the TAG and TS2 formations), the CACP is displaced from the drill string and squeezed into the loss zone with the annular preventers closed. At this point, pressure is held on the pill for several hours. After the pill has set, the plug can be drilled/reamed through and drilling can recommence.