

Low Density Lost Circulation Plug for Low Temperature Applications

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Abstract

Experiencing lost circulation in the oil and gas industry has become more common as operators drill through more challenging formation zones. Limestone formations with vugs, formations with large fractures, faults, and depleted zones are some of the most difficult scenarios control mud losses that can lead to more severe situations with limited operational solutions. These scenarios can become even more problematic when the lost circulation zones have a low fracture gradient with a low temperature gradient, rendering the use of cement for zonal isolation, an unfavorable option. However, there is another ‘plug-setting’ technology with updated chemistry that can overcome the cement plug limitations.

The proposed lost circulation pill/plug is a magnesia-based phase transformation technology. In liquid phase, it is thixotropic when sheared and yields high compressive strength when it sets to a rigid, solid, plug. A few other advantageous that the magnesia plug has over a cement plug is its ability to set at right angles with faster setting time. Additionally, the lost circulation material/plug (LCM) is a fit for purpose technology with over 90% acid solubility, translating to a favorable solution for reservoir sections. Moreover, the lost circulation pill/plug is pumpable through the drill string, BHA, and drill bit while able to be used as an isolation plug to cure severe to total losses in both reservoir and non-reservoir sections.

The new application development has demonstrated that the system is able to fully set at densities as low as 11.0 lb/gal (ppg) with temperatures as low as 120°F with respectable compressive strength (> 500 psi) to allow the plug to set at a high compressive strength. Furthermore, the data will show the plug was designed to set within a time range of 2-3 hours at different densities while controlling certain key additives. It will also be demonstrated that by controlling the balance of these additives, the plug can set between a designed thickening time of 1-4 hours if so desired.

Lastly, new preliminary data will be introduced that confirms the versatility of the system, demonstrating its potential capability to set at even lower temperatures (104 °F).

Introduction

Lost Circulation is a major driver of Non-Productive Time (NPT) in drilling operations and often times leads to stuck pipe incidents and/or well control situations. Lost circulation can

occur in any aspect of operation, such as, drilling, circulating, tripping, casing, and cementing. If total losses are experienced, the immediate danger and challenge becomes to maintain hydrostatic pressure in order to maintain pressure control and not ‘lose the well’, which essentially can become dangerous if a blowout occurs. The location and severity of lost circulation is typically affected by the formation characteristics, flow path there-in, and the overbalance pressure exerted by the fluid into the formation (Alkinani et al, 2018). Depending on the characteristics of the rock, pathways can be grouped as:

- Unconsolidated and/or highly permeable formations (seepage and partial losses).
- Induced fractures in unconsolidated formations (partial to severe losses)
- Natural fractured formation (partial to total losses)
- Caverns formation (severe to total losses)

Two conditions must occur downhole for the lost circulation to take place:

- The pressure exerted by the fluid must be higher than the pore pressure (loss of hydrostatic pressure).
- A pathway is required for the fluid to be drained from the borehole (vugs, fractures, permeable formation, caverns).

Lost Circulation has been classified by severity and classifications can change slightly depending on the operators, but generally loss severity while circulating is classified as (Alkinani et al, 2018):

- Seepage losses: 3-10 bbl/hr
- Partial losses: 10-60 bbl/hr
- Severe losses: 60-100 bbl/hr
- Total losses: no fluid return to surface

Types of Lost Circulation Plugs

Commonly used lost circulation material have include granular, fibrous, blended, water/acid-soluble, hydratable/swellable, nanoparticles, polyurethane grouting, crosslinked gel plugs, cement plug, and settable plugs. Settable plugs have been commonly used in the industry as the most efficient in terms of curing high losses. Some distinctive types of settable plugs are described below in **table 1**.

Table 1 – Typical settable plug technology in the oil and gas industry.

Type	Target	Applications
High Filtration Plugs	Severe, Total	Permeable, Unconsolidated Fractures
Thermo-Set Resins	Severe, Total	Fractured, Vugular formations, Cavernous
High-Vis/Gunk Squeeze	Severe, Total	Permeable, Fractured, Vugs
Fibrous, Granular, Flake Blend	Seep, Partial, severe	Permeable, Fractured
Cement Plugs	Severe, Total	Fractured, Vugular, Cavernous formations
Swellable Polymers	Severe Total	Fractured, Vugular, Cavernous formations
Thermo-set, phase transform plugs	Severe Total	Fractured, Vugular, Cavernous

Several types of lost circulation materials are used in the oil and gas industry with the success factor at most times being inconsistent. In general, the major typical drawbacks of the current lost circulation materials fall in one or more of the following categories:

- Lack of the required thixotropic profile to slow down flow through the pathway.
- Irreversible formation damage; impairing production.
- Inability to flash set and instantly stop losses.
- Not tolerant to drilling fluid contamination.
- Requirement of specialized equipment to mix and pump, non-practical for emergencies.

With that being said, the concept behind the development of the ‘magnesia-based phase transformation lost circulation plug’ is to overcome the drawbacks described above while still being able to restore production in case of reservoir applications.

Magnesia-Based Phase Transformation Technology

The novel LCM plug is magnesia-based, phase transformation technology that is suitable to pump downhole across a loss zone. It is customized to set and form a high-compressive-strength plug to combat a severe loss circulation incident. The magnesia-based plug exhibits several properties that are advantageous in comparison to traditional LCM’s and to other LCM plugs. One such property is the ability to have thixotropic properties by means of utilizing novel viscoelastic surfactant (VES) that makes the fluid viscous in static condition and thin upon applying shear (see **figure 1**). The amphoteric surfactant forms elongated worm-like micelle structure in presence of monovalent and/or divalent salts (Addagalla et al. 2020). This fluid phase transforming behavior is a result of pseudo-crosslink chemistry which differentiate this system from other commonly available solutions. This transformation of fluid properties with shear helps the LCM pill ‘stay’ in the loss zones after placement. The fluid becomes hard and ‘sets’ over the period of time based on application time and bottom-hole

temperature due to, primarily, the acid soluble weighing agent (ASWA). ASWA reacts with water and forms hard structure (see **figure 2**). The setting time can be optimized by using a setting control additive.

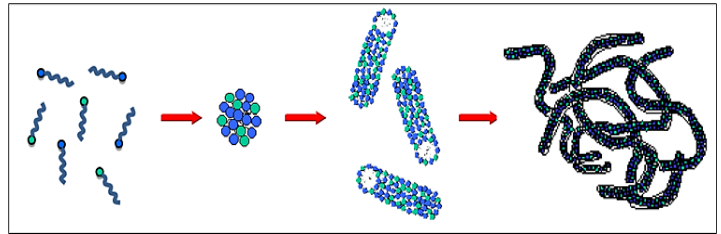


Figure 1 – Diagram of the VES surfactant.



Figure 2 – Image of the ASWA in liquid form and solid form after setting.

Magnesia-Based Setting Plug vs. Concrete Plug

In severe loss circulation event, concrete/cement plug is commonly the most adopted solution. However, the new LCM plug has many advantages in comparison to cement plug while still maintaining the same rigid structure. Such as:

1. More than 90% acid solubility whereas conventional cement is very difficult to solubilize (Yadav et al.,2017).
2. “Right Angle Set” that is set as fast as possible at targeted temperature and predetermined time, has another important feature over the low-density cement.
3. Better compressive strength than low density cement.
4. Robust thixotropic property.
5. The tripping time to run in hole with cement stringer prior to perform a cement job is tedious, the new LCM fills this significant gap. (Yadav et al. 2020).

Furthermore, the following are some prominent features and benefits of the system:

- High compressive strength
- Acid soluble
- Thixotropic viscosity
- Customizable setting time
- Tolerance to contamination
- Pumpability through BHA
- Seawater compatible
- Can be pre-mixed and stored at the rig-site as a lost circulation contingency
- Applicable for oil-based mud and water-based mud.
- Slim hole applications through BHA and directional tools (see Olivares et al., 2022)

Applications

The novel loss circulation plug has many different types of applications, such as:

- Total loss circulation (Yadav et al., 2017)
- Well control
- Wellbore strengthening (Yadav et al., 2017)
- Zonal isolation (Addagalla et al., 2020)
- Plug and abandonment scenarios
- Reservoir or non-reservoir formations
- Remediation of sustained casing pressure

Testing Methodology

A systematic laboratory testing program was planned to design the lost circulation plug. The setting time and consistency was tested with a high-pressure high temperature (HTHP) consistometer, and the compressive strength was tested with an ultrasonic cement analyzer (UCA) (API RP 10B-2 Standard). The setting time was measured according to API standards by measuring the time period for which the fluid stays pumpable from surface to down-hole. The thickening time was evaluated to measure the time required for the fluid to reach a consistency of 70 Bc (Bearden consistency units). The elapsed time from the initial application of temperature and pressure to the time at which the slurry reaches a consistency (see **figure A1**) deemed sufficient to make it un-pumpable or otherwise noted as the material being set to a solidified state (e.g., thickening at 70 Bc or setting at 100 Bc).

Formulation Design

In order to design the application, the dynamic temperature profile, density, wellbore geometry and rig capabilities are taken in consideration. For a given density and temperature the desired setting time is estimated based on operational experience, and afterwards, the setting time for laboratory and field purpose is estimated using the following equations:

For vertical hole (up to 20° inclination):

$$\text{SET TIME} = T_{\text{spacer}} + T_{\text{plug}} + \text{SVDT} + \text{TT}$$

For angle smaller than 45° inclination:

$$\text{SET TIME} = (T_{\text{spacer}} + T_{\text{plug}} + \text{SVDT} + \text{TT}) \times 1.15$$

For angle higher than 45°:

$$\text{SET TIME} = (T_{\text{spacer}} + T_{\text{plug}} + \text{SVDT} + \text{TT}) \times 1.2$$

Results & Discussion

The lost circulation plug composition contains water as the base fluid, defoamer, setting control additive for set time optimization, VES to build viscosity, monovalent or multivalent salt as ionic additive to increase the efficiency of VES, acid soluble weighting additive (ASWA) to achieve the required density. The formulation forms a solid hard plug when the ASWA powder reacts with water, and the reaction is retarded with the setting control additive (Elkatatny et al. 2020). In the case for the low-density application, hollow glass spheres were used that were commercially obtained. The material had

been engineered specially for high strength-to-weight ratio that was able to withstand pressures up to 10,000 psi.

As it can be seen from **table 2** and **figure 3**, four formulations were successfully achieved ranging from densities of 11.0 -12.5 ppg while keeping the operational parameters consistent (temperature, pressure, and ramp time which equates to pumping time), thereby validating the systems capability to achieve specifications by modifying key reaction components.

Table 2 – Thickening time for 11.0 to 12.5 ppg of LCM plug at 120°F, 3000 psi, with a 30 min ramp time. The formulations were designed to thicken/set within 2-3 hrs.

	11.0 PPG	11.5 PPG	12.0 PPG	12.5 ppg
Temp (°F)	120	120	120	120
Pressure (psi)	3000	3000	3000	3000
Ramp Time (min)	30	30	30	30
Thickening Time @70 Bc (hr:min)	2:25	2:40	2:36	2:23
Thickening Time @100 Bc (hr:min)	2:29	3:04	2:50	2:29

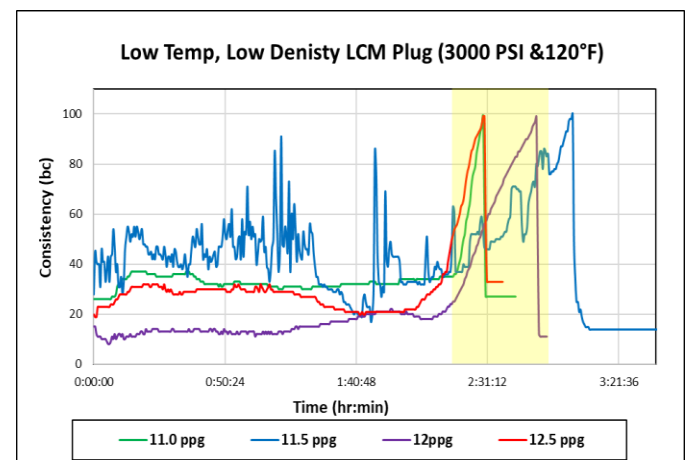


Figure 3 – Diagram of the consistency of the formulations obtained from consistometer testing.

In order to determine the systems flexibility in setting time, the 12 ppg formulation was modified for shallow depth application. By controlling the salt/ionic additive and retardant concentration, a 1:15 (hr:min) thickening time was achieved at 70Bc. In contrast, for loses at deeper sections, the system was able to achieve a thickening time at 4:11 (hr:min) @ 70 Bc. The system showed it is versatile and adaptable to utilize in various applications depending on depth (see **table 3**).

Table 3 – Thickening time for 12.0 ppg LCM plug at 120°F, 3000 psi, with a 30 min ramp time. The formulations were designed to thicken/set at 1,2, and 3-4 hrs.

	12.0 PPG	12.0 PPG	12.0 PPG
Temp (°F)	120	120	120
Pressure (psi)	3000	3000	3000
Ramp Time (min)	30	30	30
Thickening Time @70 Bc (hr:min)	1:15	2:36	4:11
Thickening Time @100 Bc (hr:min)	1:20	2:50	5:00

Additionally, experimental testing was performed at temperatures of 90°F and 104°F to determine if the system is able to push its applicational temperature limits. As it can be seen from preliminary data in **figure C1-C2**, the system has potential to reach even lower temperatures if further fine tuning can be performed on the formulations.

Future Work – High Density High Temperature (HDHT) LCM Plug

In contrast to designing a lost circulation plug with low density suitable for low temperature applications, further application development was investigated to determine the systems capability to function at high density for high(-er) temperature applications. Preliminary data bare promising as the system was designed at 15.5 ppg and 16.25 ppg at temperature of 230°F and pressure at 9000 psi with a ramp time of 45 minutes (see **figure 4, figure B1, and table 4**). The weighting material was a mixture of the ASWA + MnO₄. Achieving this feat became plausible by controlling shearing, additives concertation ratios, mixing order, mixing time, as well as ensuring the additives were dispersed and soluble during the mixing phase. More on this topic will be presented on a future paper that is outside the scope of this current paper.

Table 4 – Thickening time for 15.5 and 16.25 ppg LCM plug at 230°F, 9000 psi, with a 45 min ramp time. The formulations were designed to thicken/set at approximately 2 hrs.

	15.5 PPG	16.25 PPG
Temp (°F)	230	230
Pressure (psi)	9000	9000
Ramp Time (min)	45	45
Thickening Time @70 Bc (hr:min)	1:35	2:10

Conclusion

Based on the latest testing performed on application limitations on the magnesia-based lost circulation plug, it is apparent that the system is able to achieve low density properties for low temperature applications exhibiting significant versatility in design and applicable for various field applications. The system in itself, based on its intrinsic design, is able to:

- Achieve thixotropic shear thinning gels.
- Can prevent gas migration for well control applications.
- Customized setting time based on applications, environment, and field operations specifications.
- High compressive strength can be utilized to set as an isolation plugs, (while still being able to drill through to section).
- High acid ssolubility 90%+, suitable for production zone.
- Can flash set based on bottom hole temperature
- High tolerance to contamination allows variation with mix water, sea water etc.

Furthermore, effective compressive strength characteristics of the lost circulation plug allows it to effectively seal fractures, vugs, caverns, depleted formations, unconsolidated zones, thief zones, and highly permeable formations. Its particle size distribution and unique formulation allows it to be squeezed into the loss zones, forming a solid plug that stops severe losses and reduces wellbore stress.

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Nomenclature

- ASWA = acid soluble weighting agent
- Bc = bearden consistency
- BHA = bottomhole assembly
- NPT = nonproductive time
- ST = set time estimation for lab customization
- SVDT = String displacement time
- Tspacer = Time to Pump lead spacer
- Tplug = Time to pump PLUG pill
- TT = estimated tripping time to pull top of pill
- UCA = ultrasonic cement analyzer
- VES = viscoelastic surfactant

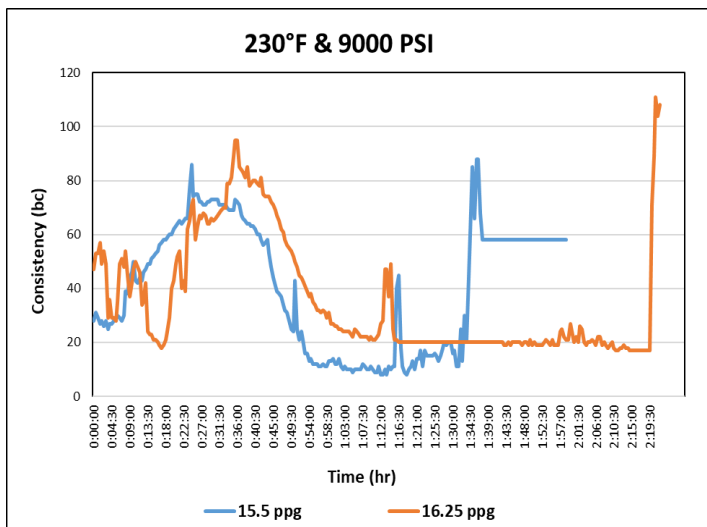


Figure 4 – Consistency diagram of high density lost circulation plug for higher temperature applications.

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Appendix

Appendix A: Images of magnesia-based, phase transformation lost circulation pill/plug.

Not-Set plug (still wet)



Semi-Solid plug (partially wet)



Set pill/plug (solid, stable)



Figure A1- Images of inadequately designed and not 'set' plug versus of a properly designed 'set' plug that is solid.

Appendix B: Images of magnesia-based, lost circulation plug at 16.25 ppg (weighted up with ASWA+MnO₄)



Figure B1- Images of adequately designed high density plug after 'setting' in the consistometer.

Appendix C: Preliminary data on low temperature application of the 12.5 ppg lost circulation pill/plug at 104°F & 10,000 psi.

The pill design for 12.5 ppg at 104°F and 10,000 psi, achieved a thickening time 5:00 (hr: min) at 70 Bc. The design was intended for 1-2 hours, but the formulation designed demonstrated that the system can set at even lower temperatures than initially developed. However, further work is needed to fine-tune the concentrations of the additives and balance the ratios in order to achieve a stable solid plug that can thickening at a more suitable and realistic pump time, therefore needing the plug to thicken, and eventually set at approximately 2-3 hrs.

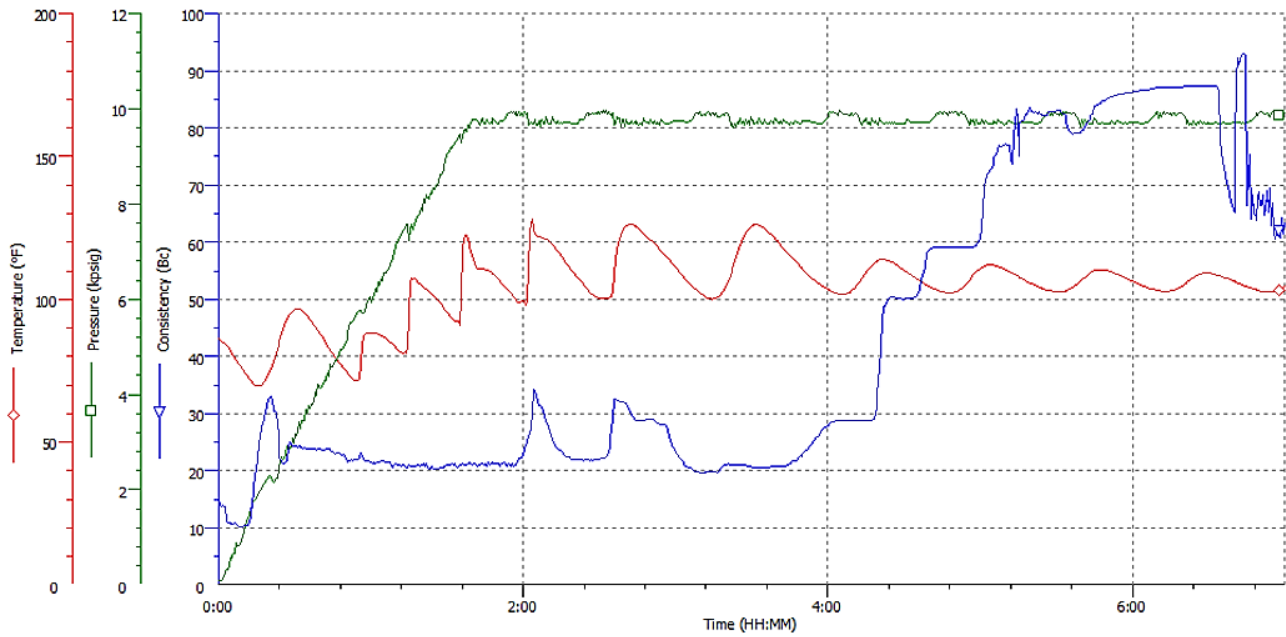


Figure C1- Chart of the consistometer results for the 12.5 ppg lost circulation pill. Note - Some temperature variations noticed, test needs to be repeated to determine validity and repeatability.



Figure C2- Image of lost circulation plug after consistometer testing. By observation, it was noticed that the plug was solid and stable (i.e., not crumble) nor was it excessively 'wet'.