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A New High Fluid Loss Squeeze: Design to Delivery in the Field

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Abstract

A new high fluid loss squeeze (HFLS) material has been developed and successfully implemented in the field. On its first application, the product significantly reduced downhole losses and prevented sidetracking or well abandonment scenarios, saving >2,000 barrels of oil-based mud. The composite blend outperformed a cement squeeze, improving well integrity and allowing the operator to drill to total planned depth.

The single-sack product contains a blend of lost circulation material, which provides a rapid de-fluidizing effect. Severe to total lost circulation events can be challenging, whether the loss zone is due to natural or drilling induced fractures. When conventional lost circulation material (LCM) is unable to alleviate downhole losses, a HFLS is considered as one of the last options. While many fluids can be used to spot LCM, fluids that have a high fluid loss rate are ideal. As an initial bridge forms, the base fluid is filtered out of the slurry into the formation, depositing a firm plug within the fracture itself. The plug provides a new substrate to build a filter cake and improves the integrity of the loss zone, allowing the fracture to withstand higher pressures and eliminate losses.

Laboratory development included a thorough screening process involving fluid compatibility, pressurized-slot testing, and material strength. A final blend resulted in plugging of >5,000 micron opening at >1,000 psi pressure, with elevated unconfined compressive strength. The authors provide a case history of the field application, revealing new findings not commonly associated with traditional HFLS procedures.

Introduction

Lost circulation is a frequent challenge in many drilling environments. Narrow pore pressure/fracture gradient margins and loss-prone formations present significant engineering challenges to limit the occurrence and severity of lost circulation.

The overall cost of lost circulation occurs in the form of whole drilling fluid losses, treatment materials, nonproductive time, and the risk of a lost wellbore or well control incident. An SPE workshop estimated the volume of drilling fluid lost per year at 1.8 million barrels. (Alsaba 2014).

Best practices focus on drilling practices, proper drilling fluid selection and wellbore strengthening techniques to prevent lost circulation (Growcock 2010). When losses still occur, lost circulation materials must be applied based on the nature of the loss zone and the loss rate.

Severe to total loss rates of more than 100 bbl/hr are urgent as large volumes of fluid are required to maintain a hydrostatic column in the wellbore. Typically, a lost circulation treatment uses increasing particle size distribution and higher material concentration to treat increasing loss rates.

When bridging and sealing fails, a high fluid loss squeeze is one of the last options before a cement squeeze to seal the zone . Cement squeezes are expensive, time consuming, and risky (Algu 2010). This makes the success of a high fluid loss squeeze critical to lower risk and reduce lost time.

Squeeze Options and Limitations

A HFLS product is engineered to rapidly de-fluidize downhole by exerting pressure, typically via mud pumps. The “squeeze” technique is intended to leave behind a resilient solid plug across the loss zone/void space. The mechanism by which a typical HFLS works is well understood.

Over the years, many HFLS products have been introduced, many of which claim unique properties and components. Given the cost and complexity of placement, most require an onsite representative to provide oversight of mixing and pumping procedures.

HFLS products have a low packing efficiency to have a high fluid loss. This forms a solid plug material in the loss zone. Products that contribute to fluid loss control, such as polymer viscosifiers, are excluded. Suspension agents, such as clay materials, are utilized at concentrations where they do not contribute to reduced filtration.

The success of a HFLS application is just as dependent on the pumping and placement procedure as the product design itself. An HFLS treatment requires proper planning and a collective effort of everyone at the rig site. A high-level summary of the operations procedure is listed in Figure 1.

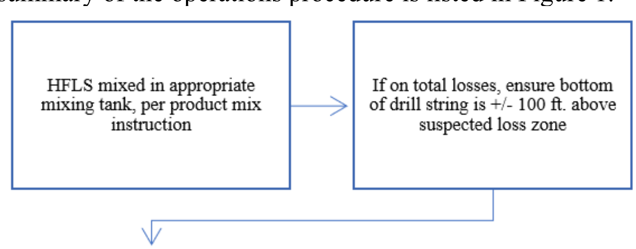

Figure 1 – Summary of most HFLS pumping procedures (continued next page)

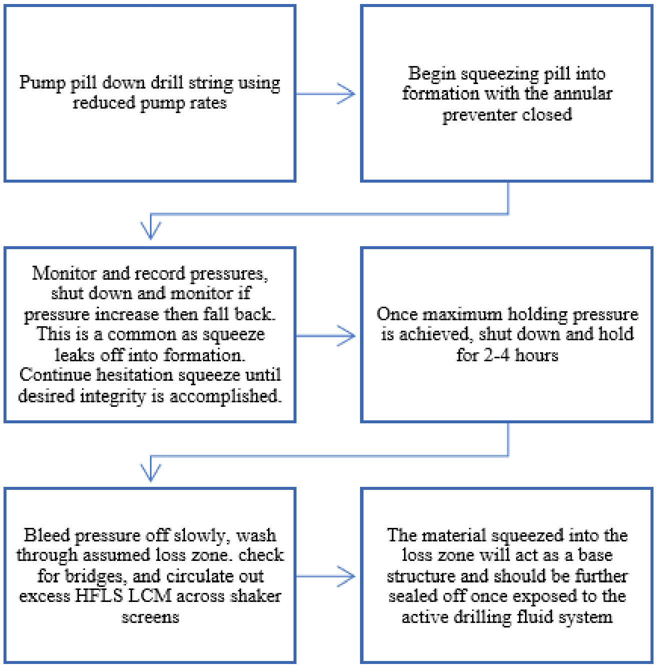

Figure 1 – Summary of most HFLS pumping procedures (continued from previous page)

A HFLS product is inherently inclined to plug and seal downhole tools where flow restrictions provide opportunity for the HFLS to de-fluidize prematurely. Tool compatibility should be reviewed. Most HFLS applications are performed with BHA configurations to minimize risk of plugging such as:

- Open-ended
- Circulating sub, often activated by ball drop
- Bull nose assembly with large orifice opening

Design Criteria

The design criteria was established as part of the initial concept phase of the product development process. Testing criteria was determined based on a review of existing products across the industry, a study of technical literature, and a survey from various field personnel knowledgeable in HFLS applications. Table 1 summarizes the established design criteria.

Table 1: Criteria for HFLS Product Development

Criteria/Feature	Benefit or Purpose
Unconfined Compressive Strength	Support formation under elevated pressures
Seal up to 5,000 micron opening at 1,000 psi	Form a solid bridge/plug across large openings
Weight-up option	Improve HFLS placement downhole
Performs in WBM / OBM / Brine / Base Oil	Broader application window
Single-sack product	Lower waste and risk of improper mixing
Readily available raw materials	Reliable supply and cost conscious

Competitor Product Reviews

A thorough review of publicly available information on competitor HFLS offerings provided insight for design criteria. Several common product features and promises were evident across different HFLS offerings.

Unconfined Compressive Strength

Unconfined compressive strength (UCS) is one of many ways to measure the strength of a given material. The measurement is commonly seen in the fields of geology, geophysics, and formation evaluation. It can also help optimize the strength of single or multi-component blends of LCM. The UCS can be defined as the maximum axial compressive stress that a right-cylindrical sample of material can withstand under unconfined conditions. It can also be termed the uniaxial compressive strength of a material because stress is applied to only one axis (Figure 2).

Elevated UCS can promote improved strength under stress - indicating a higher chance of the blend maintaining compaction and form under pressure.

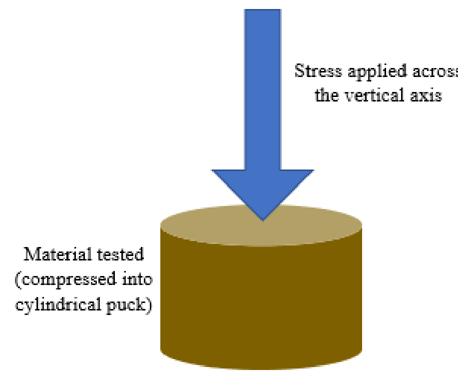

Figure 2 – Illustration of UCS measurement concept

Single Sack

Many LCM applications require a multitude of separately bagged products to arrive at a target blend. As blends increase in number and complexity, so does the risk of mixing errors. Typically, as a last resort, a HFLS must be mixed and pumped without error for the highest chance of success. A single-sack blend limits these mistakes by requiring the rig personnel to only blend one product on location.

Weight-up Option

Many HFLS rely on a specific particle size distribution to form the highly permeable, high strength plug. When operational requirements dictate the pills density to be increased with barite, this will often alter the particle distribution significantly. The resulting effect is a loss in packing efficiency and poor bridging in larger openings. A HFLS designed with the ability to form a solid bridge across large openings with or without the inclusion of barite expands the application window and overall success rate.

Base Fluid Performance

After decades of addressing lost circulation challenges, the industry has developed a set of commonly shared theories and observations. For instance, it is well understood that the development of a new lost circulation material should have workable/controllable set times and should be functional in oil-, synthetic- or water-based systems (Bruton 2001). The development criteria included the ability for a HFLS to perform across all common base fluid types, including diesel oil, fresh water, and "cut brine" (approximately 9.5 lb/gal sodium chloride brine).

Slot Testing

Particle plugging apparatus (PPA) and HPHT fluid loss apparatus are commonly used as standard tests to evaluate the ability of LCM performance. Slotted or tapered disks are used to simulate natural/induced fractures, while ceramic disks simulate porous formations. Many of the standard tools and associated equipment often accompanying a typical PPA test were used for evaluation. However, a customized PPA apparatus was utilized, which includes fit-for-purpose spacers, sealant rings, and a clear reservoir cylinder to make visual observations as the HFLS leaks off.

Based on other benchmarks, testing criteria included the ability for a candidate HFLS to form a plug across a 5,000 micron slotted disk (Figure 3) under 1,000 psi pressure. There have been documented PPA test procedures that have deviated from the standard protocol due to the difficulty of accurately mimicking hesitation squeezes in the field. Some procedures utilize a method of 'stroking' the hydraulic pump at a specific rate in accordance with hesitation squeeze operational procedures (Savari 2016). These types of procedures were not utilized in the development testing of this HFLS. The slot-testing procedure is summarized as follows:

- Load test fluid in the PPA cell
- Affix the 5,000 micron slot
- Apply 1,000 psi maximum pressure to hydraulic pump
- Allow fluid to squeeze through slot, leaving behind a solid plug
- Reset hydraulic pump and load "circulating" fluid (i.e. normal drilling fluid to be circulated around after spotting HFLS)
- Apply 1,000 psi maximum pressure to hydraulic pump
- Observe for no further fluid loss, indicating HFLS plug has maintained strength

Figure 3 – 5000 micron slotted disk

HFLS Material Composition

Current market conditions have encountered a supply "squeeze" on many raw materials - some of which are commonly used in LCM. Many engineered, composite LCM products rely on supply of raw materials which service multiple industries. Commodities such as soybeans, cotton, corn, seed, pecan nut, walnut, and graphite are all subject to market supply/demand forces outside the oil & gas industry. The development of a new HFLS should account for the changing supply/availability of these products to ensure consistent supply of a final product.

Laboratory Evaluation and Results

All testing was performed at room temperature. Test blends were composed from a selection of over 15 different raw materials. Raw material type, concentration, and combination varied across test blends. HFLS blend optimization occurred in a sequential manner, where different combinations were attempted as performance data was generated.

Table 2: Example of various experimental HFLS blends attempted (measured in %/weight)

Product	SQZ1	SQZ2	SQZ3	SQZ4	SQZ5
Exp Raw 1	20%				
Exp Raw 2	20%				40%
Exp Raw 3	20%		15%		
Exp Raw 4	20%	10%	20%		40%
Exp Raw 5	20%				
Exp Raw 6		36%	20%	50%	12%
Exp Raw 7		10%			
Exp Raw 8		8%			
Exp Raw 9		16%			
Exp Raw 10		8%			
Exp Raw 11				3%	3%
Exp Raw 12		12%	10%	5%	5%
Exp Raw 13				15%	
Exp Raw 14				15%	
Exp Raw 15				12%	
Exp Raw 16			15%		
Exp Raw 17			20%		

HFLS Raw Materials

A wide range of HFLS raw materials were utilized during the product development phase - ranging in both particle size, shape, and type. Particle bridging is the fundamental concept driving raw material selection. It is widely accepted that to form a stable high-pressure bridge, strong granular materials are required (Scott 2020). Often, fibrous and laminated/flake shaped materials do not perform as well as granular materials. However, due to the specific function of a HFLS - forming a strong bridge, but maintaining high permeability to facilitate leak off - combinations of all LCM types were utilized in experimental blends.

Slot Testing Results

Plugging efficiency was graded based upon the bridging of the 5,000 micron slotted disk and de-fluidizing of the HFLS pill at a constant pressure of 1,000 psi. Figure 4 illustrates the base fluid (water) extruded out of the HFLS material after forming a plug.

Figure 4 – Base fluid of the HFLS experimental blend after applying 1,000 psi across a 5,000 micron slotted disk

Table 3 lists slot testing results of various squeeze formulations testing. Squeeze 6 and Squeeze 11 both met the criteria of bridging off a 5,000 micron slot up to 1,000 psi.

Table 3: Select slot-testing results of various HFLS experimental blends tested in diesel-oil

	Test Pressure (psi)				
	50	100	250	500	1000
SQZ1	x	x	x	x	Blowout
SQZ2	x	blow out @ 100psi			
SQZ3	Blow out at 50 psi				
SQZ4	mixed, not tested, too thin				
SQZ5	no seal				
SQZ6	x	x	x	x	x
SQZ7	Blow out	x	Blow out		
SQZ8	no seal, completely pushed through				
SQZ9	no seal, completely pushed through				
SQZ10	x	x	Blowout		
SQZ11	x	x	x	x	x

Further testing eliminated candidates as few blends provided successful slot testing across differing base fluid compositions (brine, water, diesel base oil). Squeeze 11 replicated successful results across all base fluids. Figure 5 reveals the back side of a 5,000 micron slotted disk after de-fluidizing and plugging with squeeze 11. Testing indicated weighting up the material with barite offered varying results - often achieving elevated pressures but rarely holding at 1,000 psi.

Figure 5 – Base fluid of the HFLS experimental blend after applying 1,000 psi across a 5,000 micron slotted disk

Concurrent with slot-testing, UCS testing was performed on blends which showed promise. Relative to other experimental HFLS blends tested, squeeze 11 resulted in an elevated UCS of 637 psi (Figure 6).

Figure 6 – UCS testing performed on an optimized HFLS blend, the left image illustrating the material before deformation, and right picture illustrating the material after deformation

Experimental squeeze 11 achieved all required benchmark criteria. Further stress testing was performed in advance of any field trial opportunity. Testing included general compatibility with various field fluids and verification of optimum product concentration (75 lb/bbl). Further product characterization testing was conducted, including loose pack bulk density, specific gravity, and particle size distribution measured by gas pycnometer, pycnometer cup, and sieve screening, respectively (Table 4). The finalized product was given the experimental name EXP 4500.

Table 4: Further product characterization results of EXP 4500 HFLS

Property	Measurement
Dv 10 (µm)	123
Dv 50 (µm)	781
Dv 90 (µm)	2745
Dv 95 (µm)	3283
Specific Gravity (g/cc)	1.57
Bulk Density, Loose Pack (lb/ft^3)	19.15

Design & Product Finalization

Product testing was performed on EXP 4500 samples pulled from full scale blending and production runs to ensure performance matched that observed in development testing. Full product documentation, including an accompanying pumping and hesitation squeeze procedure was generated ahead of any field trial opportunities.

Case History

After cementing up 7-5/8 inch intermediate casing at 9,779 feet, an operator in West Texas began drilling out the 6-3/4 inch production section with oil-based mud. Multiple pills containing as much as 100 lb/bbl of LCM were unsuccessful in achieving the required formation integrity test pressure. Upon review, an approximate 14.2 lb/bbl equivalent mud weight (EMW) was attained at the casing shoe of similar depths in nearby offset wells.

A 50 barrel cement squeeze alleviated the issue, providing an EMW of 14.97 lb/gal and allowing drilling of the lateral section to commence. However, indications of formation breakdown resumed as managed pressure drilling (MPD) backpressure was staged up to 14.2 lb/gal. Despite further aggressive LCM treatments - including various combinations of granular, fibrous, and flake shaped LCM pills - downhole losses increased to 90 bbl/hr.

After more than 35,000 pounds of LCM was pumped and a cement squeeze proved ineffective, sidetracking and well abandonment scenarios were discussed. A squeeze was performed using a blend of conventional LCM with no success. Downhole loss rate persisted at 90 bbls/hr - occurring with an EMW of 13.54 and equivalent circulating density (ECD) of 13.09 lb/gal at the shoe.

As a last resort, a decision was made to pull the drilling BHA and pump a HFLS, EXP 4500, with a bullnose assembly. A 100 barrel pill consisting of 90 lb/bbl EXP 4500 and 30 lb/bbl Nut Plug M was mixed ahead of the hesitation squeeze. Due to pit space limitation, the HFLS was built in a 100 barrel mixing pit using diesel base oil.

The density of the HFLS was increased to 13.0 lb/gal with barite to improve likelihood of placement across the loss zone. The product was placed downhole per operational pumping procedures. Ten hesitation squeezes with EXP 4500 resulted in the ability to hold 1026 psi. After tripping to bottom, no losses were observed with a 13.9 lb/gal equivalent mud weight (EMW) at the shoe. Downhole loss rates increased to 20 barrels per hour once full circulating rates were achieved (14.2 lb/gal EMW at shoe). Another HFLS with 100 lb/bbl of EXP 4500 was pumped, eliminating losses and allowing the casing shoe to withstand the pressures required to reach TD - EMW of 13.97. While drilling ahead, sloughing shale dictated an increase in mud weight and extra pressure was applied with MPD to stabilize the wellbore. Hydraulic modeling indicated pressure at the shoe was approximately 13.7 lbm/gal while drilling to TD. Mud caps were placed in the vertical section while tripping out for wellbore stability. Table 5 summarizes the various attempts to strengthen the intermediate casing shoe and reduce/eliminate downhole losses throughout the well.

Other indications of successful squeeze placement and performance included the improved performance of a normal LCM regimen while drilling - likely improved due to the strengthened substrate/base structure provided by EXP 4500.

The casing run saw surge pressures as high as 14.3 lb/gal at the shoe with only partial losses. No further losses were observed while circulating casing on bottom and cementing the well (Figure 7).

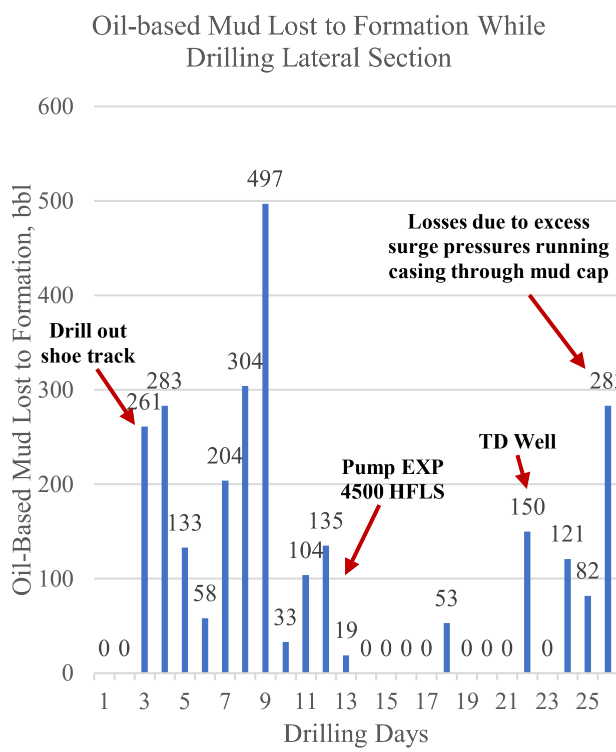

Figure 7 – EXP 4500 HFLS eliminates downhole OBM losses

Table 5: Sequence of events during EXP 4500 HFLS Field Trial

	Pill Description	Pill Volume, bbl	MW, lb/gal	TVD, ft.	EMW, lb/gal	Loss Rate	Notes
Pill #1	50 lb/bbl blend of fibrous, flake, and other composite material	20	12.4	9,682	13.25	Loss rate up to 90 bbl/hr	Squeezed with 427 psi before leakoff. Failed Initial FIT
Pill #2	70 lb/bbl blend of fibrous, flake, and other composite material	30	12.4	9682	13.34		Squeezed with 476 psi held before leakoff.
Pill #3 Pill #4 Pill #5 Pill #6 Pill #7	Continue to squeeze LCM pills of increasing concentration and size, up to 105 lb/bbl	50 - 100	12.4	9682	13.85		Achieved up to 720 psi - not high enough for desired pressure to drill ahead
Pill #8	Cement squeeze	50	12.2	9682	14.97		Achieved highest recorded pressure at 1394 psi. Did not achieve desired 15.0 lb/gal EMW
Drill ahead			12.6	10,877 (MD)	-	80 - 90	Losses more progressive after drilling out curve section and attempting to hold backpressure at 14.2 lb/gal with MPD
Pill #9	50 lb/bbl blend of fibrous, flake, and other composite material	50	12.9	9682	13.54	80 - 90	Well was losing 15 bbl/hr at 52 gpm flow rate and 13.09 ECD at shoe
Pill #10	EXP 4500 (HFLS) at 75 lb/bbl	80	12.9	9682	13.57	80 - 90	Float on BHA failed - POOH to change out float
Pill #11	EXP 4500 (HFLS) at 90 lb/bbl + 30 lb/bbl Nut Plug M	80	12.5	9682	14.2	20	Perform 10 hesitation squeezes and achieved 1026 psi. Trip to bottom and estabish loss rate. No losses at 13.9 lb/gal EMW at shoe. 20 bbl/hr loss rate when increased to 14.2 lb/gal EMW.
Pill #12	EXP 4500 (HFLS) at 100 lb/bbl + 30 lb/bbl Nut Plug M	80	12.5	9682	13.97	0	Perform 18 hesitation squeezes. Achieved 740 psi. Picked up drilling BHA - well holding with an ECD at shoe of 13.60 lb/gal and ECD on bottom of 14.4 lb/gal - no losses observed drilling ahead

Product Commercialization

The successful field trial verified the performance of EXP 4500 as a viable solution. Commercialization strategy included product naming, generation of marketing materials, and pricing guidance for the sales team to provide the product as a cost-friendly solution relative to other HFLS options.

Conclusions

- The development of a new HFLS, composed of an optimized blend of fibers and cellulosic material, achieved all necessary testing criteria. Sealing up to 5,000 micron widths and providing elevated compressive strength to maintain integrity under formation pressures
- Field trial indicates the HFLS product can be weighed up with barite and still provide a successful plug/substrate to improve formation integrity and stop severe losses
- Laboratory test methods enlisted for the development of a HFLS product were verified through successful field application
- Effective mixing, pumping, and placement procedures are essential to field success. Communication across all parties, including product development team, project manager, field personnel, drilling engineer, rig crew, and all others involved is critical for ensuring highest chance of success.

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