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Development of Unique Equipment and Materials with Field Applications to Stop Severe Lost Circulation

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Abstract

The development and testing of lost circulation materials (LCM) in a laboratory is hampered by the scale of the tests, versus the scale of the application in the field. If actual fractures are initiated and propagated, as done in Drilling Engineering Association Project 13 in the mid-1980s, the large test blocks and equipment used are on a "pilot scale" – but are expensive and difficult to manage.[1] If scaled down to a 4-in diameter core, as was done in GPRI Project 2000, "Mitigating Lost Circulation in Synthetic-Base Fluids", the testing becomes more manageable, but remains very time consuming and expensive.[2]

By using an engineering model to estimate large fracture widths, a major drilling fluids company has designed new equipment to simulate sizeable fractures as well as design new materials which have proven in the field to mitigate severe to total lost circulation. The new equipment uses standard industry test procedures and is efficient in screening the best candidates for field evaluation. The design model and lab results are reviewed for two new systems, along with field results from one technology which has proven to mitigate total lost circulation events in the Piceance Basin and Cana Woodford fractured shale formations.

Planning

Controlling circulation loss of drilling fluid during well construction is more than just selecting the proper type of lost circulation material (LCM). A fully engineered approach is required.[3] This approach incorporates borehole stability analysis, equivalent circulating density (ECD) modeling, leak-off flow-path geometry considerations, drilling fluid type and LCM material selection to help minimize pressure effects on ECD, prevent data acquisition interference with on-site monitoring tools such as pressure-while-drilling (PWD), and the assurance of timely applications of LCM treatments. In many cases, the success or failure of LCM will be largely dependent on the decisions taken and methods employed when using the LCM.

Wellbore Stress Management (WSM) services supply engineered solutions designed to reduce drilling non-productive time (NPT) due to lost circulation. A menu of services and tools is available to support the planning and application stages. Specialty software is used during the planning stage, which leads to the application of unique products and systems during the delivery stage. A feasibility study by technology specialists may include a wide range of tools during the planning stage to support data acquisition, modeling and design of its applications.

Planning services include hydraulics and fracture characterization modeling to assess expected ECDs and their effect on potential lost circulation intervals. The fracture characterization modeling for borehole stress treatments uses a module within proprietary engineering graphics software to estimate both the expected fracture width and the particle size distribution (PSD) of the materials required to isolate the fracture tip from pressure transmission – thereby preventing its propagation. Application services may include delivery of specialized LCM and systems in either a preventive (pretreatment and/or borehole stress treatments to strengthen the wellbore) or corrective mode (mitigating lost circulation and, where possible, providing additional wellbore strength).

Prevention

Wellbore Stress Management (WSM) achieves wellbore strengthening by changing the "stress state" around the wellbore. This is done by deliberately allowing fractures to form in the wellbore wall and sealing them with a material of sufficient size and concentration, so that they act as "wedges" to compress the rock within a zone around the wellbore, increasing the "Hoop Stress."[4] The sealing particles must prevent the fracture from closing near the fracture mouth, and they must seal sufficiently to provide fracture tip pressure isolation to prevent fracture propagation. Provided the induced fracture is created and sealed at or close to the wellbore, then an increased hoop stress is established around its circumference.

Fracture Size

Fracturing theories can be used to estimate the fracture width/length for a given rock type and pressure regime. Rock mechanics modeling has been developed which enables certain fracture widths to be estimated. This modeling uses the change in stress state around the wellbore and can relate the fracture width to the rock elastic properties for a given set of conditions.[5]

In the model, the calculation of the fracture width (W_f)

takes into account the in-situ stresses as well as factors such as Static Young's Modulus and mud ECD. By varying near wellbore fracture length (R), the fracture width can be calculated. To effect good wellbore pressure confinement, the fracture length (R) is limited to within a few inches of the wellbore circumference. Delta P is the differential pressure held by the sealed fracture, as seen in **Eq. 1**.

$$\Delta P = \left(\frac{\pi}{8}\right) \times \left(\frac{W_f}{R}\right) \times \left[\frac{E}{(1-v^2)}\right] \quad\text{...............} 1$$

ΔP = excess pressure within the fracture
W_f = fracture width
R = fracture radius
E = Static Young's Modulus of formation
ν = Poisson's ratio of formation

How and Where Is the Fracture Sealed?

Particle size distribution (PSD) of the combination of sealant materials should be such that its d50 (preferred) or d90 equals the predicted fracture width, thereby bridging at or just inside the point of fracture initiation. To manage data uncertainty, the particle size distribution would be set with the d50 equal to the predicted fracture width. This may provide a sufficient amount of material both larger and smaller than the estimated fracture width to still obtain a seal.[3] The seal should not allow pressure transmission behind the bridge which would allow fracture propagation. Pressure should be able to be bled off into the formation. Therefore these techniques work best with higher permeability formations and/or zones with a high fracture density.[6]

Mitigation of Severe Lost Circulation

Resilient Lost Circulation Material Development

Effectively controlling lost circulation (LC) is more than just selecting LCM; it requires an engineered approach. Particulate LCM like ground marble, graphitic carbon and cellulosic fibres have been widely used, but careful consideration must be given to how these materials are combined based on fracture types. Induced fractures created when the ECD exceeds the formation fracture gradient or during wellbore strengthening applications could be "pressure-sensitive" – as reported in fracture closure studies.[7] Resilient graphitic carbon (RGC) has many unique properties that can be exploited in lost circulation scenarios.[8-10]

Resiliency associated with RGC can be enhanced in an LCM combination that exhibits a granular nature, rather than forming a solid plug. RGC also imparts crush resistance to other more brittle LCM and can help reduce attrition of lost circulation seals, thereby retaining particle size for effective wellbore strengthening, while also acting as a solid lubricant.[11]

RGC is manufactured in a proprietary two-stage furnace process that produces 99.9% carbon content. It is a conductive material with no magnetic properties, so it does not interfere with logging tools (e.g., density and neutron) or other downhole equipment. RGC is suitable for use in reservoir sections because it is completely inert and can be combined with acid-soluble ground marble.

Resiliency is defined in **Eq. 2**, where 'H_r' and 'H_c' are defined in **Figure 1**. Examples of the resiliency demonstrated by different graphitic materials are shown in **Figure 2**.

$$\%Resiliency = \left(\frac{H_r}{H_c} - 1\right) \times 100 \quad\text{.................} 2$$

New Laboratory Tools for LCM Analysis: Constant Area Slots, Tapered Slot and a Modified Receiver for the Particle Plugging Apparatus

Tests were first performed on the permeability plugging apparatus (PPA) with constant area slots. Fluid loss and breaking pressures for various combinations of LCM were recorded when used in water-based mud. In straight slots, particles seal at the face, as seen in **Figure 3**. The LCM particles were observed to be sitting on the face of the fracture, which can be eroded due to shear stress of the drilling fluid. Considering this aspect, a tapered slot was designed and fabricated so tests could be performed so as to evaluate the effectiveness of various LCM to seal *within* the induced fracture.

The purpose for designing and building the new tapered slot is to evaluate the performance of the LCM using a media that more closely resembles an induced fracture. Using the tapered slot in the PPA tests, it is expected that the LCM particles should form an immobile mass inside the slotted media. Once the bridge formed inside the slot, tests were performed to determine the breaking pressure of the plug. A comparison was done to benchmark the performance of the new tapered slot. Tests were done on different size constant area slots/straight slots and the tapered slot. As the tapered slot varies from 2500 microns at the opening to 1000 microns at the tip, the fluid loss value observed was in-between the smallest and the largest size of the constant area slots. This indicates the effectiveness of the tapered slot.[8]

A second unique piece of equipment was designed to accommodate the large particles which pass through the slots wider than 1000 microns. This is a modified PPA receiver with a larger bore between the PPA cap and the elongated reservoir, as shown in **Figure 4**. This receiver includes a pressurization port for use with high temperature testing when steam formation is a hazard.

Engineered Combinations of LCM

By combining past experience with the ability to model the particle size distribution of LCM mixtures, unique blends containing optimized types and sizes of LCM have been formulated. Two technologies have been recently developed, each with an optimized particle size distribution (OPSD). The OPSD is validated by laboratory data showing efficient sealing of 500 to 3000 micron constant area slots, as well as the tapered slot (**Appendix 1**). Specifically speaking, this

effectiveness in sealing such a wide range of fracture sizes is possible due to an optimized *multi-modal* PSD design for the suite of material types (**Figures 5** and **6**).

ECS-1 LCM

ECS-1 LCM, shown in **Figure 7**, is a particulate-based "engineered-composite solution" (ECS) that is designed to mitigate partial to severe drilling fluid loss rates. The composition of ECS-1 LCM is formulated to comprise specific materials with precise sizes at a unique engineered concentration. This can save the operator from incurring more NPT while mixing the individual components of the blend. The multi-modal composition is designed to provide superior fracture sealing performance in zones with severe drilling fluid losses.

The novelty of the ECS-1 lost circulation technology is not only due to its ability to isolate the tip of the fracture. The individual additives of its formula have been designed to synergistically create a composite with an increased degree of "toughness" over other lost circulation solutions that are used today. This is an important materials science property that lost circulation seals should have, as it should resist pressure fluctuations commonly encountered downhole such as swab/surge pressures, wellbore breathing, and mechanical abrasion from the drill string and bit. The OPSD of ECS-1 LCM is designed to plug a wide range of fracture sizes which cause mild to severe lost circulation. It is designed to be compatible with all fluid types. Pills with concentrations of up to 80 ppb have been successfully pumped through typical drill strings and applied in the field.

While the formula for ECS-1 LCM is proprietary, the components are common in the industry. This allows for the material to be priced at a competitive cost, while supplying superior fracture sealing. It has been lab tested and field validated to provide an optimized multi-modal solution to lost circulation that is able to seal fractures and then manage fluctuations of downhole pressure.

The PPA data shown in **Figures 8** and **9** demonstrate the more effective fluid loss control for ECS-1 LCM versus a commercial product in both water- and synthetic-based fluids. This comparative analysis was performed over a wide range of fracture widths (1016μm, 2032μm and 2540μm). The superior fluid loss performance of ECS-1 LCM vs. "Competitive Product A" LCM is even more notable considering that the pressure differential for the ECS-1 technology was 1000psi while it was only 500 psi for the competitive material (as this was the highest differential pressure this particular product could resist before failing). This effectiveness has been further demonstrated in field applications.

ECS-2 LCM

ECS-2 LCM, shown in **Figure 10**, is an ECS designed to mitigate partial to severe drilling fluid loss rates, while strengthening the wellbore with a sustained increase in hoop stress. The ECS-2 technology provides many of the same fluid loss attributes as the ECS-1 product, as shown in **Figure 11**, but also contains specialty additives (RGC) that impart "resilience" to the "tough" lost circulation seal. The high resiliency of the ECS-2 material is particularly suited for depleted zones where fracture closure stresses are typically substantial and differential pressures are high. The increased resistance to higher differential pressures is shown in **Figure 12**.

Field Applications

Piceance Basin Applications

An operator was experiencing severe lost circulation while drilling the intermediate section of a shale-gas well in the Piceance Basin, an area known for problems associated with significant drilling fluid losses. This section is made up of highly fractured and drawn down formations. These formations consist of the Wasatch G, Wasatch I and the Ohio Creek, all of which have been produced for many years.

Because the high drilling fluid losses could not be prevented due to natural fractures throughout the entire intermediate section, the operator chose to pump dedicated mitigation LCM pills via sweep every time the dynamic fluid loss exceeded 100 bbl/hr. In this particular scenario, the so-called "Competitive Product A" LCM was first attempted by the operator multiple times with little to no success. ECS-1 LCM pills (80 lb/bbl) were then mixed, pumped through a drill string and bit (equipped with 6 X 13/32" nozzles) and applied several times (**Figure 13**) throughout the length of the problematic zone – each time significantly reducing the loss rate – until total depth was reached.

These applications allowed the operator to save costly NPT, as well as saving time when mixing the individual pills. Drilling was never stopped to mix the ECS-1 technology, as it had been with previous LC pills, because the technology is delivered as a multi-component blend in one sack. A total of 7 hours of mixing time was saved, and the ECS-1 solution cost 42% less than the same amount of the competitive product. Therefore, in addition to the cost savings of valuable drilling fluid, the reduced price for LC mitigation materials resulted in savings of over $20,000USD per LCM pill to the operator.

Texas Panhandle Application

After landing the curve at 90° in an 8 ¾-inch Granite Wash well in north Texas, an operator experienced complete lost returns. An 8.1 lb/gal non-aqueous fluid (NAF) invert emulsion system was being used while drilling with a 6 ½-inch turbine assembly down hole. After several attempts with third-party LCM squeezes, no circulation improvement was observed. A 50-bbl NAF pill containing 80 lb/bbl of ECS-1 LCM was mixed and pumped through 5-inch "dumb iron" drill pipe at 118 gal/min and bit (equipped with 4 X 14/32" & 2 X 12/32" nozzles) and spotted at 11,680 feet MD.

The pill was allowed to soak for 7 hours before shutting the wellbore in and pressuring up to 100 psi for 1 hour. After bleeding the pressure off of the well, they began slowly raising the pump pressure until they were able to resume drilling with full returns. The operator was able to complete the well without having to pull out of the hole (POOH) to remove the

bit, nor performing costly cement squeezes or setting a 7-inch liner. The well was drilled to a total depth of 16,800-ft MD within 10 days of first incurring the initial severe losses to the wellbore.

Cana Woodford Shale Application: Horizontal Well

An operator in the Cana Field was in the process of drilling a well with a projected MD of 18,086 feet – including a 7,500-ft lateral – which was their longest lateral to date in the field. A bit trip was made in the lateral with a 13.1 lb/gal NAF diesel based system at a MD of 12,204 feet and a TVD of 10,714 feet. Once on bottom, severe LC was encountered. A 60-bbl (20 lb/bbl) pill of a competitor's product was pumped with no improvement in returns. A second pill was then pumped with 40 lb/bbl of the same LCM with no improvement. The concentration of the competitor's product was limited to ensure it could be pumped through the tight clearances of the directional tools. The decision was made to POOH to 10,100 feet with no returns and to lower the fluid density to 12.5 lb/gal.

Due to the success with ECS-1 LCM in similar formations, the advantages of the product were discussed with the operator. The first question raised was cost, which turned out to be less than the cost being paid for the competitor's product. The decision was made to use ECS-1 LCM, the one-sack solution containing engineered particle types and sizes. The plan was to fill the open hole section with an 80-lb/bbl pill and wait 8 hrs. The 80-lb/bbl pill was pumped successfully through a BHA that included a 6 ¾-inch motor, an MWD tool with pulser restriction that had a nominal ID of 1.92 inches and a suggested maximum LCM limit of 40-lb/bbl, and bit (equipped with 7 X 16/32" nozzles).

The pill was allowed to soak in the open hole section for 8 hours; upon completion of the waiting period, they began to run in the hole, circulating with full returns. Subsequent preventive LC pills of 50 bbl containing 80-lb/bbl of the ECS-1 material were pumped and swept through the open hole every 1,000 feet. Once on bottom, they circulated bottoms up with full returns and returned to drilling with no losses.

A total of 943 bbl of NAF was lost prior to the pumping of ECS-1 LCM with zero losses after its applications. The ability to pump ECS-1 LCM through the directional tools saved the customer from having to POOH to remove the bottom hole assembly. The directional tools would normally have had to be laid down to pump coarse LCM that is traditionally used for severe losses – resulting in added drilling NPT and, therefore, additional cost for the operator.

Monitor Severe Lost Circulation Treatment Applications for Continuous Improvement

In order to drive continuous improvement for customer service, a new "Lost Circulation Report for Pill Applications" has recently been introduced for use in all applicable operations around the world (**Figure 14**). The standardized data collection form has been designed to capture key criteria surrounding the application of engineered lost circulation pills that are deployed to mitigate significant drilling fluid losses.

This new tool is technically efficient and user friendly, and designed to be quickly completed on location at the time of each LC pill application. The drilling fluids specialist uses the template to electronically record the operational details surrounding major LC pill applications. The database provides a means of tracking the historical use of engineered technologies on a global basis.

The new report presents significant advantages to operators. By capturing key criteria at the time of each application, the service company delivers more details regarding the past use of specific lost circulation solutions. In addition, the database for the global report is used internally to help direct future research developments.

Conclusions

- The fundamental understanding of how to mitigate lost circulation was covered by Messenger[12] in 1981, but engineering improvements are still possible as demonstrated in this work.
- New materials are always of interest, as well as understanding the fundamental material properties and how this affects efficiency and "toughness" of the composite seal once placed in the flow path.
- Prevention still remains a significant goal but, realistically, that is not always possible. Thus, planning and quick implementation of a mitigation strategy remain effective tools in the reduction of drilling NPT caused by lost circulation.
- A major hurdle to mitigation of lost circulation exists in a great portion of the hydrocarbon bearing world; namely, how to effectively manage lost circulation in naturally fractured formations that result in the most severe drilling fluid loss scenarios.
- Particulate solutions are seldom effective and chemical sealants are only effective when they are not over-displaced from the wellbore.
- The door is still open for the combination of better material systems and engineering practices for these applications.

Acknowledgments

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Appendix 1: Laboratory Protocol for Evaluating LCM

Base Fluid

In order to maintain the quality and consistent properties of base fluid throughout a test series, it is recommended to prepare enough fluid to be used during one week of testing. The procedure for preparing our base fluid is a follows: add citric acid to the mix water to adjust the pH to 4; then add 1.75 g of a dispersible xanthan polymer for each 350 ml of mix water. Let the mixture stir for an hour. Adjust the pH back to 9.0 using NaOH. Add 0.5g of a biocide for each 350 ml of water and mix for an additional hour using a medium shear mixer. **Table 1** shows the nominal rheological properties for the base fluid. Initially, only 1.25 ppg of polymer was used in the base fluid, but settling of solids in the PPA tests at 250 deg F required a higher concentration.

Fluid Loss Tests

Initial screening tests for ECS-1 LCM and ECS-2 LCM were conducted on a 2540 micron slotted disk in a PPA at 75 °F (24 °C) and 1000 psi pressure differential using the 12 lb/gal fluid above. Those formulations selected for further study were evaluated in a second set of tests run with the same base fluid, but using constant area slotted disks with opening widths of 500, 1000, 1500, and 2000 microns and the tapered slot. A third set of tests were conducted at 150 °F (65 °C) and 250 °F (121 °C) and the overall mass of fluid that flowed through the slots was determined at the end of the 30-minute test. (It should be noted that other slot sizes may be used for specific field-related projects.)

Finally, a series of tests under the same conditions of temperature and pressure were run on different types of drilling fluids that were maintained as standards. These were a 12.0 ppg dispersed water-based fluid, fresh water non-dispersed fluid, salt water non-dispersed fluid and a non-aqueous fluid, respectively.

Tables

Table 1 Rheological properties of fluids

Dial Readings	Low-density xanthan	12 ppg xan-than gum	12 ppg modified polymer
600 RPM	39	54	117
300 RPM	31	45	92
200 RPM	27.5	40.5	74
100 RPM	23	34.5	54
6 RPM	17	21	23
3 RPM	13.5	19.5	21
PV, cP	8	9	25
YP, lb/100ft^2	23	36	67
n,	0.575	0.371	0.455
K, lb*s^n/100ft^2	0.473	3.128	4.721
τ_0, lbs/100ft^2	14.34	13.88	9.57
10s gel	13	18	24
10m gel	15	21	63

Figures

Figure 1 Test sequence for determining resiliency
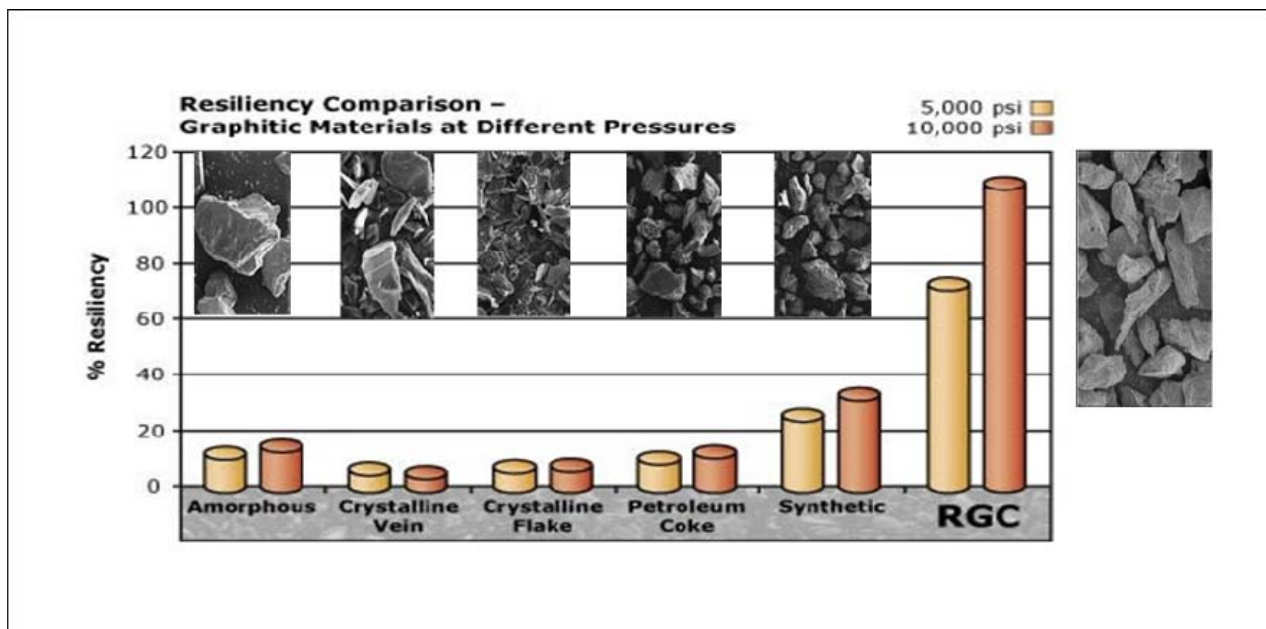
Figure 2 Resiliency results of various graphitic materials
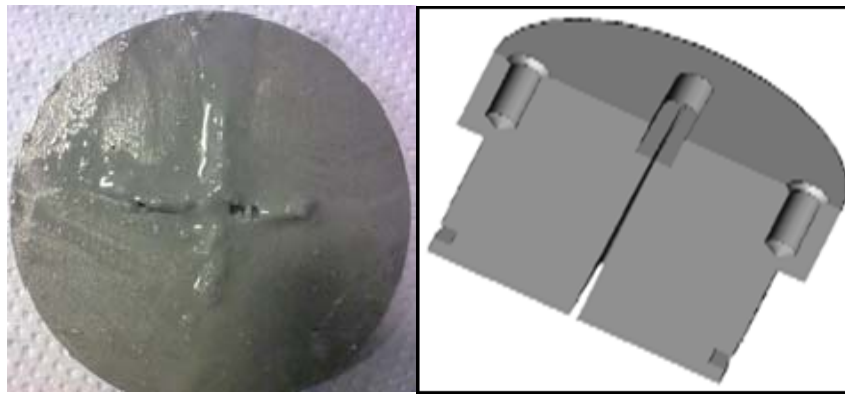
Figure 3 Images of constant area and tapered slots, respectively
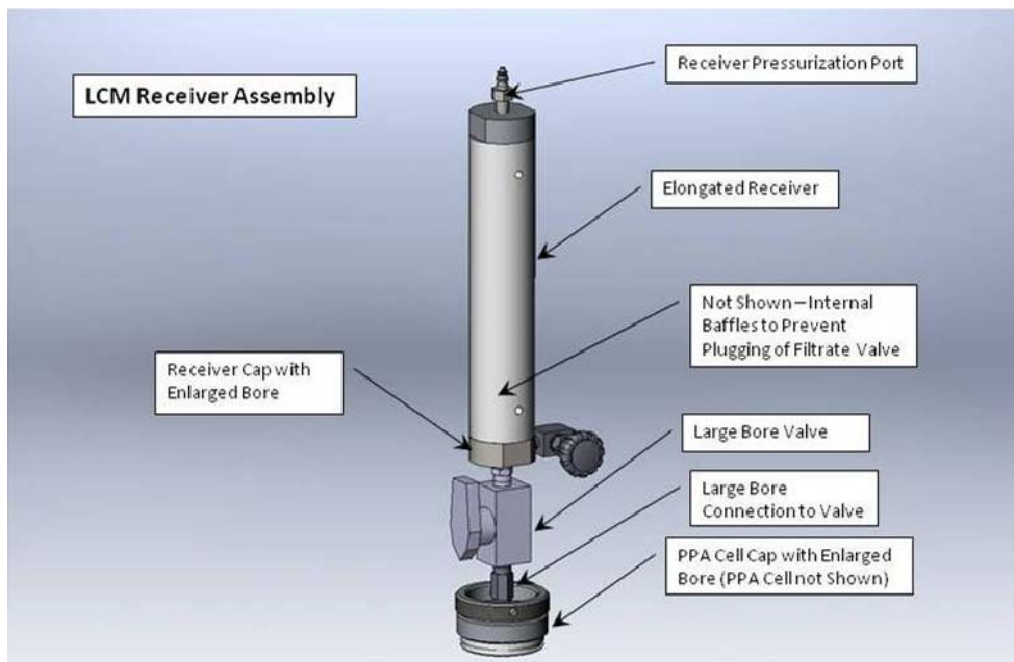
Figure 4 Modified PPA receiver for accommodation of large LCM particulates
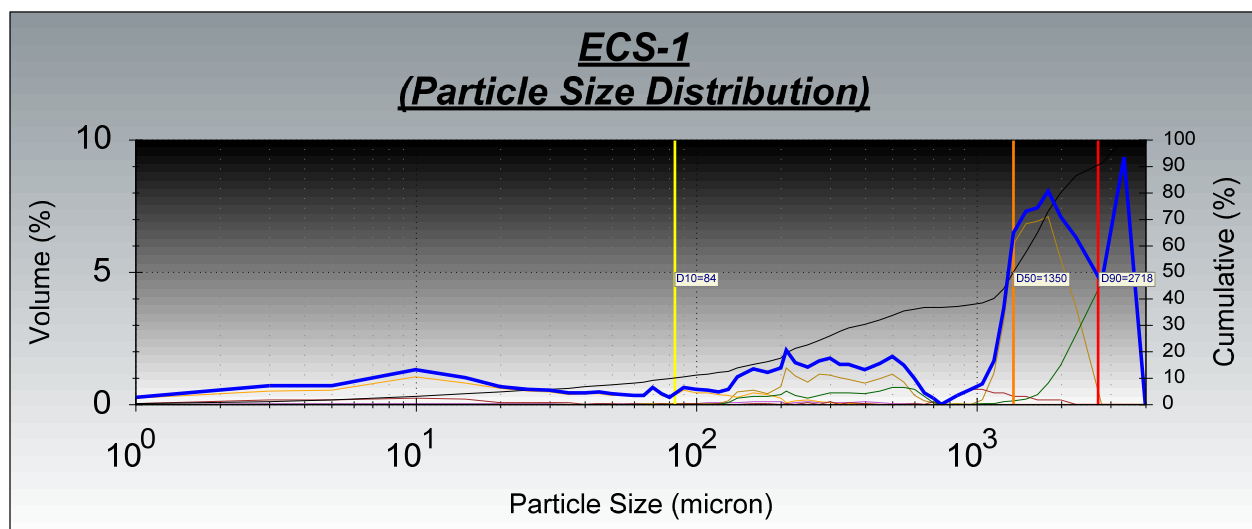
Figure 5 Multi-Modal PSD of ECS-1 LCM
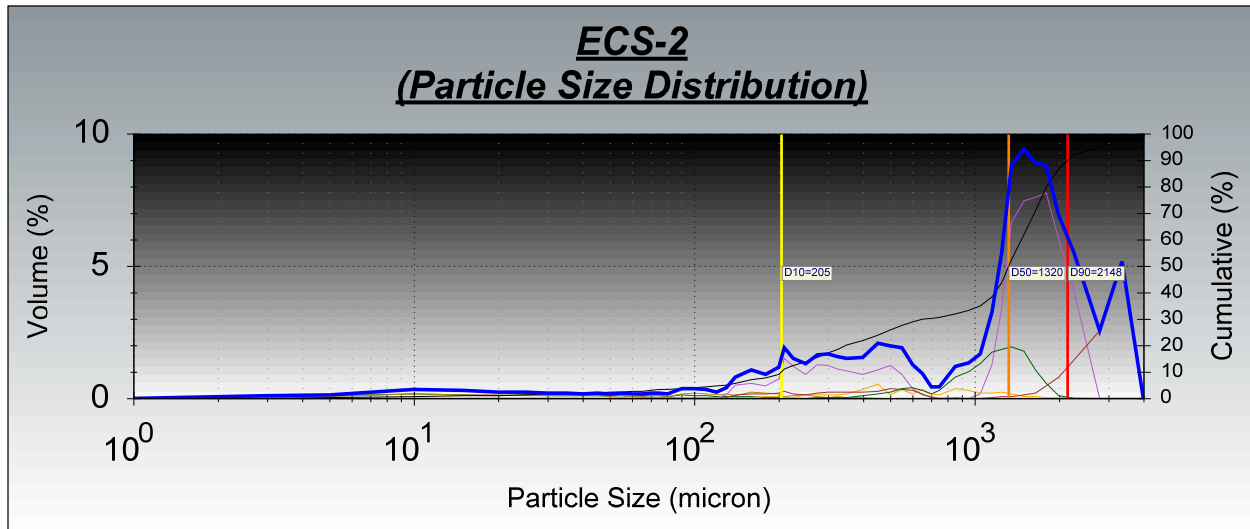
Figure 6 Multi-Modal PSD of ECS-2 LCM

Figure 7 ECS-1 LCM
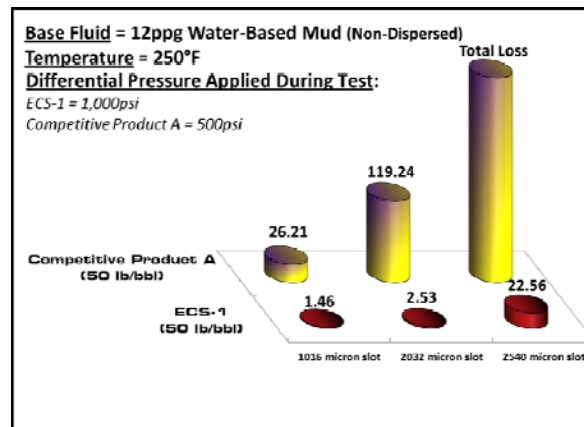
Figure 8 PPA data (total fluid loss in grams) for ECS-1 LCM vs. "Competitive Product A" LCM in non-dispersed water-based mud
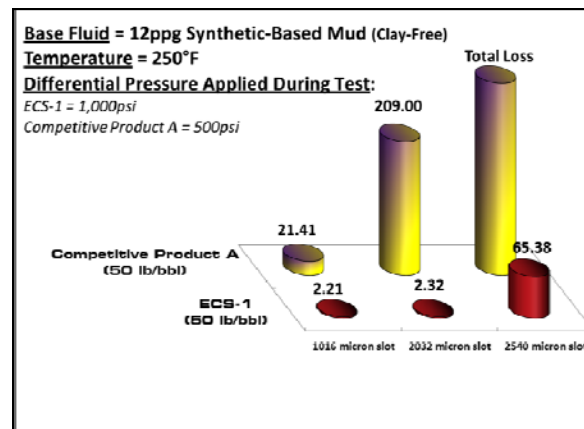
Figure 9 PPA data (total fluid loss in grams) for ECS-1 LCM vs. "Competitive Product A" LCM in clay-free synthetic oil-based mud

Figure 10 ECS-2 LCM
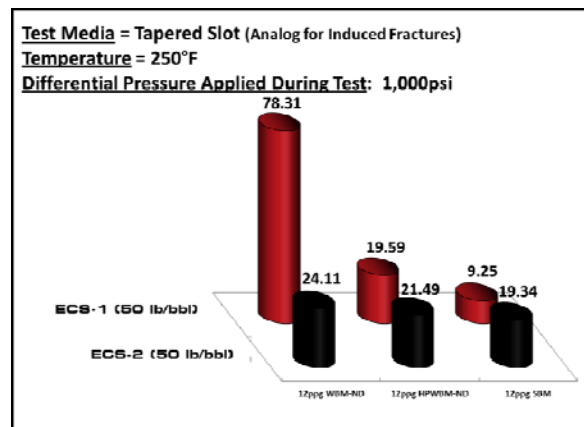
Figure 11 PPA data (total fluid loss in grams) for ECS-2 LCM vs. ECS-1 LCM in various drilling fluids
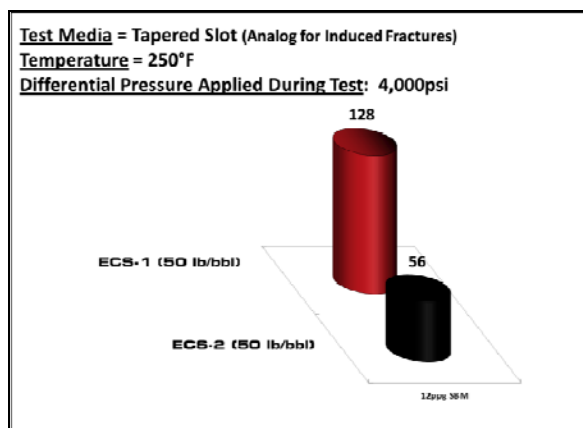
Figure 12 PPA data (total fluid loss in grams) for ECS-2 LCM vs. ECS-1 LCM at a higher differential pressure
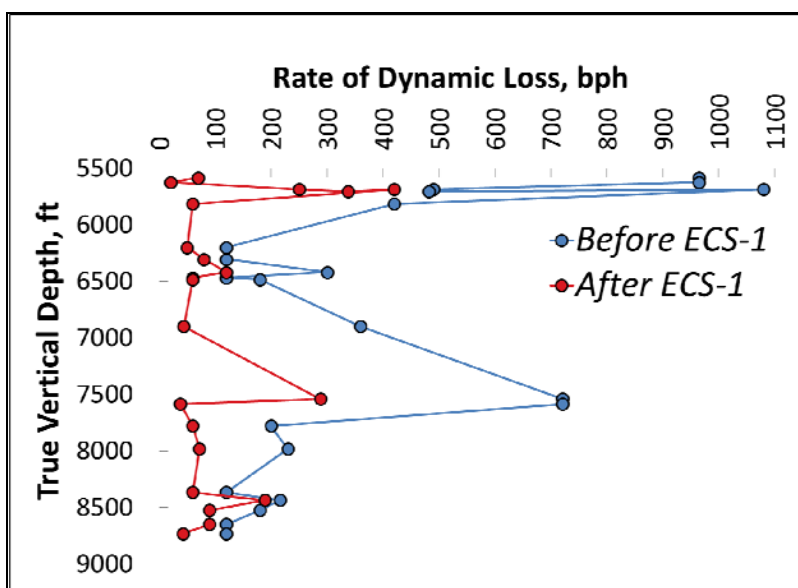
Figure 13 Reduced dynamic loss rates in the Piceance Creek Basin, per application of ECS-1 LCM

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Lost Circulation Report for Pill Applications

http://sphou/sites/KMBaroid/LCRPA/default.aspx

Well Location Information

Date:		Country:	
Rig Name:		Territory/State:	
Mud Report #:		Field/Block Name:	
Pill/Treament #:		Well Name:	
Mud Engineer Name:		Rig Type (choose one):	○ Land　○ Offshore

Mud Properties

Attach Most Recent Mud Report (at Time of Pill Application)

Drillstring Component Description

Attach Most Recent BHA Report (at Time of Pill Application)

Lost Circulation Material - Pill Application Plan

Product User (Customer Company Name):

Product Service Provider (Service Company Name): ○ Baroid　○ Other

Primary Product Name in Pill (if applicable):

Pill Type (choose only one):		Pit Size (Total Volume Capacity):		bbl
○ Particulate ○ Chemical Sealant ○ Combination		Overall Pill Volume:		bbl
Base Fluid for Pill (choose only one, if applicable):		Overall Pill Concentration:		ppb
○ Fresh-Water		Pill Density:		ppg
○ Brine ○ Water-Based Mud	Mud System (Name)	Agitator(s) in Pit?:	○ Yes ○ No	
○ Synthetic Oil ○ Oil-Based Mud		Thinner Used?:	○ Yes ○ No	
○ Mineral Oil		De-Foamer Used?:	○ Yes ○ No	
○ Diesel ○ Other		PBL-Sub Used?:	○ Yes ○ No	

Spotting Method (choose only one):	Pump Type Used to Spot (choose only one):
○ Hesitation Squeeze ○ Sweep/Circulate	○ Mud Pump
○ "Pump and Pull" ○ Other	○ Cement Pump

Well Specifications at Time of Pill Application

Last Casing Size (ID):		in
Last Casing Shoe Depth (MD):		ft
Last Casing Shoe Depth (TVD):		ft
Open Hole Length:		ft
Open Hole Diameter:		in
Open Hole Volume:		bbl
Most Recent Formation Integrity Test (FIT):		ppg
Bottom Hole Temperature (circulating):		°F

Evaluation of LCM Pill Application

Rate of Loss Before Pumping Pill static:		bph
Rate of Loss After Applying Pill static:		bph
Rate of Loss Before Pumping Pill dynamic:		bph
Rate of Loss After Applying Pill dynamic:		bph

Loss Zone Information (at Time of Pill Application) - if known

| Formation Type (choose only one)	Formation Name:	Permeability Classification	Loss Source (choose only one):
○ Sand ○ Dolomite		○ High (> 5mD)	○ Vugular/Cavernous
○ Shale ○ Limestone		○ Low (< 5 mD)	○ Fractured
○ Silt ○ Other			○ High Permeability (Matrix)

WellSET® Information (at Time of Pill Application) - if known

Suspected Depth of Loss (TVD):		ft
Young's Modulus:		psi
Minimum Horizontal Stress:		psi
Equivalent Circulating Density (ECD):		ppg
Poisson's Ratio:		
Median Permeability:		mD

Additional Comments (Activites Prior/During/After Loss)

Lost Circulation Material - Pill Formulation Plan

Identification of Individual Ingredients in Pill

Primary Product Name in Pill		Concentration	Unit
			ppb
			ppb
			ppb

Additional Component Name (if applicable)	Concentration	Unit
		ppb
		ppb
		ppb
		ppb
		ppb
		ppb
		ppb
		ppb
		ppb
		ppb
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		ppb
		ppb
		ppb

Lost Circulation Material - Hesitation Squeeze Details (if applicable)

Per squeeze, monitor for increase in pressure over time

Time (00:00:00)	Pump Strokes	Drill Pipe Pressure	Unit	Surface Pressure	Unit
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
			psi		psi
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HALLIBURTON | Baroid

Figure 14 Lost Circulation Report for Pill Applications