

Addressing the Challenges of Lost Circulation Using Novel Chemistries, Test Equipment and Data Science Tools

Ahmed Amer, Newpark Fluids Systems, Arthur Hale, Aramco Service Co. & Saleh Al Haidari, Aramco Oil Co.

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Abstract

In today's oil and gas drilling industry, lost circulation remains a key contributor to non-productive time and added well costs. A significant challenge to lost circulation prevention and mitigation is choosing the appropriate products from those available on the market. Rather than a shortage of such products, the industry suffers from an overabundance of lost circulation materials (LCM); the majority of which are variations of a few non-innovative types.

Current research and development efforts should be focused on unique and novel solutions that deliver performance in the field. Fast tracking LCM deployment in the field can facilitate the availability of technologies that are more suited to regional challenges and curing the lost circulation mechanism prevalent in each basin. Testing, modeling and implementing various solutions in the field is challenging as neither test equipment, data, or preferred products may be available at the rig site, nor are they standardized in the industry. Difficulties associated with testing includes the scalability of temperature, volumes, and flow profile variabilities from the lab to the field. In addition, field implementation is hindered by the absence of sufficient data to arrive at the correct solution.

Simplified testing methods, statistical analysis, and machine learning can shorten the time needed to arrive at a solution. The authors are suggesting a solution-based categorization approach to this problem that integrates loss rates and loss mechanisms and links them to the solution having the highest probability of success.

Data science can address these challenges by capitalizing on learnings acquired from previous wells and the effectiveness of various solutions suggested.

Introduction

Lost circulation remains a key contributor to non-productive time and added well costs. The cost ranges from thousands of dollars of lost fluid to millions of dollars when considering loss of well control, loss of the well, and above all, the rare but tragic, loss of life. Lost circulation is a major contributor to non-productive time (NPT) and flat time. It affects planning and execution of the next wells (e.g., batch drilling) and limits drilling performance in terms of rate of penetration (ROP) versus sustainable losses rate. Last but not least, lost circulation can impact hole cleaning, wellbore stability, surge-and-swab pressures, well control, the plugging of wells, etc.

Even though there are hundreds of products and multiple strategies focused on solving lost circulation, there are few that are based on proven science and engineering associated with remediation. Most LCM products are variations of a few general classes. Categorization or classification of LCM has seen several attempts over the years going back to Robert White in 1956, Joseph Messenger in 1981, and Alsaba and Nygaard in 2014 who developed 7 categories of LCM based on appearance and application as: granular, flaky, fibrous, mixtures, acid/water soluble, high-fluid-loss squeeze, swellable/hydratable combinations, and nanoparticles. More recently the classification was updated by categorizing LCM in the context of losses per hour – seepage losses being up to 6.3 bbl/hr, partial losses up to 63 bbl/hr, severe losses being greater than 100 bbl/hr, and total losses being no returns (Alkinani et al. 2018).

Although we can categorize the products associated with the types of wellbore inconsistencies – natural including non-sealing faults, induced fractures from over-pressurizing the wellbore (surge pressures, depleted zones with reduced fracture gradient), unconsolidated and/or highly permeable zones, and large aperture fractures and/or cavernous formations – remediating or even mitigating losses is still an art rather than a science in most cases.

Rates of loss of whole fluid into a formation, while circulating or not, is data that is used to characterize treatment approaches. This rate is typically not based on the geometric dimensions of the loss zone. Classifying a loss rate has minimal contribution to what the fracture looks like or how many fractures exist in that loss zone. Without other geo-mechanical data such as Mechanical Earth Models, the loss rate itself tells us nothing about the width, length or extent of the fracture. However for the most part, our techniques for remediating a fracture are based upon bridging strategies. It is the lack of this fundamental information that ensures that our ability to remediate losses will remain an art with approaches requiring wide ranges of particle sizes and types of materials in hopes that something is the right size to fit the fracture.

If offset data is available, then the next well should have some reasonable estimate of what worked and what did not and at what interval. Although this seems reasonable, many times the rig data as to volumes lost, products utilized, and volumes consumed are not well documented. However, this data issue, as documented by Alkinani and Al-Hameedi in multiple publications, does not completely remove the ambiguity of

defining the size, nature and scope of the loss zone. Wells from the same pad or platform, but in different directions, may have totally different stress states and stress distribution, and maybe even formation differences depending on up-dips and down-dips in the rock and governing faulting regime. For offset data to be useful, a large amount of data must be collected from potentially a large number of wells including: formation type (shale, sand, carbonate), directional azimuth and depth, stress orientation, depletion status, with or without natural fractures or faults, location of loss, volume loss, loss rate, drilling parameters (ROP, ECD, mud type, mud properties, surge swab pressures, circulating rate), well and drillstring geometries, etc.

One of the consequences of real-time monitoring and data capture during drilling operations is that much of the data needed for quality data analytics and modeling can now be collected without bias. With the adoption of data analytics and modeling, real estimates of the probability of losses can be made with equal opportunity to project what solution or strategies can be utilized to mitigate or remediate lost circulation.

Recently, several new technologies have been developed that can be used to address some of these lost circulation challenges. These technologies utilize viscosity, plugging, unique metallurgy, and reaction chemistries that result in forming high-compressive-strength seals to fractured zones. These technologies need more work to determine where and when they should be applied. Combined with new tools such as data science and modeling, these technologies, when applied under the right conditions, can mitigate and reduce the impact of lost circulation on drilling operations.

LCM Categorization

One would expect over time, the LCM industry would go through various metamorphosis stages to end up with fewer products that work better. In reality, the classifications have changed a few times over the years, but the actual number of products remains relatively the same. The large number of available products makes the case that groundbreaking technology is indeed what the industry needs to address this challenge and maybe move to novel solutions that are better-performing and hence leading to fewer products.

Looking at the efforts to categorize the LCM into various sets provides some context to understanding LCM usage and where efforts have been focused historically (Figure 1).

By Type

Fibers: Fibers are rarely used as a single LCM. They usually are applied in combination with flake and granular materials. Typically, these combinations are used for severe to total losses but can be applied for partial losses if other strategies do not work. These combinations ensure a wide particle size distribution. Figure 2 shows a typical fiber LCM.

Flakes: Like fibers, flaky materials (Figure 3) are not used alone and typically are applied during high rates of mud loss. Since flakes bridge with other materials, they may be used in combination with fibers and granules for high lost circulation rates and with granules for partial to high seepage rates. These

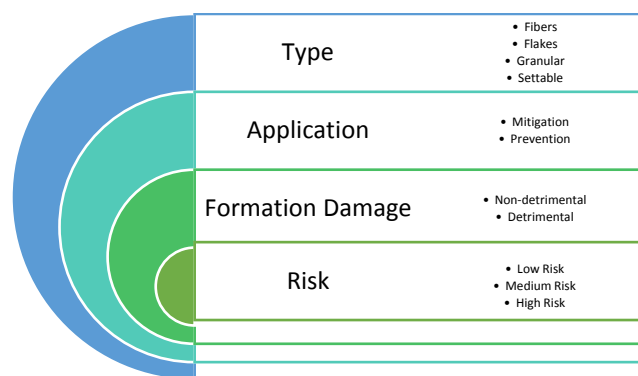


Figure 1 – Classifications of lost circulation materials.



Figure 2 – Typical fiber used as LCM.



Figure 3 – Flake lost circulation material.

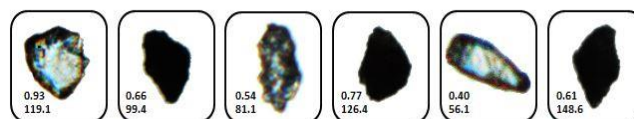


Figure 4 – Granular material with typical variance in size and shape.

combinations typically utilize a wide particle size distribution.

Granular: These materials are typically always associated with seepage to partial losses events. Often granular LCM (Figure 4) are run alone with a wide range of particle size distributions.

Settable Fluids: These fluids change to a solid state when stimulated by an external stimulant from the surrounding environment such as pH, temperature, salinity, or by undergoing a chemical reaction with an activator or a cross-

linker (Figure 5). They are typically used when the loss rates and the fracture geometry are beyond the practical limit of fibers and granular material.



Figure 5 – Solid material formed from settable LCM.

By Application

Mitigation: For obvious reasons, most of the focus of LCM usage is directed to remediation. However, mitigating or eliminating losses is a negative observation and is hard to prove the LCM was effective. That being said, mitigation is a viable strategy when used properly. Mitigation treatments typically use a particle size range of granules that can bridge small fractures near the wellbore. The strategy takes advantage of the hoop stresses created by being overbalanced and maintains these increased hoop stresses by stopping or reducing the creation of wider and longer fractures.

Mitigation also plays a role in plugging natural fractures assuming that the opening is not large and poses the low risk of partial to seepage losses. Utilization of particulates with a wide particle-size distribution can mitigate the loss substantially. A wide range of chemistries have been tried ranging from precipitated silicate to granulate rubber and marble.

Prevention: Most recently strategies have been researched that prevent the development of fractures. The approach is focused on preventing pressure communication into the formation. Much of this approach has recently been focused on various types nanoparticles (silica based, calcium carbonate based, metals, etc.), and precipitated silicate as well as larger granular particle blends.

Probably the best example is casing drilling with water-based muds. As discussed by van Oort (2014) the phenomenon called casing smearing has resulted in lowering the risk for lost circulation. There are three possible mechanisms that can result in improve stabilization:

- Wellbore Stress Augmentation (WSA) – increasing the hoop stress or closure stress which in turn increases the apparent fracture gradient
- Solids plugging of the fracture tip, thus decreasing the propensity for fracture propagation
- Wellbore Face Sealing (WFS) – sealing the wellbore face to stop fracture growth from invasive wellbore fluids. Smearing is one form of WFS.

All three mechanisms have been observed in other strategies minimizing lost circulation. Which mechanism is

dominant is most likely dependent on the formation, materials, and strategies.

By Formation Damage Criteria:

Non-detrimental: Most of the formations drilled, with the exception of conventional reservoirs, certain injection zones, and other client-defined formations, can tolerate formation damage due to the fact that they are either non-producing or will have to be treated after drilling where the damage will be reduced or eliminated.

Detrimental: The major challenge in controlling lost circulation in the reservoir is the added challenge to block fluids from entering the formation while not interfering with recovery of valuable hydrocarbons flowing from the formation. There are almost no lost circulation remedies for the reservoir. Calcium carbonate (granular or flake) is about the only material available that can mitigate loss and then be removed with acid prior to production. Acid-soluble pills, such as cross-linked Hydroxy-Ethyl Cellulose and Borate-polymer acid-soluble pills can be used, but typically they are applied only when losses are in the partial to severe range. Table 1 shows the acid solubility varies by LCM product and temperature. The reservoir is an area in lost circulation research where much more work needs to be done to find non-damaging and degradable materials.

| Table 1 – Acid Solubility (%wt) | | | |
|---------------------------------|----------------|--------------------|-----------------|
| Product | Granular Blend | Spun Mineral Fiber | Synthetic Fiber |
| Temperature | | | |
| 75°F | 12.9 | 98.1 | 1.3 |
| 200°F | 41.9 | 38.2 | 1.2 |

By Risk to Operations

Low Risk: Fine and medium granular particles can be used where the risk of plugging or setting up around the drillstring is minimal.

Medium Risk: Coarse particles can lead to plugging tools in the drillstring causing rig delays and contribute to NPT.

High Risk: Fiber-based solutions are considered high risk because of the problems that can ensue if the LCM is pumped without consideration for the clearance spaces in and around tools like circulating subs and settable fluids.

Table 2 compares common risk factors based on LCM operational conditions.

Table 2 – LCM Risk Factors

| Zone | Complexity | Cost Impact | Time Impact | Use of High Fluid Loss Pills | Environmental Considerations | Temperature Limitations of Reactive Pills |
|------------|-------------|-------------|-------------|-----------------------------------|------------------------------|--|
| Shallow | Low | Low | Low | Unlikely (no BOP) | High | Low temperature considerations, need catalysts |
| Medium | Medium | Medium | Medium | Likely, limited squeeze pressures | Medium | No special considerations |
| Deep | Medium-High | Medium-High | Medium-High | Likely | Medium | No special considerations |
| Ultra Deep | High | High | High | Likely | Low-Medium | Need retarders |

Test Methods

A key challenge in qualifying any new or existing lost circulation material is the lack of standardization around the test methods and the interpretation of the results. Tests can be split into two main categories – quality and performance.

Quality tests for many common drilling fluids additives are covered under API Spec 13A which provides the specification and related test procedures for those additives. That said, API 13A does *not* address LCM quality nor LCM properties. Another layer of complexity is introduced when material properties – such as *hardness* of calcium carbonate, *size* of granular material, *compressive strength* of high fluid pills, and *resiliency* of carbon-based additives – are required to qualify the products while there remains ongoing variation in the test methods and resulting conclusions.

Performance tests (Figure 6) typically study the effectiveness of the LCM in sealing a certain size disc of a known geometry or a permeable disc of a known porosity and permeability. These types of tests also vary in the thickness of the slot (which represents fracture length) and whether is tapered or parallel. The results can also be interpreted in various ways as some products, like a high-fluid-loss pill, are designed to lose the fluid phase quickly while other products, such as ultra-low invasion fluids, are designed to have minimal fluid loss. Tests on manufactured discs are also limited in test volume and ability to simulate various rock types. When real rock samples are used, the natural variability and fractures of the rock plays havoc with repeatability.

Novel test methods that have additional capabilities of circulating the fluid and reaching higher temperatures, pressures, and flow rates are being used to provide more insight on how the LCM behaves in a certain environment. These test methods have led to a step change in the industry, but suffer from the fact that lab results can't be duplicated by simple tests available at the rigsite. A few of these test methods are listed below.

Radial Test

Figure 7 shows the equipment for a custom-made test for radial fluid loss that uses cores with a borehole in the center. The core is sealed from top and bottom by epoxy and sand-packed then a confining pressure is applied. The test fluid is then injected and radial flow is measured (Howard 2017). As it stands today, the system is designed more for studying seepage losses through the rock matrix and has not been used for fractured rocks.



Figure 6 – Equipment for testing LCM performance.



Figure 7 – Radial test equipment

MudFrac System

The MudFrac System applies isostatic stress to a core sample by compressing the confining fluid (Figure 8). It is used for fracture development studies (Razavi 2015). The system has the advantage of being versatile and simulating various scenarios with the exception that it is not designed run tests with temperatures close to what would be in-situ downhole temperatures.

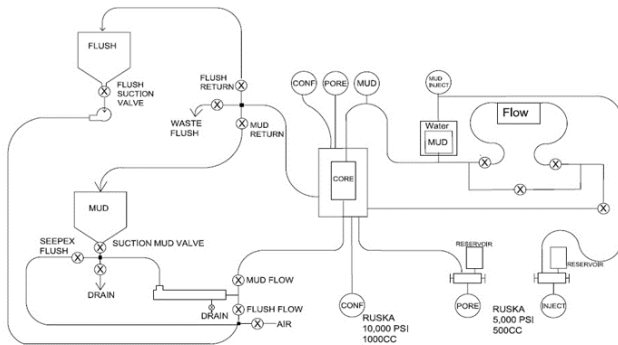


Figure 8 – MudFrac schematic.

Downhole Simulation Cell

The downhole simulation cell is an in-situ tester where cores are restored to downhole conditions before the test is run with various fluids. The test has the ability to control the various stresses including borehole, pore and confining pressures around the wellbore with the added ability of modulating temperature. The test can analyze the core before and after the exposure to various fluids from various physical as well as chemical properties when combined with other techniques (Figure 9).

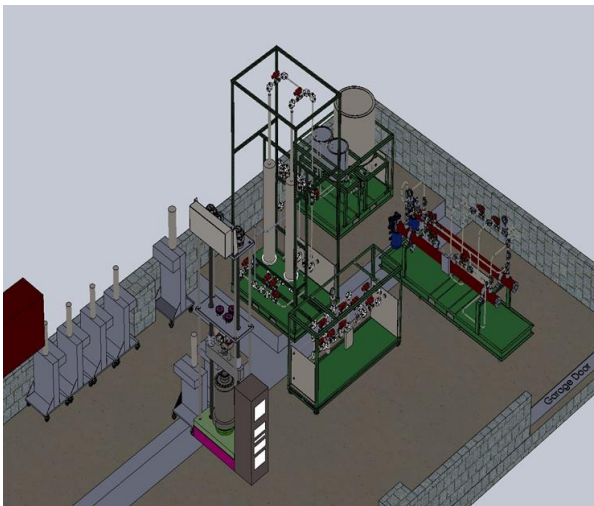


Figure 9 – Downhole simulation testing.

The downhole simulation cell can also measure porosity, permeability, fluid velocity and pressure among other drilling parameters.

Fracture Tester

In the fracture tester, LCM-laden fluids flow through an artificial metal-plate structure using precision syringe pumps. Fracture width, conductivity, and fluid pressure are used to measure performance of various LCM blends (Sanders et al. 2008).

Novel Solutions

A new generation of lost circulation solutions have been developed, or being developed, that are mainly focused on settable-fluids chemistry. The choice of reactive pills as an alternate to granular/fibrous material is mainly driven by the fact that these fluids have virtually no flow restriction limits and should be able to go anywhere a drilling fluid can go without the risk of plugging tools, etc. Unlike designer granular pills, that vary by anticipated fracture width and material type, these fluids can also take the shape of any fracture once driven there by pressure or gravity. This broad application potential makes them an appealing solution to the universal set of lost circulation challenges.

The authors have noticed a general shift away from conventional granular solutions toward these settable fluids in various markets. While that shift may currently be slow, it is increasing, and will be further accelerated by the exploration of novel ideas that can increase the success rate in the field while simultaneously minimizing the risk profile. A few of the novel materials used in settable pills are listed below along with some data science tools that are being used to evaluate LCM performance.

Crosslinked Polysaccharides

Certain polysaccharides can be crosslinked by the introduction of divalent ions, mainly calcium. The degree of crosslinking and the delay time can be controlled by the solubility of the calcium.

Thermal Wellbore Strengthening Treatments

A unique way of artificially strengthening a wellbore is increasing the thermal stresses which around it which in turn enhances the hoop stress. This has been done in the past by various methods including heating the fluids on surface as mentioned in prior art (Gonzalez et al 2004, Shahri et al 2015, van Oort et al. 2018a, van Oort et al. 2018b). The latest advancements in this area focus on exothermic reactions and how they can be utilized in what is now known as “thermal wellbore strengthening”.

Settable Silicate Pills

Unlike traditional solutions using sodium silicate and cement, or other sources of calcium, the addition of aluminum improves the chemical stability and the strength of the set. The reaction of the pill components also allows it to expand in volume in a controlled fashion if needed.

The novel silicate-based pills can be deployed as either a one or two-component system. The one-component system is a standalone pill while the two-component system is added to a non-aqueous drilling fluid.

Crosslinked Solutions for Non-Aqueous Fluids

Current market offerings include chemistries such as resins; however, the current resin chemistry being deployed can have shortcomings when it comes to temperature and contamination limits as well as being somewhat cost-prohibitive.

Recent research has developed a variety of solutions specifically designed for non-aqueous fluids where the cross-linkage chemistry was limited due to various reasons. One of these solutions revolves around the use of unique monomers and co-polymers that can be activated with an external factor to transform to a solid state and have an acceptable compressive strength.

Low-Melting-Point Alloys

Eutectic Metals: A novel way of creating a durable seal is using a eutectic metal combined with a heat element to melt the alloy. Once the alloy melts, it has very low viscosity which allows it to flow anywhere. Additionally, the high specific gravity allows it to displace other fluids with minimum pressure. The material also expands while solidifying which creates a better metal-to-metal seal. This idea has been tested on multiple applications including water shut-off applications.

Data Science Applications

Data science is not necessarily new to the industry but has been historically challenging due to scarcity of data, computing power, and lack of structure and variability in sources. Recent breakthroughs in both cloud and edge computing has allowed data science to provide solutions for complex challenges.

Some of the most recent applications of data science in the field of lost circulation are utilizing the following data analysis tools.

Data Analysis can be applied to a large set of well parameters, mainly drilling and fluids properties to look for correlations using statistical tools while respecting the boundary conditions of physics and science in general (Al-Hameedi et al. 2018c). This approach not only works for finding the right set of conditions to minimize losses but also helps identify options for drilling optimization.

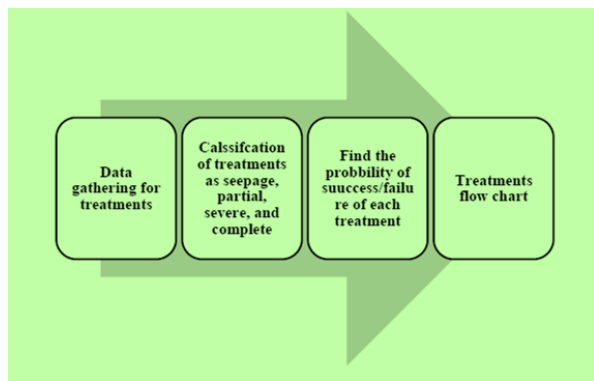


Figure 10 – Flow chart of LCM data analysis.

Predictive Data Mining creates a model to predict losses based on the findings of the larger data analysis set. Simple

linear regression models are not typically preferred here due to the number of factors involved. Multi-linear regression models can be developed and tested up to a pre-selected confidence level (Al-Hameedi et al. 2018a).

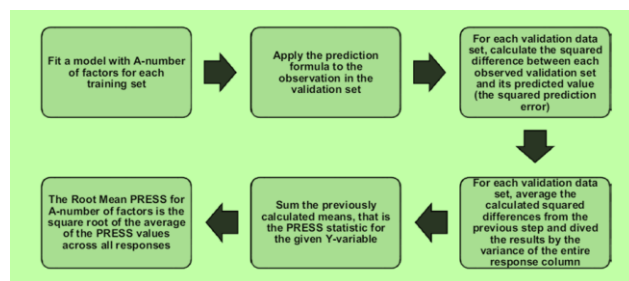


Figure 11 – Flow chart of LCM data mining.

Machine Learning can take place once a model has been validated at the predictive stage. Filters can include using variable importance in projection (VIP). Tools such as Partial Least Squares can be used to explain the relation between factors. At this stage, models need to be tested and overfitting should be avoided by data augmentation (Al-Hameedi et al. 2018b).

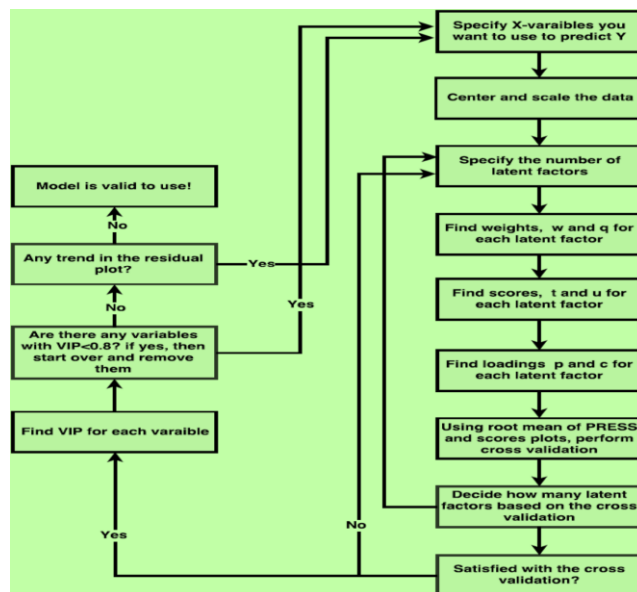


Figure 12 – Flow chart of machine learning.

Artificial Neural Networks are a variation of deep supervised machine learning where the model can now be tested on new data and new wells. An optimum number of hidden layers and neurons should be selected. Training functions vary and should be tested for fit depending on the total average absolute deviation.

While the various forms of data science have proven valuable in addressing lost circulation challenges, there are barriers to scalability including cost and complexity of deployment, cost of software ownership, and cyber security.

Conclusions and Future Work

The authors would like the audience to recognize that there is a set of new data tools, test methods, and novel chemistries that will in time lead to a paradigm shift in how lost circulation challenges can be handled in the planning phase of a field rather than one well at a time as loss events occur.

Future work will include in depth studies combining specific solutions with data science tools to identify performance-based solutions tailored for specific formations and fields.

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