SPE-210091-MS

Optimizing Focused Reservoir Fluid Sampling Using a Deterministic Causation Artificial Intelligence Intuition Technology

Rabindra Chakraborty, Senslytics Corporation; Chengli Dong, Formerly with Shell International E&P Inc; Hani Elshahawi, NoviDigiTech, LLC; Jeroen Smith, Formerly with Shell Global Solutions, B.V; Shyam Ramaswami, Shell Global Solutions, B.V

This paper was prepared for presentation at the 2022 SPE Annual Technical Conference and Exhibition held in Houston, Texas, USA, 3 - 5 October 2022.

Abstract

Samples collected using Wireline Formation Testing (WFT) provide vital information throughout the lifetime of the reservoir. Contaminated samples can lead to erroneous fluid analysis results with potentially huge economic consequences. On the other hand, sampling operations need to be optimized to minimize the cost without compromising the quality of the collected fluid samples. Today the success of an operation depends on real time human interpretations of the fluid cleanup based on in-situ fluid properties as measured by insitu downhole sensors. There is a need for an application that can assist engineers to accurately infer the state of fluid contamination as well as recommend actions when an operation has gone astray.

We have developed and patented Intuition Technology, which is an advanced causation-based artificial intelligence framework designed to forewarn complex, hard to detect state changes in chemical, biological and geological systems. This paper describes the development of a WFT contamination forewarning application based on the Intuition Technology framework which de-risks the formation sampling process by advising real time decisions regarding the state of fluid contamination and recommending rate schedule or other changes that will help optimize the WFT operation. This application has potential to save millions of dollars per annum through operational optimization, value assurance, and risk mitigation.

Objectives/Scope

Formation fluid samples provide valuable information for field development, production planning, development of operation contingencies and economic estimates. For example, in Deepwater developments, flow assurance is a major concern, and formation fluid samples are essential for operators to optimize investments in upstream exploration, appraisal, and development, in production facility design, as well as in downstream refining and distribution. However, obtaining a representative sample from the reservoir often below the required contamination thresholds is not always easy. Drilling mud filtrate contaminates the sample quality and the impact of basing well decisions using a wrong quality sample can be devastating.

Conventional sampling typically requires extensive pumping times to guarantee that a collected sample is free from contamination. This can often become costly because both on-station pumping times and rig-times are quite expensive and carry an increased risk of mechanical failure and tool sticking [1].

Over the last decade, focused fluid sampling has emerged as a viable alternative and is considered as the most efficient technique for sampling of challenging fluids and formations. The method is depicted in Figure 1 and uses a special probing tool containing two distinct flow areas - the central (sample) inlet is connected to a Sample line – often with an associated pump, while the peripheral (guard) ring is also associated with a dedicated pump. Focused sampling usually results in faster clean-up but comes with increased operational complexity. Akin to driving a manual-gear shift automobile, the flowrate of the sample and guard lines must be properly adjusted and synchronized for each case at hand, and the interpretation of the signals downhole measurements on both sides is significantly more complex than for conventional sampling operations. If the cleanup state of the sample is not well synchronized and/or interpreted, sub-optimal and potentially unusable samples may be collected with considerable field development implications.

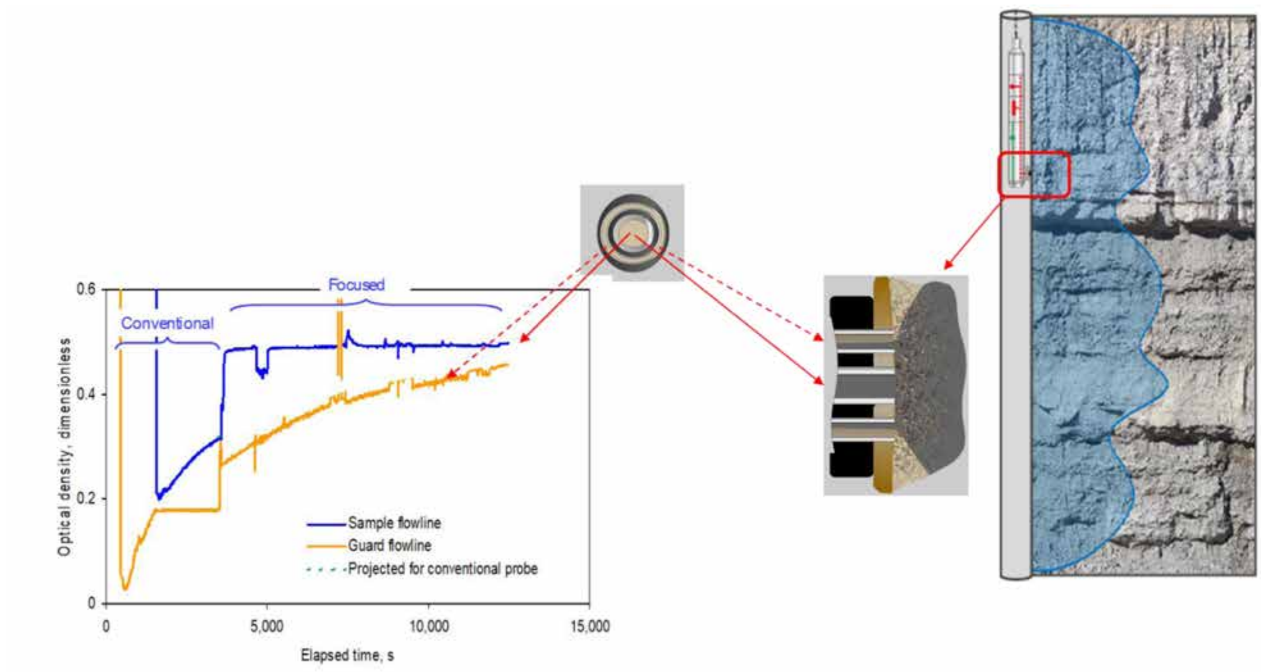

Figure 1—Principle of Focused Sampling

The success of the fluid sampling operations is highly dependent on human interpretations of the real time downhole sensor data such as optical density, sound speed, density, GOR [2].

Focused sampling is carried out by manipulating the differential rates of sample and guard pumps in order to stimulate and accelerate sample cleanup. Various types of flow regimes can be observed during focused sampling operations and may be classified as follows:

- Idle: During such regimes, both Sample and Guard pumps are turned off, and as such no cleanup takes place, and fluids in the tool's sample lines and detected by the downhole analyzers remain stagnant. Pretests before and after sampling and buildups conducted during or at the end of the sampling operations fall in this category.
- Commingle: During commingling, either the Sample pump or the Guard pump is running, but flow occurs through both the sample and guard areas combined. The cleanup proceeds as with conventional sampling, exhibits similar asymptotic cleanup behavior, and takes just as long to achieve cleanup.

- Split flow: In such periods, both Sample and Guard pumps run simultaneously but at different flow rates with fluids moving at different speeds through the sample (central) and guard (outer) areas. Split flow does not guarantee successful focusing. The flow rates of the pumps will generally need to be tuned or adjusted to in order to properly focus the flow. That tuning is highly dependent on the tool geometry, its relative position in the wellbore, as well as rock and formation fluid but is critical to getting clean samples. When focused sampling does work properly, cleanup can occur much faster, with a drastic reduction in contamination often indicated after switching to split flow.

In the three types of flow regimes described above, various fluid properties e.g., optical density, sound speed, physical density, capacitance, GOR display different characteristics and resolutions and unique signature, but their trends will be broadly indicative of the reservoir fluid cleanup. Making sense of all these various measurements in real time remains a challenge particularly because the physics of fluid flow in the near-wellbore porous media are highly complex and challenging to compute analytically and difficult to numerically simulate at a relevant scale-especially in the context of real time operations.

In principle, an artificial intelligence tool can help make real time decisions regarding the state of cleanup with less ambiguity. Several real time monitoring, prediction, and interpretation attempts have been made in the past with relatively limited effectiveness [3,4,5]. Our own attempt at applying classical machine learning algorithms such as long short-term memory (LSTM) fell short of providing useful interpretations of fluid contamination state, due to the typical lack of the massive amounts of data typically required for machine learning and also due to the complex multivariate dependencies of fluid cleanup on situational context namely fluid properties such as fluid viscosity, formation fluid-mud filtrate contrast and formation properties such as porosity, permeability, permeability anisotropy, distance to boundaries, etc.

We have developed " Intuition Technology", which is a new AI paradigm that uses scientific learning as its fabric and mimics the human decision-making process by iterating hypotheses and weighing situational changes, surrounding dynamics simultaneously while keeping an eye on the possible asymptomatic behavior. The process involves harnessing experts' subtle knowledge of fluid properties and change behavior as hypotheses and iterating them with the situational and time series data to generate a scientific fabric that governs the cleanup. A contamination forewarning application, built on this intuition framework was able to successfully interpret the fluid cleanup state in all the examples examined as part of this pilot.

Methods, Procedures, Process

The intuition technology framework not only processes intelligence from the parameters that describe the system (Core data) but also from monitoring the changes in situations and surroundings (Ring data) as shown on Figure 2 and can compute time distant cause-effect correlation [6,7]. This makes it an excellent fit to the problem of fluid cleanup assessment during focused sampling operations.

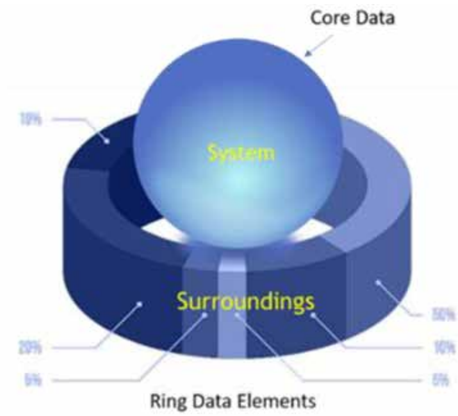

Figure 2—Core-Ring Data Processing

Time distant cause-effect correlation plays a critical role in non-mechanical systems because in these systems, often a cause does not show an effect instantly, yet plays a big role in triggering a future state change [8]. Moreover, in most complex systems, an exact analytical model does not exist, and any simulations must use highly simplified assumptions. Operational knowledge of such systems will often exist in the form of experiential learnings and heuristic rules in the heads of experts. In fact, one can argue that most real-world industrial problems in which complex decision making is required would fall in this category. The intuition technology framework captures such knowledge as hypotheses and progressively refine them using hypotheses scoring and iteration while vetting against the observations of patterns and trends. Utilizing this experience base is a robust methodology to model the behavior of complex systems [9]. Hypotheses iteration plays a key role in finding the lead indicators that indicate state change and its complex correlation with the ring data under a given situation. Ring data are the set of influencers that are constantly changing and impact the state of the output instantly or in a time-delayed manner.

In the specific application of the intuition technology framework to focused fluid sampling, the sample and guard pump rate act as the stimulus for cleanup and are labeled as the ring data, whereas fluid properties are labeled as core data which are the tangible views of the intended output – the state of contamination of the sample fluid. Henceforth, this will be referred to as the " forewarning application".

Each core data represents one view of the fluid clean-up. The intuition-based forewarning algorithm dynamically evaluates and chooses the best set of views that represent the changes in contamination and converge the interpretations from each fluid clean-up views to clean-up inferences.

Formation tester data is typically ingested in the form of time series which include fluid properties along with guard and sample pump rates, along with pressure and temperature sensor data, etc. Fluid property data may include:

> **Optical Density:** The most commonly used Optical Fluid Analyzer output is the optical density (OD). Optical density represents the absorbance spectrum and depending on the wavelength, can by indicative of the color of the fluid as well as the molecular fluid composition in the line. Colored chemicals absorb light in the visible portion of the electromagnetic spectrum, which has a wavelength of approximately 400 – 700 nm. The color of the absorbed light depends on the amount of energy the chemical absorbs and can hence be indicators of the contamination. However, the channel that is the best representative of the contamination varies from one operation to another. Optical density is the most sensitive variable of the fluid properties and behaves nearly linearly to the contamination change. However, it cannot always be used for determining contamination especially in cases in which the contrast in color between reservoir fluid and mud filtrate is subtle or in which there is excessive noise relative to the signal being measured.

Sound Speed: The speed of sound in the fluid also can indicate the real time contamination level in the fluid. However, it is not as linear or as sensitive as OD or GOR. As such, sound speed is mainly used as a secondary indicator of contamination or for vetting an inference.

Density: Physical density of the fluid changes as the fluid cleans up and this change can be indicative of the contamination state change of the fluid and is easy to interpret as it corresponds directly to a physical property that is measurable both via pressure gradient analysis and in the lab. However, the difference between drilling filtrate density (especially of oil base muds) and reservoir hydrocarbon density (especially oils) is generally small (0.1-0.3 g/cc), so even if the measurement is sensitive, its dynamic range is limited compared to optical density or GOR.

Capacitance: The patterns in capacitance behavior can indicate fluid clean up state as well but is only useful when sampling oils in water-based mud systems or water in oil-base mud systems and tends to saturate/short circuit at high water fractions.

Gas-Oil Ratio (GOR): GOR can also indicate contamination level in a fluid and is a variable used for determining the cleanup state of the fluid in the line. By definition, GOR cannot physically be measured in the insitu fluid state because no phase separation actually takes place. Instead, it is inferred based on other measurements such as for instance, the relative height of the methane and Heptane+ peaks on the optical spectrum. GOR has in theory the largest dynamic range possible ranging from zero (for a dead fluid such as oil base mud filtrate) to infinity for a pure dry gas, and so it is highly sensitive. It is particularly valuable where the fluids are light in color and hence difficult to distinguish from filtrates.

A typical contamination forewarning application to a given sampling station would include the following analyses:

Idle Section Analysis: Idle sections where both pumps are idle are ignored, and thus no analyses are performed.

Commingle Analysis: During a commingling operation, the forewarning algorithm derives the direction of cleanup and the core variable noise levels and pump noise levels for either or both the Sample and Guard lines.

Split flow Analysis: In split flow, the forewarning algorithm first determines if focused sampling is functioning and then confirms the cleaning action within a few minutes after split flow begins. The goal of split flow analysis is to determine early on if the fluid is cleaning or not. Once the cleaning action is established, the algorithm then determines if the sample can be considered sufficiently clean or not, based on two independent methods.

a. **Pump Event Analysis:** Field engineers change the pump rates to see the impact of the rate changes on the fluid property change. Proper and expected changes confirm that the fluid in sample or guard line is " cleaning", improper changes indicate the operation is not going right and if no changes in fluid properties are observed consistently at pump rate change, then it indicates the fluid has reached its acceptable clean state and operation is successful. WFT operations are often not straightforward, and whenever there is slugging, plugging, or pump malfunctioning, fluid property data can give mixed signals – indicating a sample is stable clean for some time and then indicating it is cleaning up further or even becoming more contaminated. For such operations, the Intuition algorithm depends on a vetting mechanism and derives the state of cleanup of the fluid using an independent method called trend analysis.
b. **Trend Analysis:** In general, the pump rate influence on the fluid properties reduces as cleanup progresses. When the sample and guard line fluids have both cleaned up to irreducible levels, fluid properties will hardly change with pump rate, because the fluid is homogeneous. Trend

analysis computes for this hypothesis and once the trend change becomes below noise level, the Intuition algorithm infers the fluid to be (irreducibly) clean.

When the pump event analysis and trend analysis agree, the fluid is declared (irreducibly) clean. If a station has multiple split-flow sections, each split flow is evaluated independently, and conclusions or recommendations are presented accordingly. Thus, one can compare one flow period to the next independently but realizing that in general and barring any anomalies, cleanup should reduce with time (and pumped fluid volume).

Results, Observations, Conclusions

A total of 11 data files with various degree of clean-up complexity has been processed using by the contamination forewarning application that was built using intuition technology framework. Below are the examples of two of those operations evaluations. Figure 3 is an example of a good quality operation whereas Figure 4 shows an example where cleanup is not taking place. The left-hand tiles show all the ingested fluid properties.

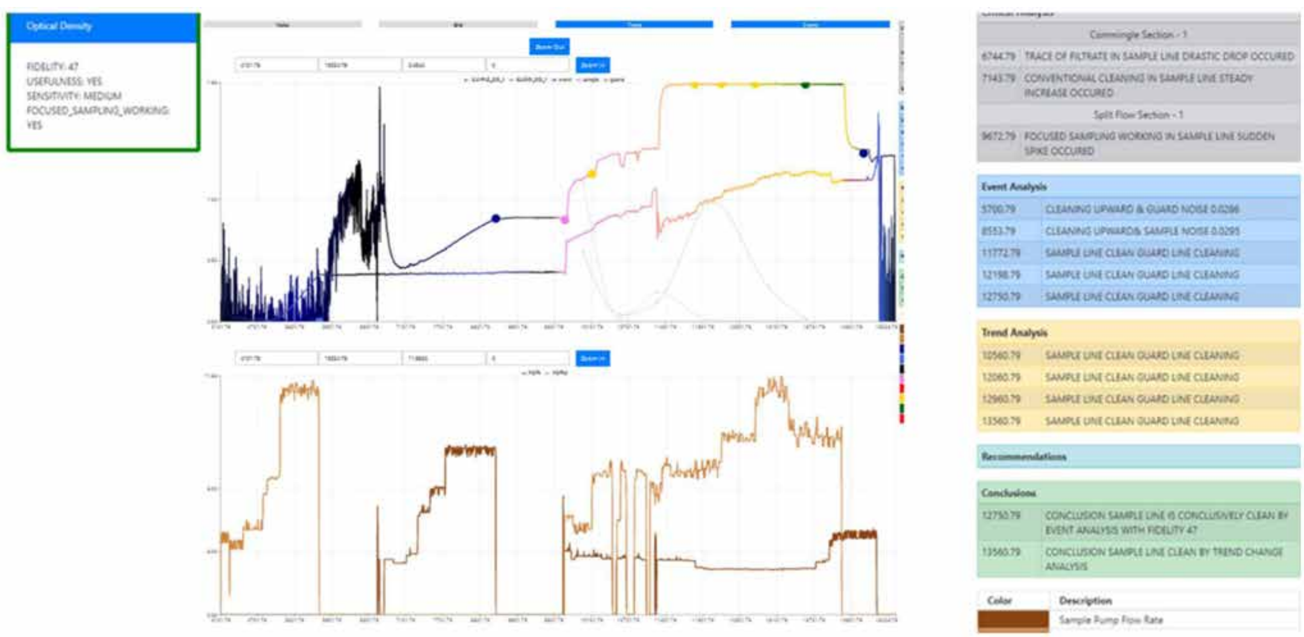

Figure 3—High Quality Sample Example

Each of these tiles refer to one view of the contamination measure. In this particular example, only OD is shown because that is the only fluid property ingested. In case a file contains OD, sound speed and density, then three Tiles are labelled accordingly. The right-hand side Table shows the main derivations such as noise, clean up direction as well as inferences and recommendations. In the center the stacked plots represent the Fluid property (top) and pump operation (bottom) against the same time stamp. Pump operations are shown on light and dark brown, representing guard pump operations and sample pump operations, respectively. The OD plots change colors as the operation moves from commingle region to split flow. For example, dark blue and light blue represent optical density in the commingling section. The color changes to pink to denote that the focused sampling has been working. Then the plot color changes to gold to indicate the fluid is cleaning, till the color becomes green indicating an (irreducible) clean state has been achieved.

The dots on the plots represent important messages. The messages can be read upon hovering the mouse over the corresponding dot. Black dots represent recommendations whereas the dots matching the color of the plot give an indication of inference, such as, the fluid is cleaning effectively or slowly, the sample is already clean within an acceptable range, or not cleaning at all, or clean-up is heading in a wrong direction. This is done by first identifying the nature of current flow pattern e.g., commingle or split flow and then establishing if the focused sampling is working or not.

Moreover, the field engineer or data analyst can see the current noise level, pump event analysis and trend change analysis on the plot. These features help the interpreted inferences. Because formation testing operations will invariably need some human judgement prior to sample collection decision, any part of the plot area can be zoomed-in for more precise visual inspection of the fluid behavior.

In contrast to the above example, Figure 4 forewarns a problematic operation. Here the red line and the red dots on the plot alert repeatedly that the operation is not going well and fluid in the flow line is not cleaning. Towards the end of the operation, plot shows the flow line started to clean but because the focused sampling did not work, obviously that the cleaning will take long time. This type of early warning can help the decision maker reposition the probe location - not only to optimize the operational duration but also to decrease the risk of collecting contaminated fluid.

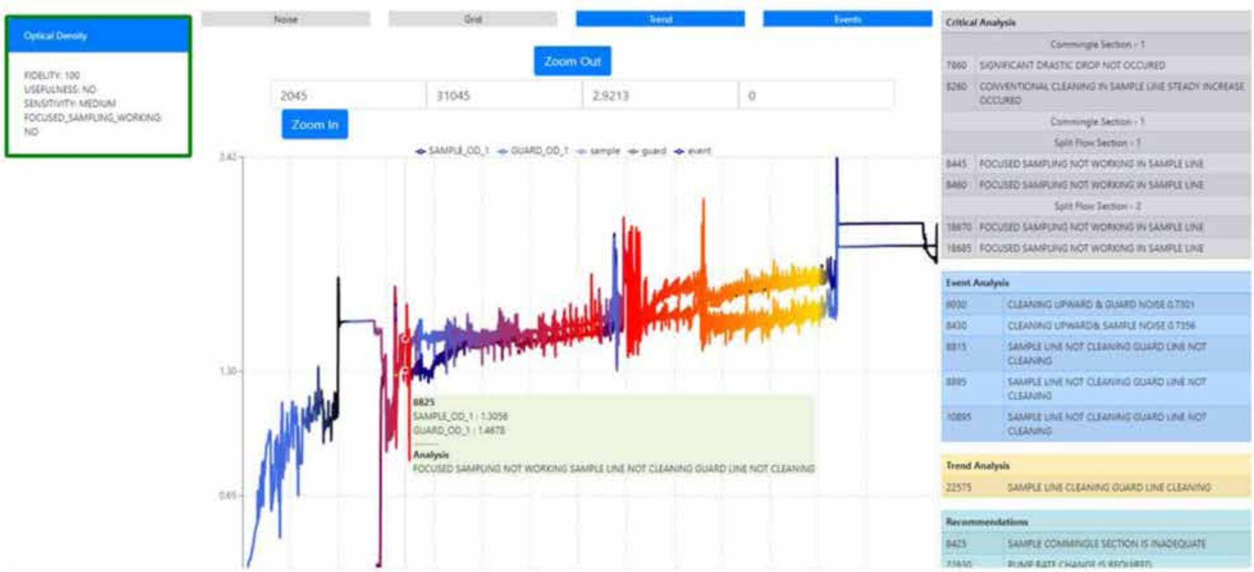

Figure 4—Low Quality Sample Example

Novel/Additive Information

Formation fluid sampling provides valuable information for field development, production planning, development of operation contingencies and economic estimates. Contaminated samples can lead to erroneous fluid analysis results with potentially huge economic consequences. At the same time, sampling operations need to be optimized to minimize the cost without compromising the quality of the collected fluid samples. There is need for an application that can assist engineers to accurately infer the state of fluid contamination as well as recommend actions when an operation has taken a wrong turn. Intuition technology provides such a solution. It is an advanced causation-based artificial intelligence framework designed to forewarn complex, hard to detect state changes in chemical, biological and geological systems. We have adapted this framework to the problem of contamination monitoring in focused fluid sampling operations, which today mostly depend on the expertise and judgement on experienced practitioners.

Our pilot application harnesses expert knowledge of fluid properties and change behavior as hypotheses and iterates them with the situational and time series data to generate a scientific fabric that governs the cleanup. In the Shell pilot, it was able to successfully interpret the fluid sampling cleanup state in multiple cases with varying complexity. This application has the potential to save millions of dollars a year through optimizing sampling times and many more through value assurance risk mitigation, so as a next step, we will deploy this methodology on real time data streaming from live wells and work on integrating it with next generation integrated formation testing platforms.

Nomenclature

WFT = Wireline Formation Testing
OD = Optical Density
GOR = Gas-Oil Ratio
LSTM = Long short-term memory

Reference

1. C. Del Campo, C. Dong, R. Vasques, P. Hegeman, and T. Yamate, " Advances in Fluid Sampling With Formation Testers for Offshore Exploration", OTC 18201, Offshore Technology Conference, 2006.
2. Chengli Dong, Peter S. Hegeman, Andrew Carnegie, Hani Elshahawi, " Downhole Measurements of Methane Content and GOR in Formation Fluid Samples", *SPE Reservoir Evaluation and Engineering*,Feb 2006.
3. Mayank Malik, Birol Dindoruk, Hani Elshahawi and Carlos Torres-Verdin, " Numerical Investigation of Oil - Base-Mud Contamination in Condensates: From Cleanup to Sample Quality", SPE 124371, Oct 2009.
4. Morten Kristensen, Nikita Chugunov, Adriaan Gisolf, Mario Biagi, Francois Dubost, " Real-Time Formation Evaluation and Contamination Prediction Through Inversion of Downhole Fluid Sampling Measurements", SPE–187432–MS, 2017
5. H.Elshahawi, M.Hashem, D.McKinney, M.Ardila, C.Ayan, " The Power of Real Time Monitoring and Interpretation in Wireline Formation Testing – Case Studies", *SPE Reservoir Evaluation and Engineering* June 2007.
6. Rabindra Chakraborty, Jay Kalra, Anupam Awasthi, Amol Awasthi, " Data Insight and Intuition System for Tank Storage", US Patent Number: 10,061,833 B2,Aug 28 2018, *Senslytics Corporation*.
7. Rabindra Chakraborty, Jay Kalra, Anupam Awasthi, Amol Awasthi, " Method of Intuition Generation", US Patent Number: 10,073,724 B2,Sep 11, 2018, *Senslytics Corporation*.
8. Rabindra Chakraborty, Jay Kalra, Anupam Awasthi, Amol Awasthi, " Method of Intuition Generation", US Patent 10,445,162 B2,Oct 15, 2019. *Senslytics Corporation*.
9. Rabindra Chakraborty, Jay Kalra, Anupam Awasthi, Amol Awasthi, " Methods and Systems correlating Hypotheses outcomes using relevance scoring for Intuition based Forewarning", US Patent 11,226,856 B2,Jan 22, 2022, *Senslytics Corporation*.