Analytical Formation Sampling During Drilling Using OPAL – On Surface Petrophysical Analytical Logging*

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Abstract

The OPAL system is a new petrophysical measurement tool. OPAL is measuring the drilling cuttings circulated up, collected and analyzed while drilling the well. The OPAL is a stand-alone unmanned unit collecting drill cuttings from the possum belly (Shale Shaker) and analyzes them. OPAL collects the slurry of drilling mud with cuttings and processes it in a close system. Sensors integrated into OPAL permit a continuous data stream of measurements analogous to logging or LWD. Examples of such will be displayed in addition to measurements intrinsic to direct and derived properties such as the Flow density curve, which is an indicator for well cleaning monitoring and quality control of measurements.

The first example will compare OPAL in comparison to MWD/LWD logs. Sensors integrated into OPAL measure:

- Total and Spectral Gamma Ray Activity
- Resistivity
- Density

The response of slow moving drilling cuttings produces high quality statistical measurements as the sensors are in direct contact with the cuttings. This will result in a better delineation in most reservoirs in comparison to MWD/LWD logs.

The second example compares the real time OPAL Gamma Ray (GR) measurement to the earlier recorded MWD/LWD GR in a horizontal well. It illustrates the bit entering a shale layer. The variance is indicative of the well bore cleaning capacity of the mud system and the difference is a direct measure of the precipitation rate of the clays which are left to precipitate in the bore hole. This is an early ‘stuck pipe

warning' indicator. This effect is confirmed by the decrease in the OPAL Flow Density curve. Other drilling issues can also be predicted using OPAL such as liquid loss or lost circulation.

The OPAL system has the capability to collect drill cuttings automatically without human intervention. This automated sample catching device is designed to continuously sample the drill cuttings flow by extracting a small portion of the cuttings effluent stream using a computer controlled sampling by lagged rate of penetration. OPAL continuously samples the drill cuttings stream and prepares a pseudo core-like sample in the storage cup. This 'Mini Core' is a system that produces a wash sample in the cup which is a layered, scaled reflection of the formation stratigraphic sequence. This Mini core can be vialed and stored in vial books.

In addition to the sequence sampled drill cuttings and their associated inline measurements, the formation gasses can pre-presented using the Differential Gas Detector. This allows the light, medium and heavy gas components to be sampled and displayed simultaneously. Supplementary detectors and their inputs can be integrated into the data collection as required.

Introduction

The OPAL is a new automated well cuttings data capture and analytic sampling system (Figure 1) using the *kGeo-Algorithms* to produce a continuous record of mud cuttings, their measurements, and integrated drilling information. Unlike conventional logging and LWD the sensors are located at the well head and are at no risk of loss compared to down hole tools. The OPAL system consists of hardware and software that is collecting cuttings and placing the depth of sample collected by lag depth measured position.

The hardware recovers the drill cuttings/mud from the return flow line and pumps it into the OPAL system. This is performed by using the dual pump system; centrifugal pump with an integrated auger accelerator.

Within the OPAL collection system the drill cuttings are separated from drilling mud (Figure 2). The separation function is performed by using device called the 'mini shaker', which is a similar to the rig shale shaker in principal. The drill cuttings are processed by the OPAL sampling device which is continuously collected and washed from the cuttings stream and deposited in the sample chamber layer by layer. This makes the collected sample chamber a visual representation of the layered formation and the changes throughout drilling.

Associated with the OPAL system is a combined 'Differential Gas Detector' with a turbine gas trap, which continuously monitors the hydrocarbon content of the drilled formation (Figure 3). The Turbine Gas Trap is augmented with a turbine to generate bubbles in the mud flow. The diffusion process equalizes the molecular pressure of gas in liquid and in the bubble instantly. Thusly a representative gas sample is collected. Conventional gas traps typically make oversaturated gas sample measurements because the molecular pressure of the gas in the liquid stream is not at equilibrium. The Differential Gas Detector uses dual gas detector sensors. First is conventional total gas sensor for measuring the gasses (C1-C5). Second is the sensor for heavy gas component detection. The heavy components are the hydrocarbons (C3-C5) in the gas stream. The *kGeo-Algorithm* makes a comparison of response quantitatively measuring total (C1-C5) and (C3-C5).

This unit can distinguish between dry gas, wet gas, oil and water accumulation (Figure 4). The evaluation of this differential gas detector can provide a continuous, hydrocarbon saturation and hydrocarbon ratio of the formation. The *kGeo-Algorithm* utilizes normalization techniques. The normalization accounts for pump displacement, pump strokes, ROP, hole diameter and enables a standardized well to well comparison. The gas concentration in the stream is used to make the mud density correction for flow line density log.

The 'Liquid Loss System' monitors the formation response on drilling mud loss in the fractures and in the porosity of the drilled formation. This is done by measuring the mud quantity and mud properties parameters pumped into the well bore and the mud quantity and parameters of mud flowing out of the well. The mud flow out device is placed on the flow line before the possum belly. The *LLS* (Liquid Loss System), measured data output is connected to the OPAL data system and connected to the rig *EDM* (Electronic Drilling Monitoring System). The EDM collects the drilling parameters for precise lag calculation and mechanical drilling information. This system enables formation fracture quantity logging in real time along with wellbore cleaning. The fracture measurement is in volumetric units and this makes it directly useful by the drilling engineering and reservoir engineering calculations. This *LLS* provide well safety and early stuck pipe prevention. Stuck pipe conditions are derived in real time and ahead of the critical event.

The OPAL software gathers the information from the drilling rig sensors or the drilling rig recorder system and calculates the appropriate lag depth for the drill cuttings. The integrated sensor and ancillary information are then collected and stored within the measurement database set at the OPAL on the rig unit. The data are transmitted to the operator upon request using data transmission protocol WITS, which can be viewed in real time at the rig site as well or remotely in the office as desired.

The OPAL Process

The OPAL System (Figure 5) consists of functional blocks:

- LLS-Liquid Loss System
- DTG-Differential Gas Detector
- Sample Measurements (GR, Spectral GR, Resistivity, Density, etc.)

These subcomponents are integrated into a synchronized mud system and cuttings database. This produces reservoir performance Parameters (*RPP*) in real time. One of the significant advantages of this system is that the well information is in real time; ahead of the logs, and is not lost if the well is not logged due to poor bore hole conditions and/or well problems.

- Poor well condition is detrimental to open hole tools to access the well bore and high quality measurements.
- The OPAL logs are complimentary to the MWD/LWD logs by providing the information that the MWD cannot provide.
- OPAL logging cuts down the risk on tool loss cost. This is accomplished by simplifying the down hole set of tools in MWD/LWD bottom hole assembly to mission critical measurements. The down hole tool can be simplified to directional, tool face, Up/Down GR

Counters, and Gamma Ray tool used for geo-steering, and depth correlation of formation tops. In wells where the up-hole time is shorter than the tool offset from the bit to the Gamma Ray tool, the OPAL system will get the information earlier then the MWD/LWD.

- If the well is lost due to bad bore hole conditions, the samples from the interval ahead of the tools to the drill bit will arrive to the OPAL system and are analyzed for the portion of the well drilled ahead of the GR sensors. In this case the MWD/LWD will not reach the formation at the drill bit.
- The OPAL system produces real-time measurements designed to provide enhanced drilling safety and drilling performance optimization, by utilizing a variety of different sensor blocks.
- The OPAL system is equipped with an automated sample collection system which collects core like samples at selected rate set by operators (Figure 6).
- Mini Core system and storage. The system is combined with a device that takes a small part of the cutting and places it in core-like vials visually presenting the formations changes – Mini-Core (Figure 7). These 'mini cores' are washed as they are collected and can be dried and stored.
- Formation contacts and the reservoir zones captured.
- The final stage of the OPAL System is the Dual Flow Mud Pump System that is designed with dual redundancy and safety. This pumping system mixes the cuttings with processed mud and pumps the return slurry back to possum belly, this completes the close system and results in no loss of mud to the environment.

The measurements devices and sub-systems are listed in Appendix A - OPAL System Mechanical Components and sensors.

The kGeo-Algorithm

The OPAL kGeo-Algorithm is composed of 4 major parts of various measurements and filtering of raw data:

Data Collection for kGeo-Algorithm

Data measurements are performed synchronously by employing various sensors (GR, ultrasonic, density, etc.) and with response times ranging from a fraction of a second to 15 seconds. The *kGeo-Algorithm* is designed for the Data Base to store the measurement converted to data in the form of conventional Open Hole standards. The *kGeo-Algorithm* is responsible to convert the data to standard WITS format, convert to standard units measurements depending on the user Imperial or Metric systems. At the data collection level the *kGeo-Algorithm* is designed to present the independent raw curve measurements and allow the data to be interpreted and calibrated by the users. This means that except of the tool calibration parameters there will be no data offsets, smoothing or any other filtering performed at data collection stage. The data in collection data base are what the tool measure right now.

The Data Synchronization kGeo-Algorithm

The data are measured synchronously on many sensors and there are some sensors delays associated with sensors location, Lag_ROP, and Lag Time calculated from to the mud pump strokes and other well parameters. This *kGeo-Algorithm* is bringing all the data from time domain to the depth domain. The time domain data are compound in time data base and are presented in Time log Monitoring software. The Rig Data Monitoring are selectively duplicate in time data base. The Rig Monitoring data that are part of the *kGeo-Algorithm* or are part of the interpretation.

Data Quality control and Safety kGeo-Algorithm

The Data quality *kGeo-Algorithm* is responsible for the controlling the sample quantity in the sample chambers and the speed of transportation of the sample along the sensors. This the linear speed of sample in sensors chamber is equal to Lag_ROP. The safety part of the kGeo-*Algorithm* is responsible for any abnormal information arriving at the Data Base. The custom alarms can be set by users on the rig. Also the logic of kGeo-*Algorithm* safety can be set to alarm the operator when there is a difference in Gamma Ray readings of MWD/LWD and the OPAL system which means the well is not delivering the cuttings to the surface. A case study in horizontal well will be presented when shale is detected by the MWD and the OPAL is detecting the shale arrival much later. The shale was precipitating in the wellbore path and not delivered to the surface. This is the case of increasing the pre-stack condition.

Data Presentation and Monitoring part of kGeo-Algorithm

This *kGeo-Algorithm* is responsible for data representation and availability. The *kGeo-Algorithm* makes the data user friendly and the access to the data flexible.

Results

Example #1 - Liquid Loss Increase When the Bit is Entering the Coal Seam

This example illustrates how the ‘Liquid Loss System’ monitors the formation response on drilling mud loss in a coal steam for Coal Bed Methane (CBM) (Figure 8). The first column from the top: (Blue curve) – the ‘Total Gas’, increases when the bit enters the coal seam. This increase verifies that the drill bit has started to enter the coal seam. The black curve, ROP, second column on the top, shows an increase in the rate of penetration. On the second track the Gamma Ray curve (Blue) also decreases as the bit enters the coal seam. The green curve, Flow QC, provides a quantitative pump out put curve. The forth track shows the liquid loss curve (red). Here you can see the result of entering the coal seam. The increase loss of fluids is due to the coal cleating and fractures in the coal seam. This log shows a near zero loss of drilling fluids in the shale and shale/sand formations. The liquid loss curve deflects down when the well path enters the coal seam. There are two closed fractures which are encountered where the liquid loss increases rapidly and comes back to the same level shortly after these fractures are filled. This shows how the Liquid Loss System, in combination with the OPAL system, is capable to define fractures reservoir properties.

Example #2 – Well Stability and ‘Stuck Pipe’ Prevention

Here we show an example where the well safety and ‘stuck pipe’ prevention detection was used in shale Figure 9. When shale precipitates in the well bore path for a length of time creating a potential hazard of the well cleaning for the Bottom Hole Assemble (BHA) and could get stuck.

Observing the well cleaning issue starts from the point when the GR-MWD increases and defines entering the shale formation. In comparison to the GR-OPAL which did not see the increasing in the Gamma Ray curve. The combination of these two data sets confirmed the loss of shale drill cuttings in the well bore, resulting in the decision to notify the drillers of a potential drilling hazard, which may require addition well cleaning. In addition, the drill cutting samples were collected and the shale was not present in 5 consequent samples. This was for interval from 2103 m to 2130 m, 27 m of the well bore. The volume of $V=0.0198*27 = 0.54\ m^3$. This shows an approximately 27 m of difference between the where GR-MWD sees the shale and GR-OPAL does not see the shale's. This indicates the possibility of shale cuttings accumulating in the well bore as they are not returning to surface. With a 159 mm drill bit offset from center, the amount of drill cuttings accumulating in the well bore would be spread for more than 100 m fill approximately of ¼ of the well bore path. Using the OPAL system, situations like this can be caught and remedied before major problems occur. Total MWD Gamma Ray Log is used to compare to OPAL the Gamma Ray Log.

Figure 10 illustrates the synchronous raze of both OPAL GR and MWD GR curves and this is the example of good well cleaning. The Liquid Loss System and Gas Detection system are synchronized with the OPAL system and Combination log is plotted and monitored in real time.

Conclusions

- The OPAL system is a tool that is logging the subsurface at the surface, and has the benefit of no parts down hole.
- OPAL is capable of logging problem wells such as high temperature, deep wells, exploration high cost, and high risk wells, with unstable formations, and high volatility.
- OPAL is a tool to have in offshore drilling.
- The OPAL's data has effective real time information and the data are un-distractible if there is loss of well integrity.
- The OPAL's data are available at the rig in real time.
- OPAL has the capability to produce a set of measurements comparable to a full set of Open Hole Logs GR, Gamma Spectrograph.
- The new principals are used in measurements of Density, X-Ray Density, Resistivity, Flow density, well cleaning or volumetric caliper, and others.
- Opal can produce a volumetric caliper of the well in real time.
- OPAL is collecting automatic samples with digital control of size and intervals required. A mini-core device collecting thin 4" long sample vials, which represent continuous formation sampling like the continuous core.
- The OPAL data in combination with conventional MWD/LWD are a valuable well bore cleaning and 'stuck pipe' prevention system for horizontal well drilling.
- The OPAL real time monitoring with 'Liquid Loss system' and 'Gas Detection DTG system' are capable of providing detailed 'Fractured Reservoir Performance data', well Stability Data and Fractureability Data. The Fracture quantities are measured by volume of liquid required to fill the fractures.

- OPAL provides a new measurement principal in the field of Petrophysics, where the measurements are performed by analyzing the cuttings column in a new way, which Open Hole logs are not capable of.
- OPAL cuttings measurements are performed by shining through the media, in opposition to open hole logs that are using the principal of reflecting the signal from the well bore wall. New principal of petrophysical approach and data applied.
- OPAL tools are providing new information, new mathematical theoretical solutions and formation properties evaluation.
- OPAL using new physical principals of continuum similar to principals of mechanics of continuum and discreet media versus the continuous matter will produce new information about oil and gas reservoir performance.

There are many applications and measurements that can be performed only by OPAL:

1. Horizontal drilling and Logging, both conventional and unconventional sample collection with integrated surface measurements.
2. Directional tools loss mitigation in the well, resulting in measurements with safety.
3. Liquid Loss combination with OPAL for fractured reservoirs evaluation and CBM.
4. OPAL data logging in difficult and high temperature wells, where the data may be at risk.
5. Real time logging data unaffected by well bore damage due to long exposure to drilling mud invasion.
6. Analytical core like sample collection for well log reconstruction and reservoir properties characterization.
7. Gama Ray log depth control and correlation.
8. Drilling parameters optimization and increasing drilling bit performance.

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Appendix A

OPAL System Mechanical Components and Sensors

1) Mini Shaker is a device that separates the drilling cuttings from the mud flow. Mud flow is delivered to the mini shaker by the mud flow pump and input control system. Figure 6.

2) Drilling Mud with Formation Cuttings pump system. Consist from hydraulic mud pump specially designed to perform in high density cuttings slurry of mud and drill cuttings. The pump has a special device to prevent the shale out during high drill cutting output and soft shale consistency.
3) Analytical digitally controlled Auger with Sensor blocks. This system combined with the drill cuttings transportation system' than moves the cuttings along the sensor blocks.
4) The digital control system synchronizes the position of the drill cuttings with the Lag_ROP parameter (Lag_ROP – is the Bit ROP at the Lag depth).
5) 'Automated Sample Catching' device is an unmanned system (Figure 11). Show the Mini Core System. This system is designed to continuously sample the cuttings stream and prepare – Core like sample in the storage cup. The sample in the cup is washed and layered reflecting the formation stratigraphic sequence.
6) Liquid flow OUT Monitoring System monitors the formation response on drilling mud loss in the fractures and porosity of the drilled formation (Figure 12).
7. Differential Gas Detector continuously monitors the hydrocarbon content of the drilled formation. Dual gas detectors measures total gas (C1-C5) and heavy hydrocarbons (C3-C5) in the gas stream.
8. Turbine gas trap, injects air into the mud to help liberate the gas in the drilling mud, based on the diffusion of principle.
9. Gamma Ray Log sensors tool. Recording the naturally occurring gamma rays in the formations.
10. Gamma Spectrograph Log sensors tool. Spectral gamma ray tools provide insight into the mineral composition of formations. The total gamma ray spectra measured is resolved into the three most common components of naturally occurring radiation in sands and shale - potassium, thorium, and uranium (K, Th, and U, respectively).
11. Triple Resistivity Log sensors tool. Hydrocarbon Saturation and formation resistivity index log.
12. Density Log sensors tool. Continuous record of a formation's density. Providing porosity and lithology log information.
13. X-Ray Density Log sensors tool. Porosity log.
14. Flow Density Log sensors tool. Quantitative quality control Log for system performance and measurements environmental correction. Well Cleaning.
15. Flow quantity control Log sensors tool. Implementing the volumetric wellbore caliper.
16. Well cleaning.
17. Mud flow out Resistivity sensors tool.
18. Mud Flow out Temperature sensors tool. Formation liquid inflow.
19. Power distribution system includs the constant flow of cuttings to the OPAL and safety devises that prevent system overflow and environmental damage by mud spill.

Associated OPAL Software

1. Control and Calibration System Software. This software correlating the Depth with Lag Depth, monitoring and synchronizing with other measurements which are not lag depth dependent.
2. Data Transmission System. The communication system uses the WITS protocol from the OPAL data base to the user, and local protocol used internally from sensors to the Data Base.
3. Flow loss Log Calculation (Software). This system is monitoring the real time data current coming from Formation Liquid Loss System In – FLLS_In, not dependent on Lag Depth, and data coming from Formation Liquid Loss Out – FLLS_Out that are lag Depth Dependent in part. The Flow quantity is not lag depth dependent and flow density is reflecting the drilling conditions at lag depth.
4. Log Monitoring software system. This is customizable software for specific needs of Drilling information, Geological information, Petrophysical Information, Down Hole tools Safety information and Drilling Rig Safety Information presentation.

Figure 1. The OPAL system at the wellsite.

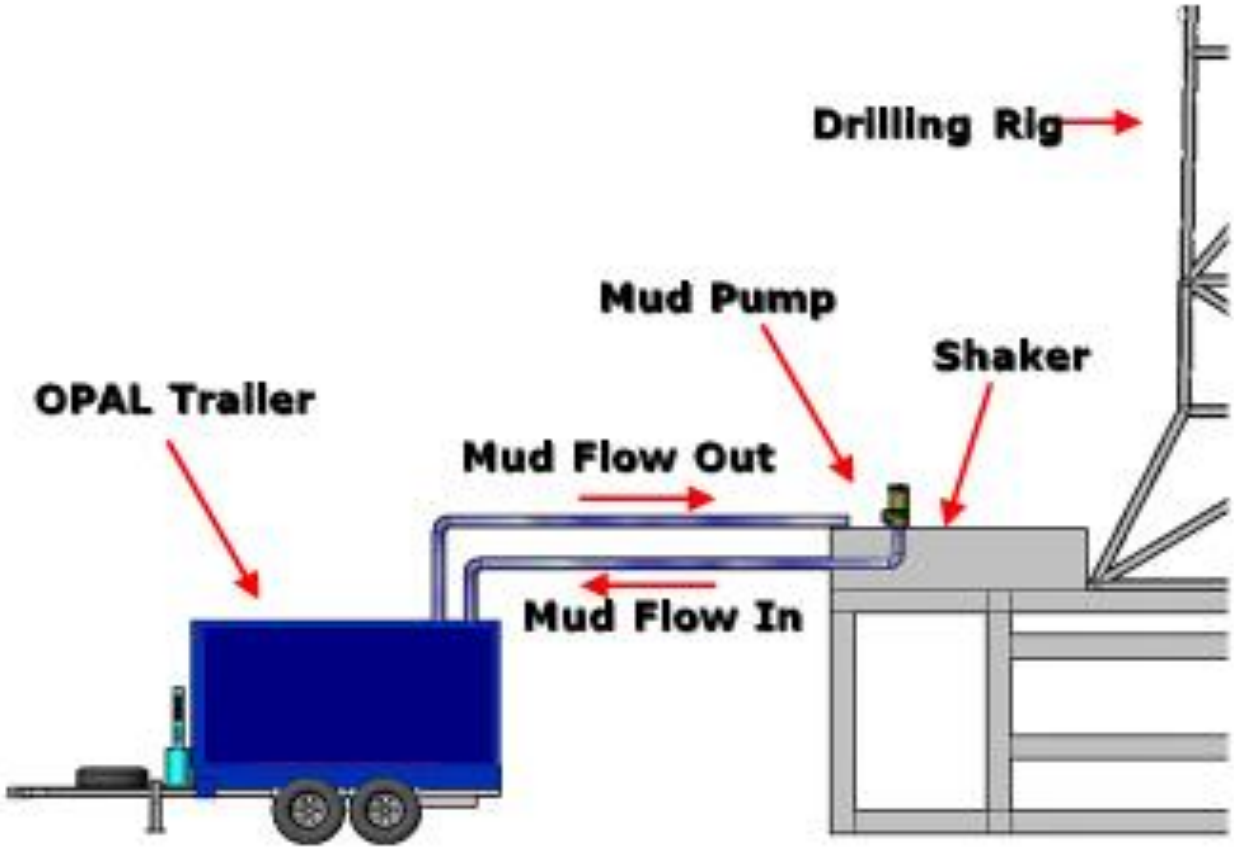

Figure 2. Conventional centrifugal mud pumps often get plugged by the drilling cuttings at the suction inlet. The dual pump system eliminates repeated clean up and guarantees improved performance.

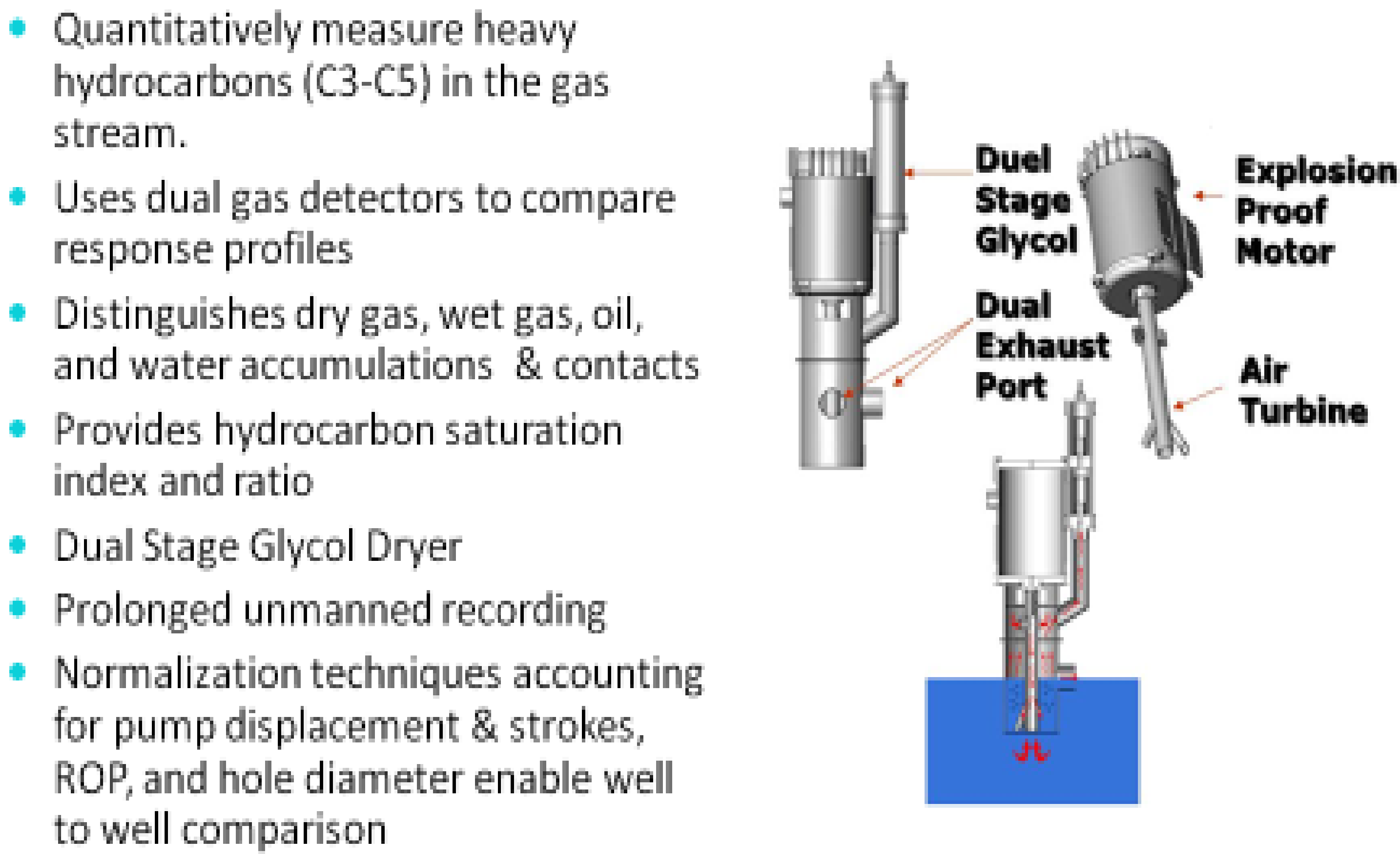

Figure 3. Turbine Gas Trap with dual stage floating bubble jar.

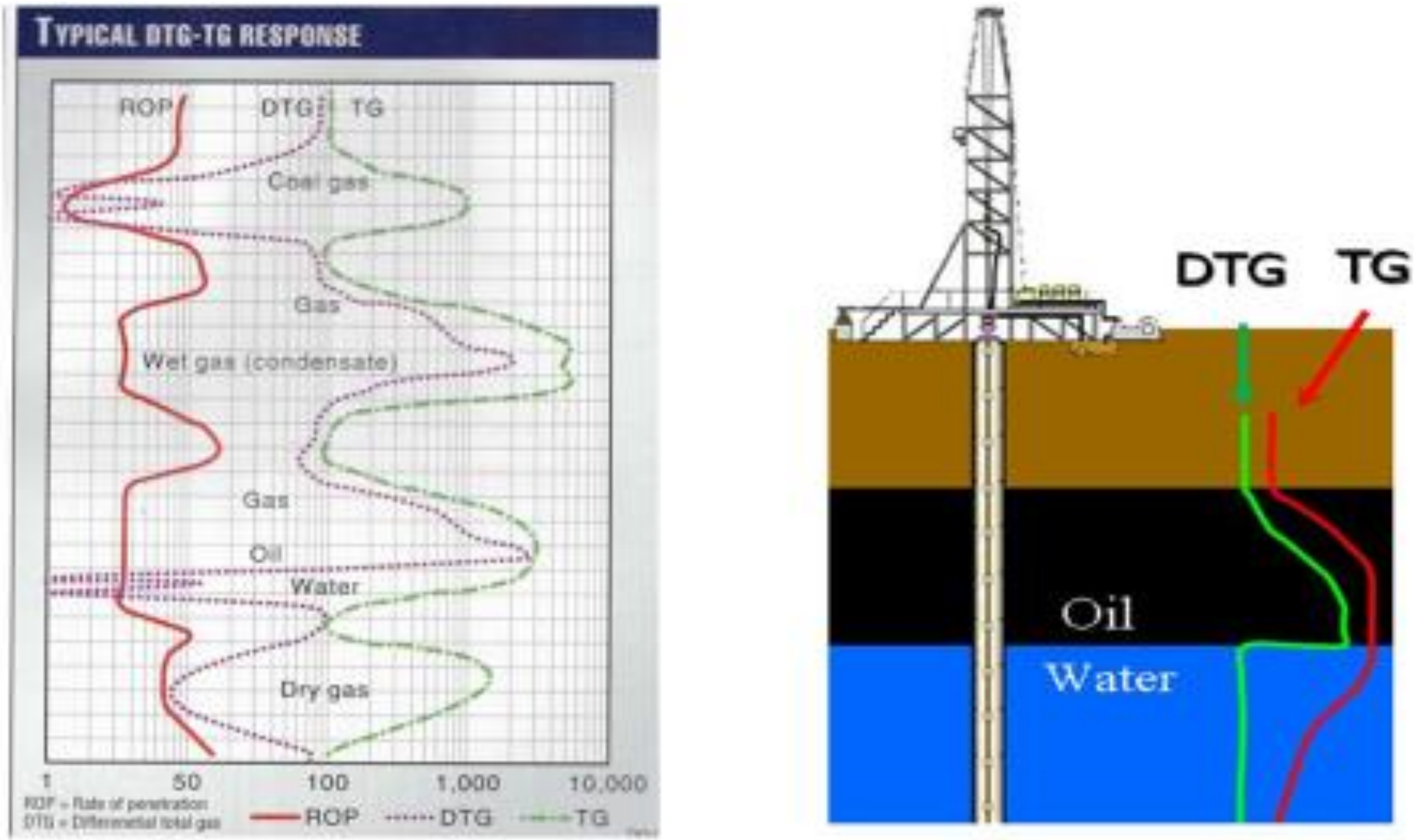

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Figure 4. DTG sensors define Gas-Condensate-Oil-Water contacts.

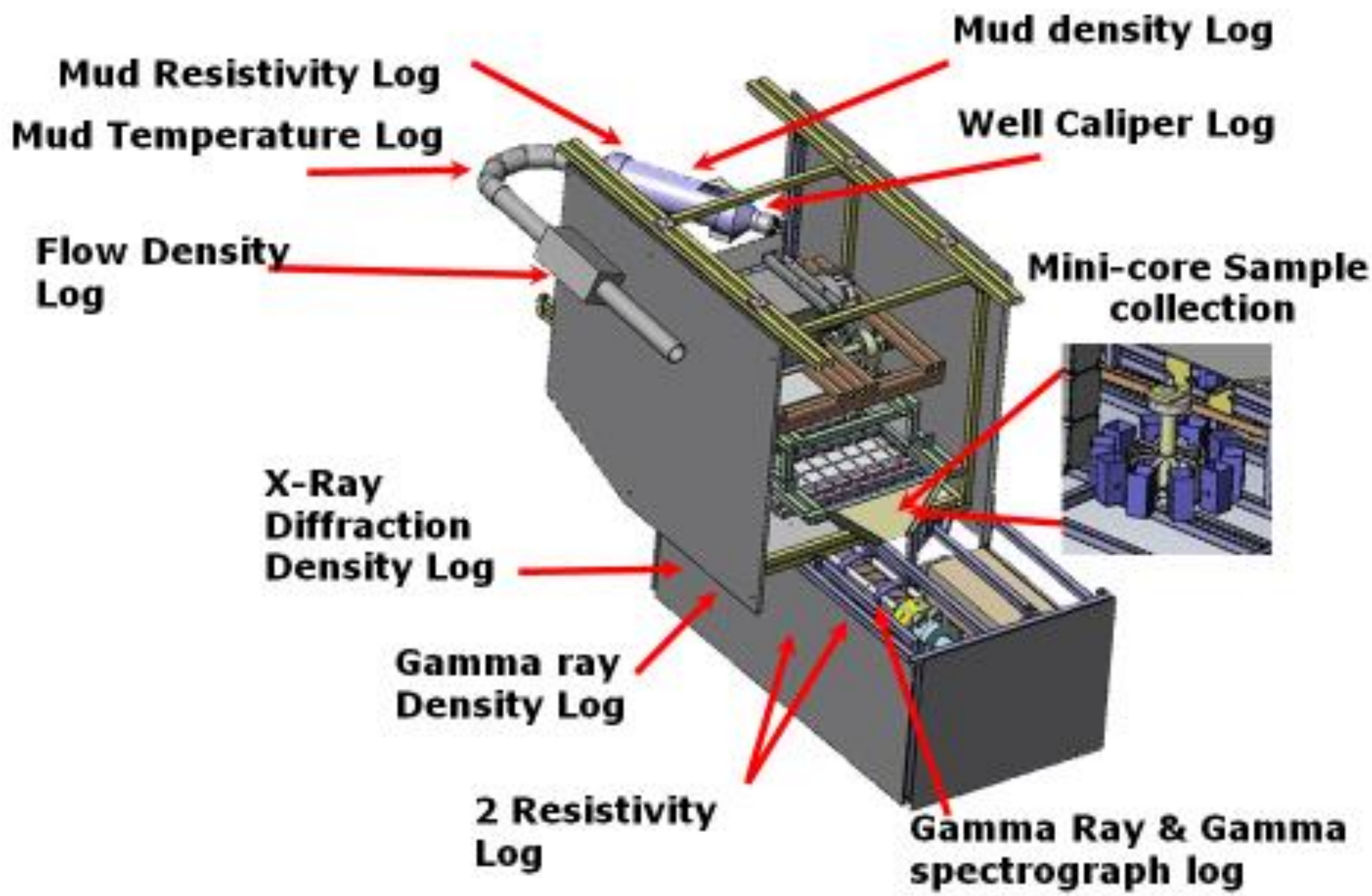

Figure 5. The OPAL produces a set of log curves that are comparable and equivalent to the MWD/LWD and Open Hole logs.

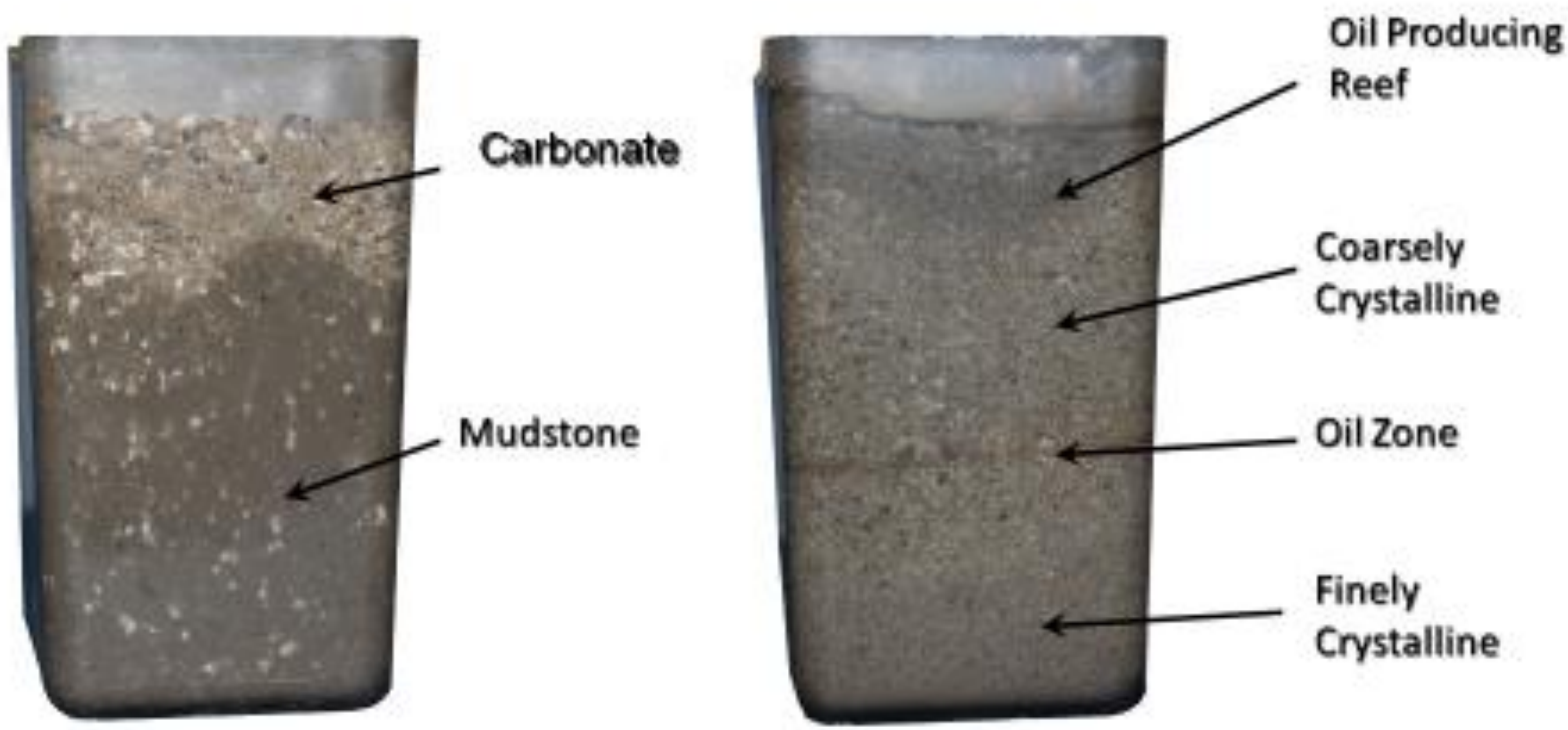

Figure 6. Depositional Sample Recovery System.

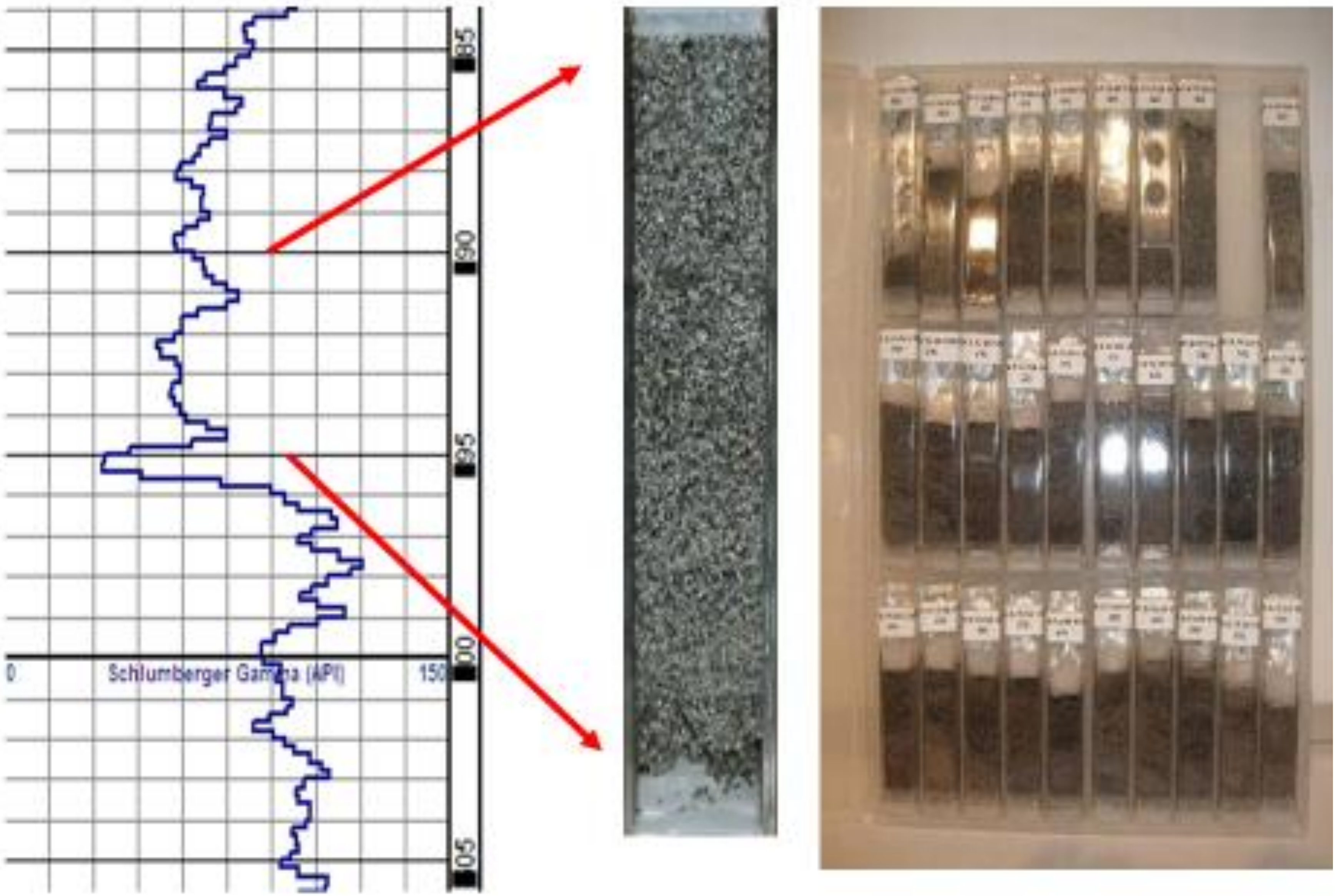

Figure 7. Mini-Core stored in vials books.

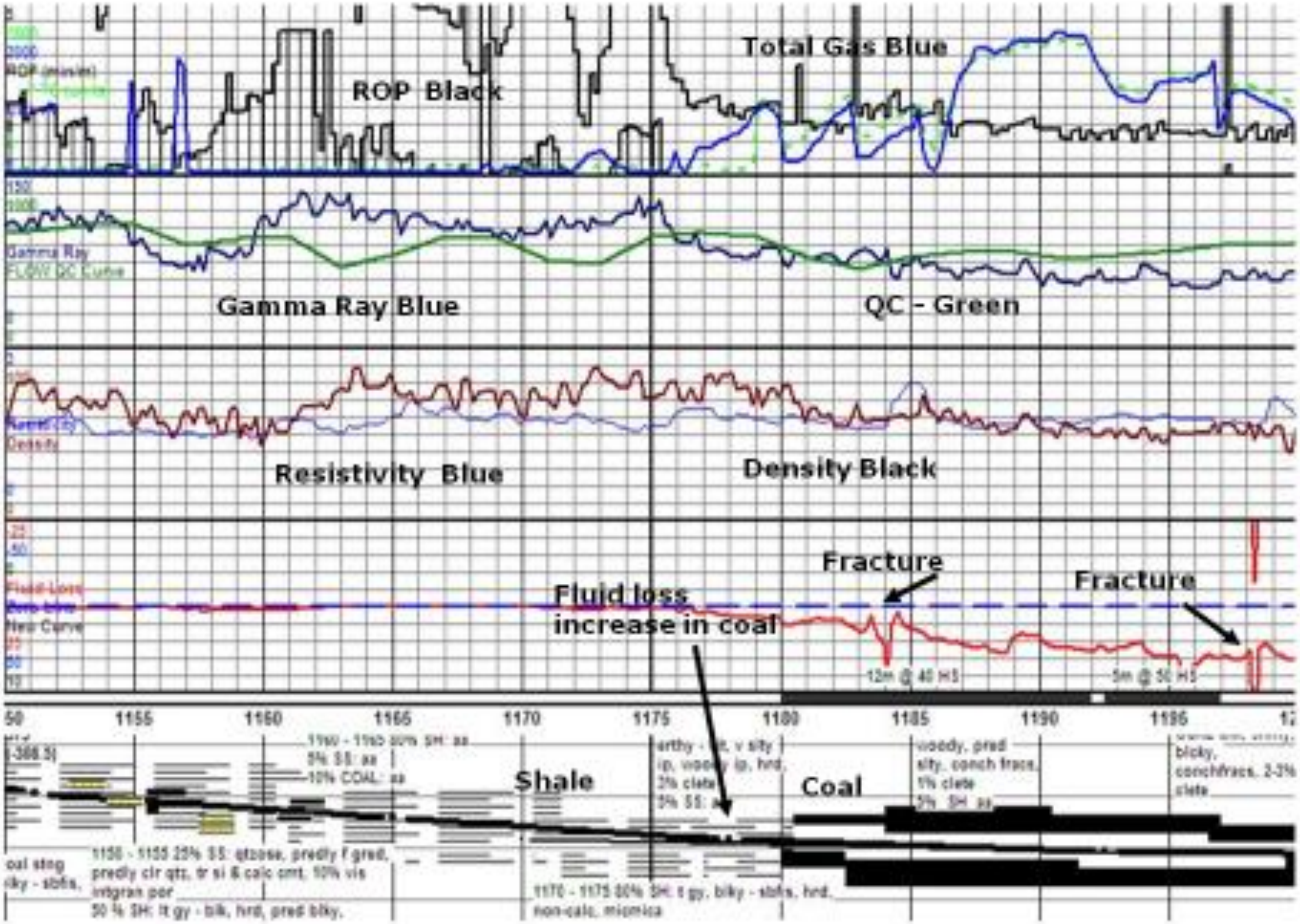

Figure 8. Example of Liquid Loss System.

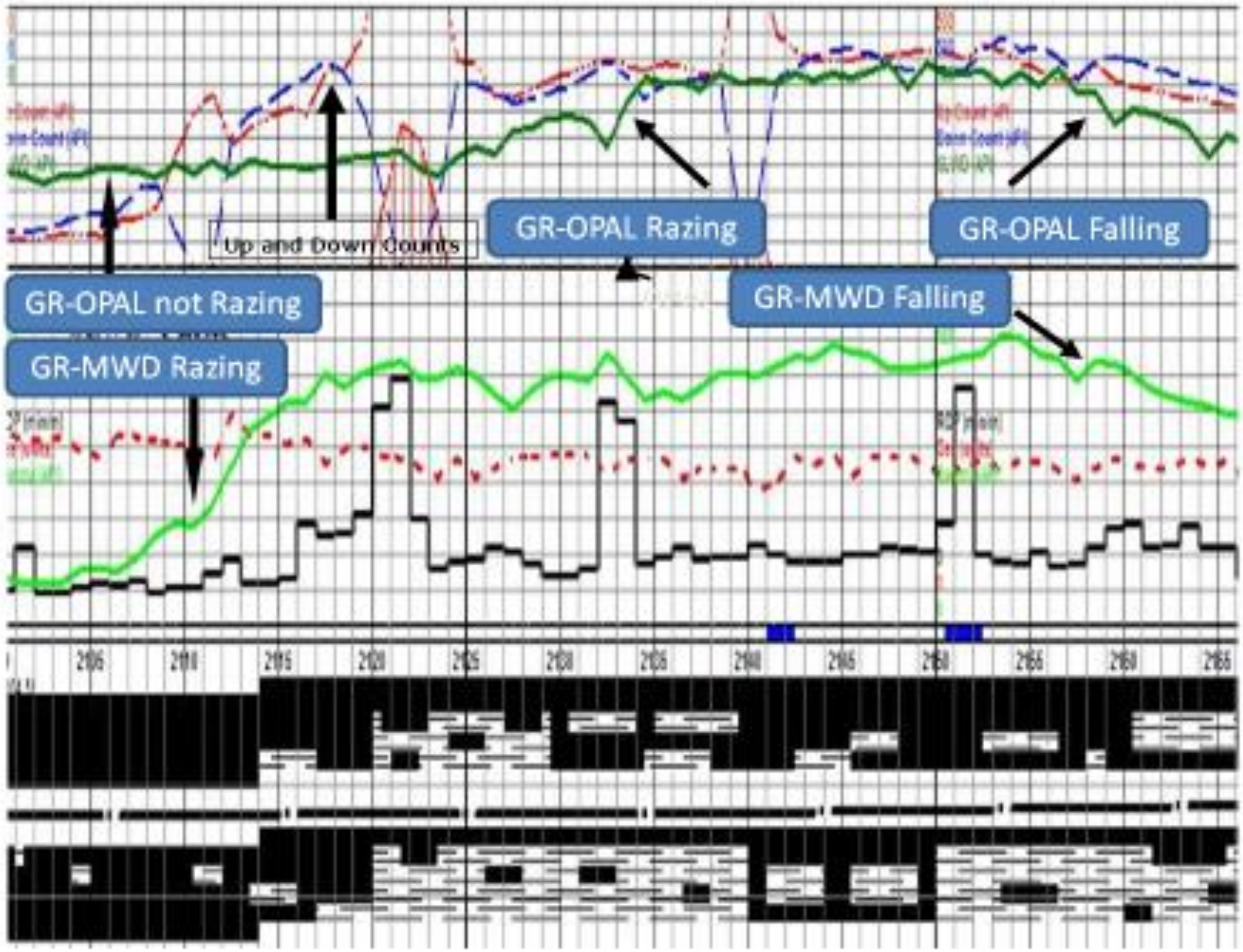

Figure 9. Example Well Stability and Stuck Pipe prevention.

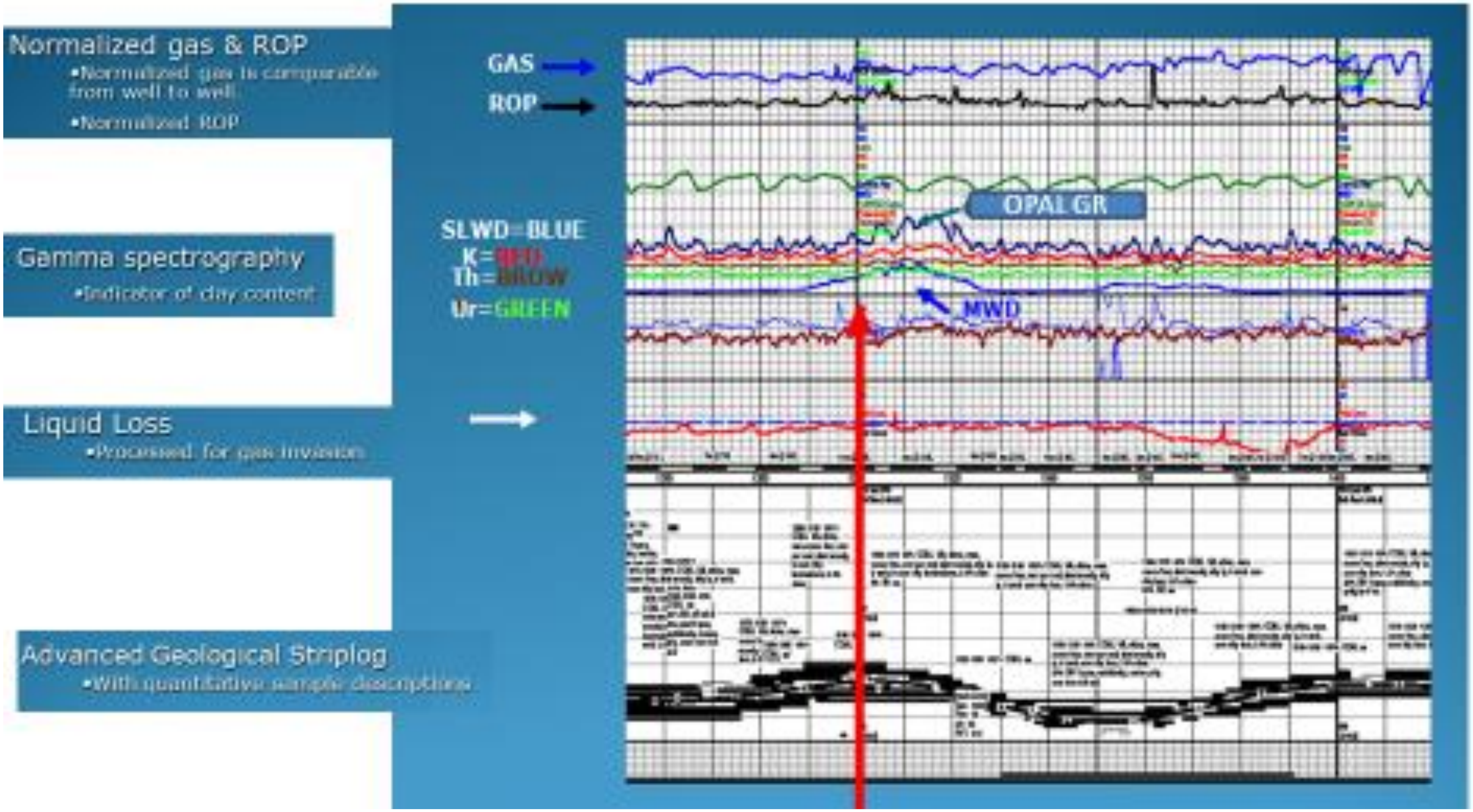

Figure 10. Example of good hole cleaning.

Figure 11. Automated Sample Catching system.

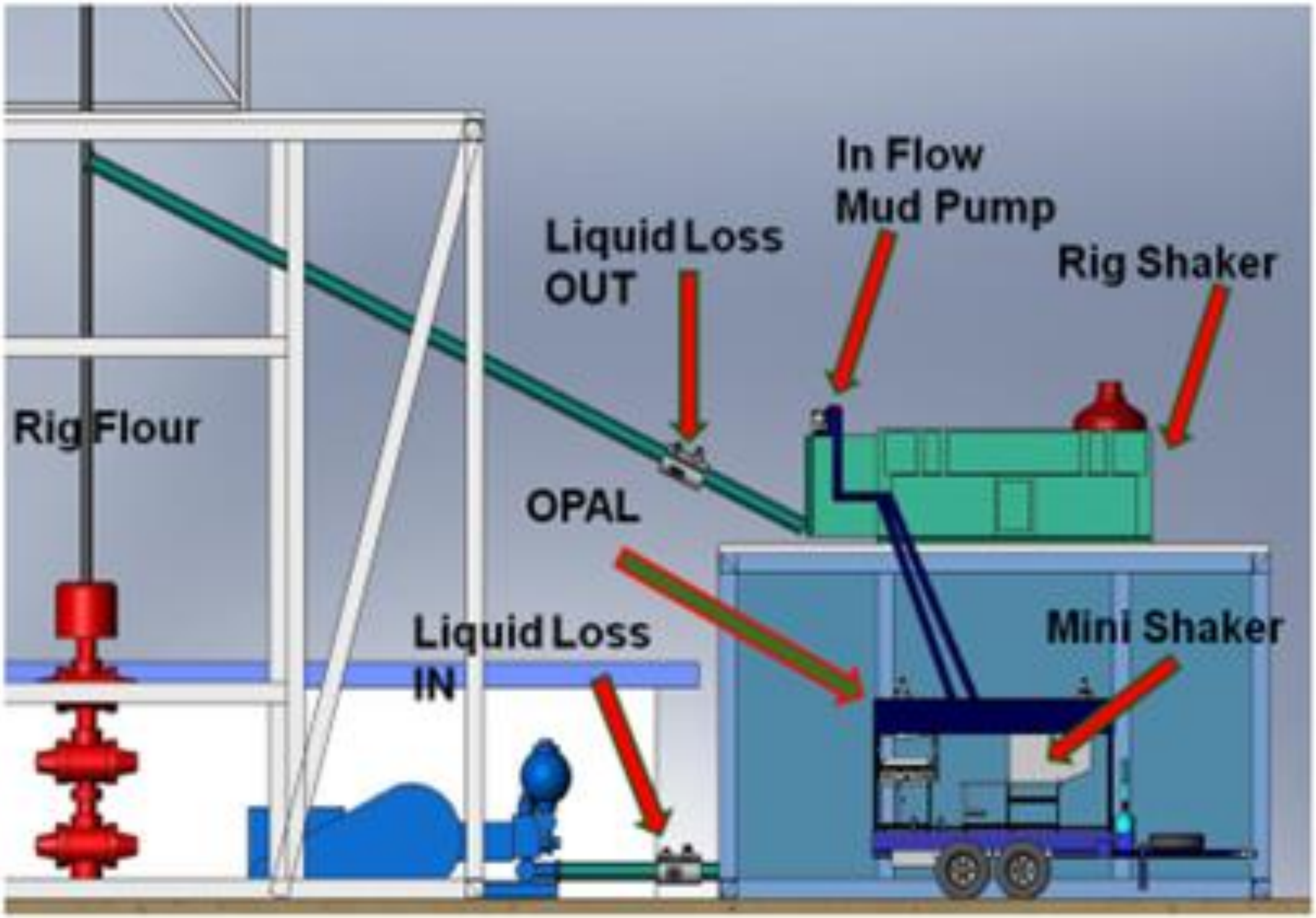

Figure 12. Liquid flow OUT Monitoring System.