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Production logging in horizontal wells without well intervention

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Abstract

For the last decade, the global trend in the oilfield industry is to improve the oil and gas production by drilling as well as by completing horizontal wells and later on, improving the process using multistage fracturing. Though the number of horizontal wells is rapidly increasing, the production of hydrocarbons is not always up to the designed volume. In this regard, acquiring the knowledge on the performance of producing intervals is an important task for operating companies to fully optimize the productivity and maximize the recovery as well. Production logging solutions proved to be efficient in vertical wells, however, encountered various challenges in horizontal laterals as the logged section is often more than 20 times longer compared to vertical wells [1]. Common factors that complicate the production logging are layered flow of formation fluid, deviation and accessibility of wellbore, and changes in fluid velocity moving past or through the tools. Direct transfer of production logging technology and interpretation algorithms from vertical wells to horizontal wells leads to erroneous conclusions about the well performance [2]. Moreover, the quality of well completion and reservoir management decisions for production wells largely depends on the production logging data such as mechanical flowmeter and fluid capacitance surveys.

Until recently, there is no alternative to wireline downhole tools being used to evaluate the placement of fracturing proppant or acids, production rate and zonal water breakthrough. In practice, well intervention in horizontal wells requires implication of coiled tubing or tractor services to deploy logging tools downhole. The success of well intervention depends on several factors and among of these are as follows: well accessibility, completion IDs and length of the horizontal lateral, etc. There are also key aspects to be considered such as the significant cost of well intervention and the availability of wireline and coiled tubing equipment. This article provides an overview of one of the alternative methods of production logging in horizontal wells which doesn't require well intervention using PLT tools, Coiled Tubing or Tractor services. This method employs tracer technology of quantum dot markers placed in the reservoir during stimulation. The method also allows reducing the cost as well as the complexity of

acquiring downhole data. Unlike the conventional PLT, the technology described below can provide production logs on demand during one year after well stimulation.

The demand for production logging in horizontal wells

In 2016, the number of horizontal wells being put into operation in Russia reached 2,457 units; an increase of 26.8% over the year. Currently, horizontal wells reached as much as 30.9% shares of all production wells [3]. It is expected that the share of horizontal drilling will increase and reach 46% of production drilling in 2018-2020 during the intensive development of new oilfields in Eastern Siberia [4]. Multi-stage fracturing operations in horizontal wells are relatively new and rapidly developing technology in the horizontal well stimulation segment. The application of multistage fracturing as a standard technique started since 2011. In recent years, the dynamics of the annual number of multistage fracturing jobs in Russia has experienced a stable growth, from 522 operations in 2010 to 3,751 operations in 2016 [5]. On average, a one multistage fracturing is operating in 7 stages on horizontal wells and 3 stages on sidetracks. However, there are few numbers of 20-stage fracturing operations executed by companies such as "Rosneft" and "Gazpromneft". In 2025-2027 perspective, as subject to active development of oil shale oil deposits, the average number of hydraulic fracturing stages increases up to 18-20 units per horizontal well [4, 5].

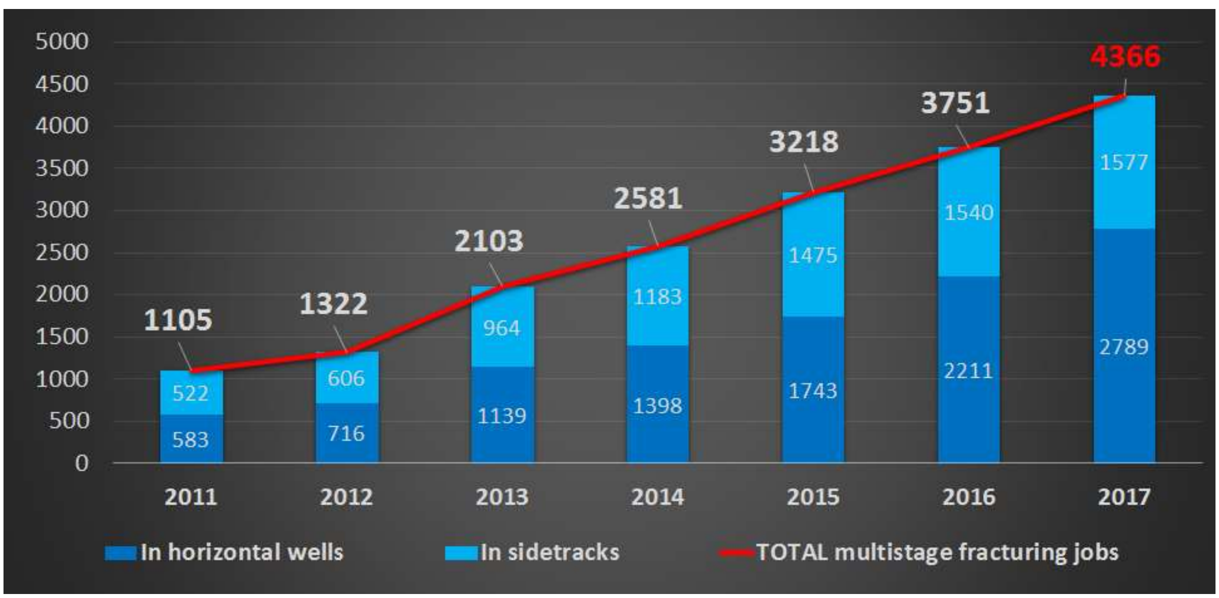

Figure 1. Dynamics of onshore multistage hydraulic fracturing operations in Russia in 2011-2017 (Sources: CDU TEK, RPI Eastern Europe).

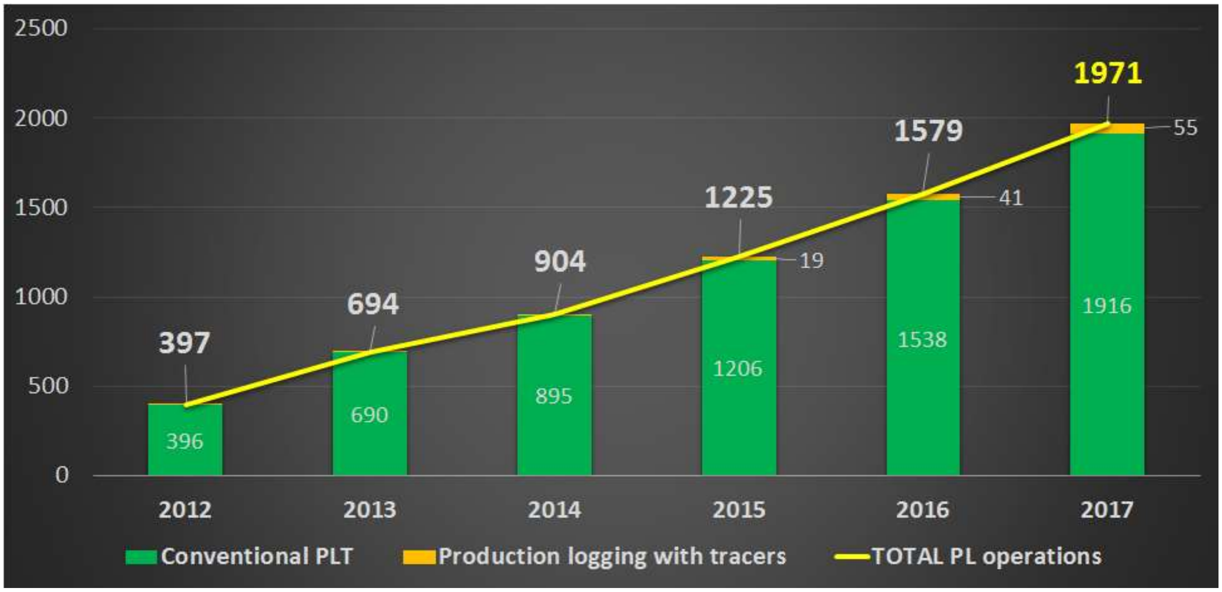

Figure 2. Dynamics of onshore production logging operations in stimulated horizontal wells in Russia in 2010-2016 (Sources: CDU TEK, RPI Eastern Europe).

Based on Figures 1 and 2, nearly half of the horizontal wells stimulated with hydraulic fracturing are examined with conventional PLT methods. At present, the completion design of horizontal wells consists of unregulated ports. Completion designs of nearby wells are often similar, and the significance of production logging is to provide well performance data with an option to optimise completion and stimulation design of planned wells. If well completion is equipped with controlled ports, this enables an option of opening, closing or regulating each port as necessary. Nowadays, only 12 % of horizontal wells are equipped with controlled ports. However, industry experts forecast that controlled and self-controlled ports will be implemented in 50% of all horizontal well completions by 2026 [6]. As oil and gas companies tend to use more sophisticated downhole equipment for multistage fracturing, the importance and demand for production logging data will also increase.

The specifications of horizontal laterals demand further sophistication of downhole tools such as increasing the number of spinners to cover wellbore cross section area. Further, when coiled tubing deploys logging tools in a wellbore, it may cause a choking effect resulting to the distortion of the downhole production rates data. Often, in horizontal wells, the standard mechanical flow measurement frequently becomes uninformative and instead, characterise fluid that filled up the lateral rather than the actual performance of the production intervals [7]. In comparison with vertical wells, the possibilities of de-noising inflows in horizontal wells by methods of thermometry are limited. This is due to a slight variation in geothermal temperature along the length of the horizontal section and lower differential pressure drawdown per layer than in vertical wells.

An equipment for measuring spectral noise downhole could help to detect a wave pattern of acoustic emission and to identify medium- and high-frequency anomalies associated with filtration of fluid through the rock within the critical matrix. These anomalies allow the determination of producing intervals differentiated from the low-frequency noise associated with the flow of formation fluid in the wellbore. However, this method requires non-stationary measurement technologies requiring periodic and time-varying measurements. The reason behind it is a sudden change in the wellbore fluid composition after the well is being put in production. The use of standard PLT downhole tools equipped with single flowmetry spinner is not adequate for horizontal well and leads to interpretation errors [8]. For better results, this required a specialized downhole tool capable of dealing with multi-phase and stratified flow [9]. Unlike in production logging with quantum dot markers, conventional downhole tools are designed to provide production data during well intervention only and do not give a dynamic picture extended in time. Finally, well intervention has some risk of coiled tubing stuck or loss of downhole tools in a well with a subsequent costly fishing operation.

Thus, there is a high demand for the development and application of more accessible production logging technologies to be used in horizontal wells. This can be addressed using alternative methods of production logging such as quantum dot tracer technology.

The technology of production logging without well intervention using quantum dot marker-reporters

Production logging data can be obtained in an alternative way using tracers embedded in proppant which are pumped downhole during fracturing. The main advantage of quantum dots tracer® technology is its ability to monitor the formation fluid production per zone at any time during a year after fracturing. Implementation of the technology is time efficient and does not require field equipment as well as crew for operation, which reflects on operating costs carried by customers. Indeed, the placement of tracers into the oil reservoir for a long-term period and the subsequent analysis of marker-reporters carried throughout the well and into the surface brings well management on a qualitatively new level. The technology features a synthesis of the combination of marker-reporters made of a few quantum dots and a mixture of the polymer-based chemical composition [10]. Quantum dots are nanocrystals produced using the process called colloidal synthesis. A single quantum dot is compounded of few hundred atoms and as small as 2-10 nanometers in diameter [11].

Colloidal quantum dots irradiated with a laser fluoresce in different areas of the electromagnetic spectrum due to quantum confinement [12, 13]. Compared with organic fluorophore dyes, also used for tracing in the oil industry, quantum dots have a fluorescence intensity 10-20 times higher [14]. Quantum dots are more chemically stable than natural fluorophors because of their chemical composition, which reduces the photobleaching effect compared to organic dyes and can withstand the impact of acids and high temperatures. The emittance of a particular spectre of light can be detected using flow cytometry method. Several quantum dots joined together creates a unique and traceable marker-reporters element. There could be a large number of possible tracer signatures (more than 60) that exclude the chance of misinterpretation during the lab analysis. This distinctive feature of quantum dot marker-reporters technology is essential in multistage fracturing of more than 30 production intervals in a single horizontal well. The polymer coating of fracturing proppant contains millions of marker-reporters and is designed to degrade gradually when in contact with hydrocarbons and water. During the fracturing operation, some proppant with tracers follow the mass of a conventional proppant. After the introduction of proppant into the formation, the coating gradually releases markers to formation fluid and further carried out into the surface. The marker-reporters can be captured either in oil or water phase of formation fluid. Due to the nanosize of markers, these materials do not have enough energy to make a transition from one phase to the other. Hence, each phase of formation fluid has its own indicators. The process continues and is without interruption for at least a year. On demand, samples of formation fluid are taken from sample point located in the production line and studied in the laboratory.

Fluid samples taken at the wellhead undergo a sample preparation procedure involving the separation of the hydrocarbon and aqueous phases of the formation fluid based on ASTM 4006 method on "Standard Test Method for Water in Crude Oil by Distillation" using a demulsifier and centrifugation at 3000 rpm.

Separated hydrocarbon and aqueous phases are further analysed in automatic mode and real time using a flow cytometer and especially designed computer equipment.

The flow cytometer suspends micro-particles in a stream of fluid and are passed by an electronic detection apparatus. The process allows simultaneous multiparametric analysis of the physical and chemical characteristics of particles including fluorescently-labelled marker-reporters.

Initially, a hydrodynamic focusing system is used in the microcapillary system, where due to the pressure difference between the sample and the flowing fluid, the marker-reporters are passed through the laminar flow of liquid one by one via the flow cell. Then, the particles are irradiated in the liquid with laser radiation and subsequently light scattering and fluorescence signals were recorded from each quantum dot in the marker-reporters.

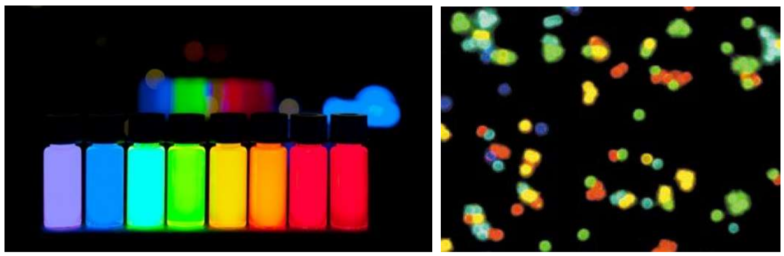

Figure 3. Colloidal quantum dots irradiated with a laser light. Different-sized quantum dots emit light of varying colours due to quantum confinement.

With the aid of a flow cytometer, the parameters of particles in the liquid being analyzed are recorded in order to determine the qualitative and quantitative compositions of the marker-reporters. The flow cytometer records two (2) types of light scattering: direct (small-angle) and lateral.

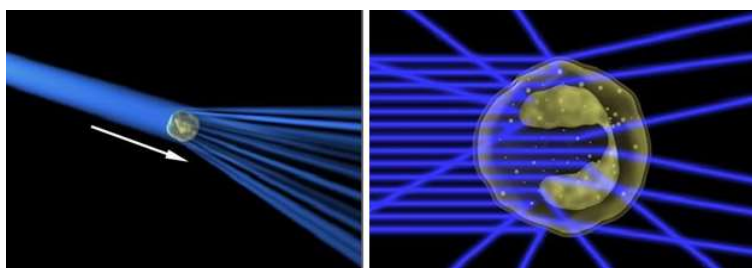

Figure 4. Direct and lateral light scattering.

The direct light scattering detector is located along the laser beam behind the flow cell and records the laser radiation, which is scattered at angles of 2-19 degrees. The intensity of light scattered at a small angle is proportional to the size of the particle. Larger particles scatter light more strongly than small ones.

The internal contents of the particles are optically non-uniform. The laser beam, passing through the particle, is repeatedly refracted and scattered in all directions. Registration of this radiation allows us to judge the shape, size and internal structure of the particle.

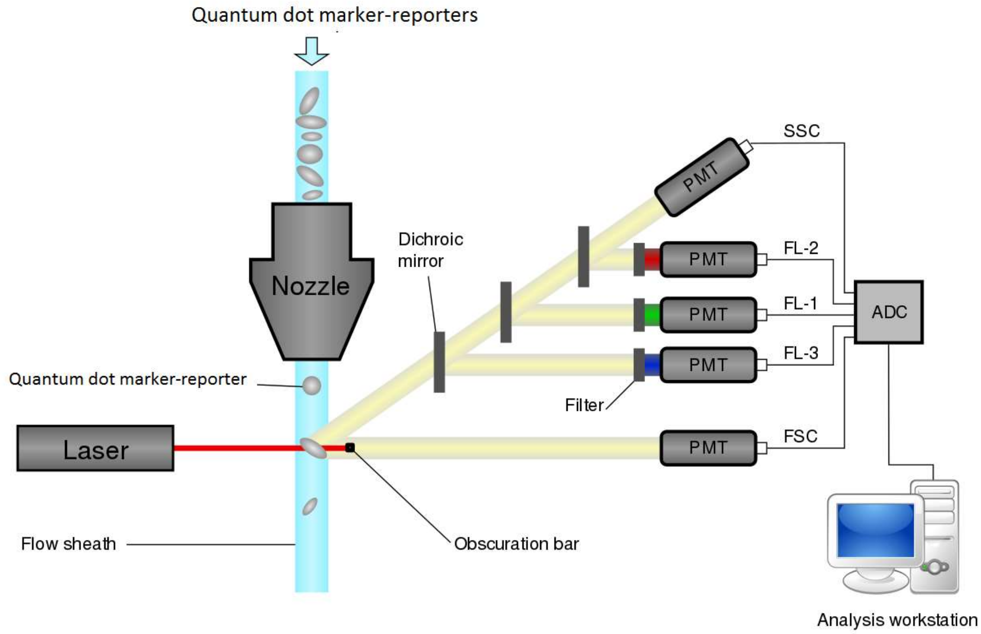

Figure 5. Flow chart of the flow cytometer.

As a result of the flow cytometer operation, "events" that are optical inhomogeneities in an optically homogeneous mobile phase are recorded. Since the optical markers used have a characteristic "glow", each in its spectral region at a fixed wavelength, the software register each of the signatures used for analysis among a large number of "events", were recorded by the flow cytometer. Quantum dots in markers-reporters are entered individually as well as in various combinations. In addition, the variable is not only their combination but also their different concentrations. Thus, using three (3) different quantum dots in various combinations by optical characteristics, as well as two (2) different concentrations (high and low), a large number of different optical signatures is created. Each marker-reporter signature corresponds to the specific region of the spectral space, which does not intersect the specific regions of other combinations of quantum dots. The software used for optical identification of each signature isolates the specific area of the spectral space (3D image) and count the registered "events" in each area. The definition of the specific regions described above is based on the data of laboratory experiments modelling each signature separately, as well as their numerous combinations. The data obtained is interpreted by a software and is visualized in the form of zones inflow charts along the stages of fracturing which shows accumulated oil and water production in each interval.

The technology validation

In 2016, the technology was tested in the laboratory under supervision of representatives of scientific centre of “Gazpromneft” company aimed to conduct research on the methodological readiness used in horizontal wells with multi-stage hydraulic fracturing. Laboratory tests performed on traced proppant technology focused on determining the initial concentrations of proppant by analysing quantum dot marker-reporters and included five (5) major steps as follows:

- Preparation and delivery of oil samples and proppant with two different signatures of quantum dot tracers;
- Mixing traced proppant with the formation fluid (a mixture of oil and water);
- Waiting until traced proppant releases marker-reporters into the formation fluid;

- Treatment and preparation of formation fluid to suit working condition of the flow cytometer;
- Determination of the initial concentration of two types of tracer marked proppant using cytometric analysis.

The laboratory tests used samples of proppant fraction 16/20 marked with two signatures of marker-reporters (GS-1 and GS-2). The experiment was conducted using crude oil samples taken from the Priobskoye field. In this study, three (3) 300 g samples were prepared and each sample had a different ratio of GS-1 and GS-2 proppant as shown in Table 1.

Table 1. Ratio of proppant GS-1 and GS-2.

Number of sample	GS -1, gramme	GS -2, gramme	Ratio GS -1 and GS -2, %
1	29	271	9,7 / 90,3
2	170	130	57 / 43
3	291	9	97 / 3

Crude oil was then added into the laboratory tanks in equal proportions by weight with the proppant. To release markers from the proppant to the liquid, samples were allowed to stand by for 1.5 hours at a temperature of 80 °C which simulate downhole conditions. After mixing, the liquid with marker-reporters was drained into a separate container. Thereafter, treatment procedure for samples was carried out to suit the requirements of flow cytometer apparatus.

Each sample treatment cycle consisted of the following:

- Formation fluid samples' phase inversion;
- Centrifugation to sediment markers-reporters at the bottom part of the sample;
- Use of surfactants and solvents to remove hydrocarbons;
- Use of membrane filters to transfer all marker-reporters into the distilled water.

Then, the flow cytometry apparatus identified the concentration of marker-reporters in each of three (3) samples and visualized results in the form of an "event registration cloud" as shown in Figure 6.

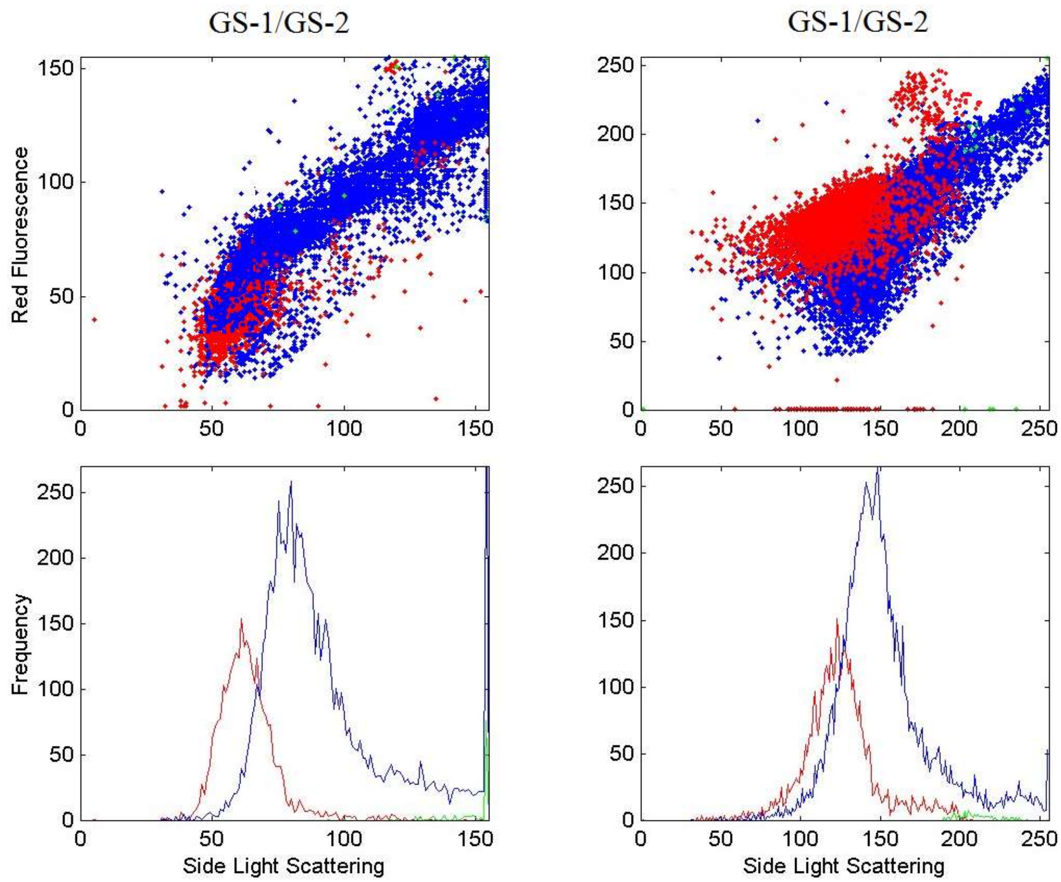

Figure 6. "Events registration cloud" shown by the flow cytometer.

The results of the cytometric analysis are presented in Table 2.

Table 2. The ratio of proppant GS-1 and GS-2 in three (3) samples, measured prior to the conduct of the study and according to the results of flow cytometry.

Sample №	Measured ratio of proppant GS-1 и GS-2, %	Ratio of proppant GS-1 and GS-2 using flow cytometry, %
1	9,7 / 90,3	10,2 / 89,8
2	57 / 43	62,6 / 37,4
3	97 / 3	96,4 / 3,6

The difference between the mixed ratios of proppant weighed before the conduct of study and the difference calculated from the results of flow cytometry does not exceed 6%. The high accuracy of the method was evident based on test results.

Meanwhile, the process of monitoring changes in inflow of several production intervals in horizontal bore was simulated in the laboratory located at Skolkovo scientific center in Russia.

The laboratory testing used an especially designed laboratory bench with a horizontally located barrel equipped with injection ports and performed at seven (7) intervals. Each interval was loaded with proppant having individual signatures of quantum dot tracers. Small electric pumps were used to inject a mixture of oil and water though the proppant simulating water breakthrough in the horizontal lateral. Injection rates and oil-water ratio were gradually altered throughout the experiment. The study was conducted based on 12 samples taken in 7 days. According to diagnostic results, and in accordance with the changes in injection rates, sequential oil inflow drops were detected in intervals 7 and 6. At the same time, both intervals showed a smooth increase in water inflow as detected by flow cytometry. The study illustrates that the total rate of water output as presented in Figure 7 revealed the increase of water production in intervals 7 and 6.

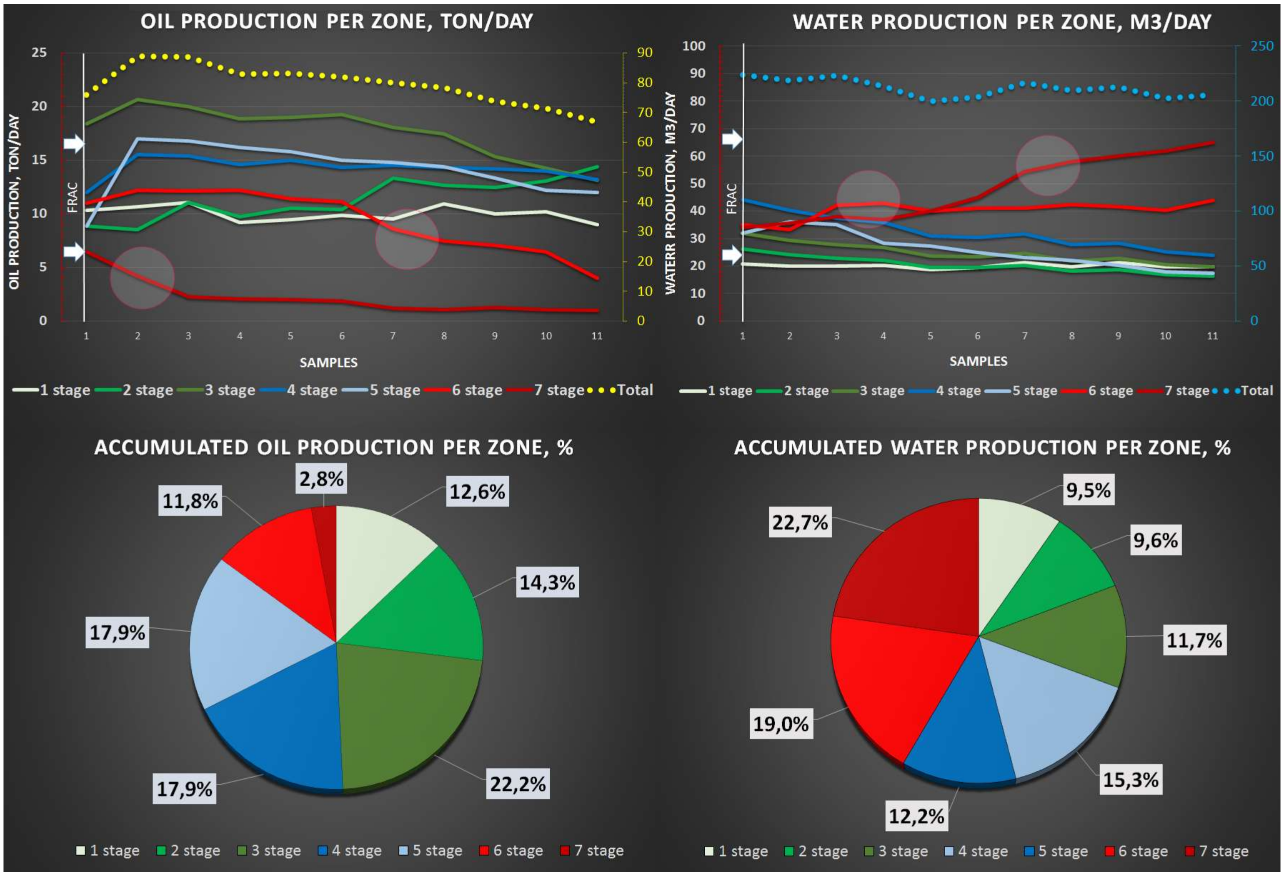

Figure 7. Consecutive decreases in oil inflow at intervals 7 and 6.

QA/QC aspects of the marked proppant field implementation

Together with the customer, the key job parameters are defined: the required number of signatures of the marker-reporters, proppant fraction to be used in fracturing operation and the schedule to obtain samples of formation fluid after fracturing. The production cycle takes 30 days, including the purchase of ceramic proppant, applying polymer coating with markers and exit inspection procedures. Further proppant is delivered to the customer's wellsite. In prior multistage fracturing operation, the field supervisor performs field quality control, which includes the acceptance of proppant at the site, validation of quality certificates and product tests. During the operation, field representative ensures the correspondence of the signatures with the assigned fracturing stage, take arbitration samples of the marked proppant, verifies the implementation of the approved work plan and track possible deviations from the job program. After the fracturing, customer representatives take samples of formation fluid at the wellsite according to the approved schedule and correctly label them for subsequent identification. Upon completion of the sample package stipulated by the contract, the company -provider of the quantum dot tracer services organises sample delivery to its laboratory. Samples are opened in the presence of the customer's representative at the same time preparing the acceptance certificate to prevent any discrepancies with the arbitration tests (stored by the customer within 1 year). Interpretation and generation of production logging report is within two (2) weeks upon which the report is delivered to the customer.

Field implementation

On August 2014, one of the oil & gas producing companies implemented hydraulic fracturing in a horizontal well located in one of the largest fields of the Khanty-Mansiysk District in Russia. Each of the four (4) fracturing intervals consumed 35 tons of regular ceramic proppant and 15 tons of proppant with quantum dot tracers. Microseismical surveillance of fracturing operation recorded data on the following: coordinates of microseismical events, excitation time, parameters of reliability, energy of each source, mean values of the propagation velocities of seismic waves from sources of origin to the surface.

Table 3. Well intervals and fracture parameters.

Production intervals				
	1	2	3	4
Measured depth, m	3134,3-3135,6	3245,7-3246,9	3343,3-3344,5	3438,7-3439,8
True vertical depth, m	2810,88	2811,46	2813,08	2813,96
Pumping rate, m^3/min	3,5	3,5	3,5	3,5
Proppant, tonne	40	40	40	40
Traced proppant, т	15	15	15	15
Parameters of fractures				
Fracture width, mm	2,57	2,94	4,21	2,9
Average fracture height, m	34,1	46,7	34,5	42,7
Fracture length, м	141,9	110,1	86,1	86,25

Microseismical survey confirms the fact of hydraulic fracturing in all declared zones. However, the subsequent one-time well intervention with production logging downhole tool showed zero production in interval 4 due to a flow rate below the activation threshold of the flowmeter's spinner, and a distortion caused by fluid layering in the wellbore. Simultaneous with the conventional production logging is the customer implemented quantum dot tracers' technology. The study of 16 samples taken during a one (1) month period indicated a well inflow per interval in dynamics. Unlike the conventional PLT well intervention method, the technology of production logging with quantum dot markers detected stable inflow in interval 4 during each of 16 studies.

Table 4. Comparison of intervals inflow data obtained using downhole tools and quantum tracer diagnostics

Production intervals				
	1	2	3	4
Production logging using downhole tools				
Interval flowrate, m^3/h	8	16	16	No data
Interval accumulated production, %	20	40	40	0
Quantum dot tracers production logging				
	19.8	13.0	14.3	12.9
	19.6	12.9	14.2	13.0

Interval flowrate, m^3/h	19.5	12.9	14.3	13.1
	19.4	12.9	14.3	13.1
	25.4	17.2	18.7	18.2
	25.4	17.2	18.6	18.3
	25.1	17.0	18.5	18.8
	24.8	16.8	18.6	19.2
	23.6	16.6	18.3	19.0
	23.1	16.5	18.4	19.6
	21.9	16.4	18.8	20.4
	21.5	16.8	19.5	19.9
	20.7	16.6	19.1	19.3
	20.5	16.9	17.4	19.0
	19.5	16.0	17.1	18.2
	19.4	15.8	16.9	18.7
Interval accumulated production*, %	31%	24,6%	22.2%	22.4%

*-Based on study of 16 samples

As shown in Figure 8, interval 4 contributed as much as 25% of the total accumulated oil production and 31% of the total accumulated water production. In comparison with the data obtained by conventional logging tool equipped with a single spinner, the data provided by tracer technology was more convincing for our customer.

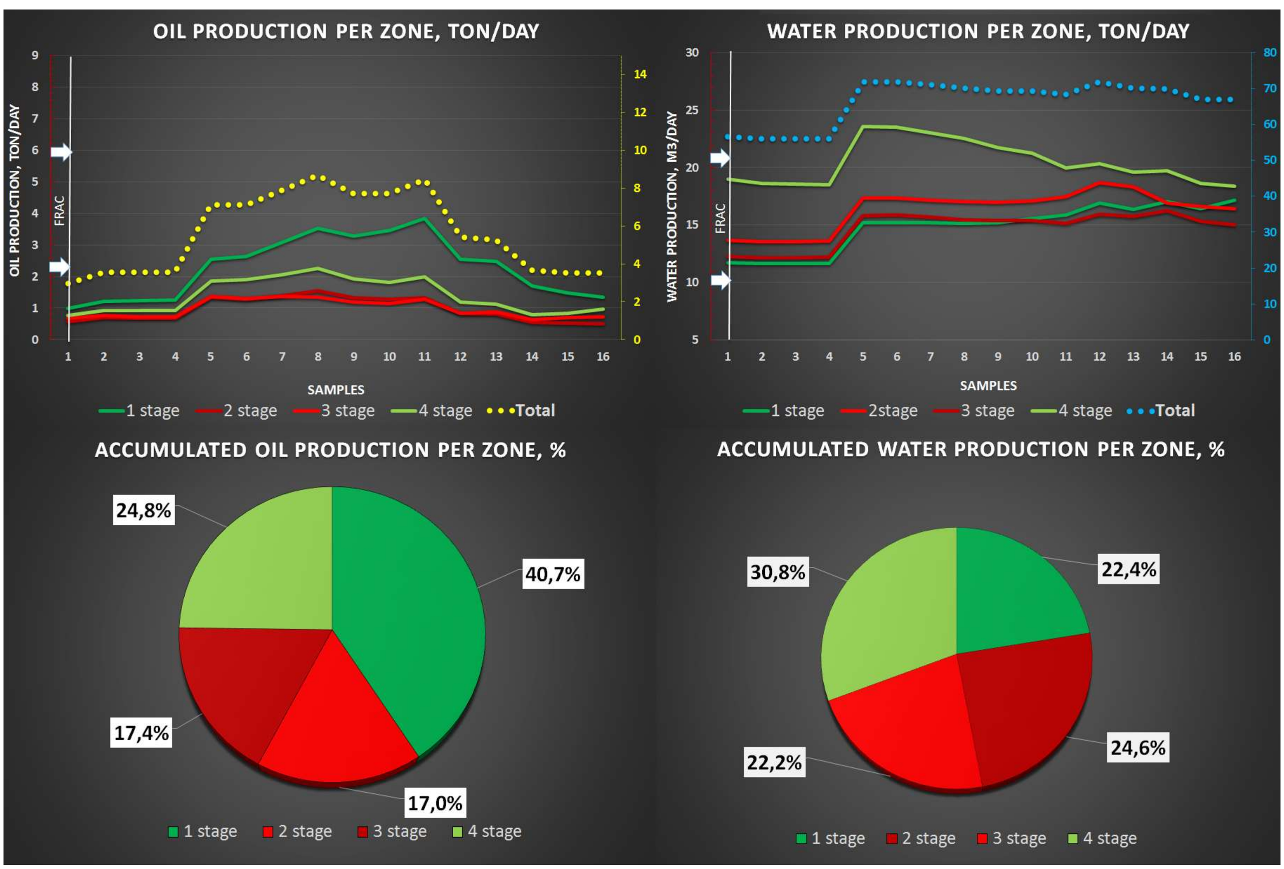

Figure 8. Interval 1 is the most productive while interval 4 is producing water at most.

Another case of tracers' technology field implementation is a horizontal well with a six-stage fracturing located in Urengoy gas condensate field. The study of production intervals inflow was conducted based on 15 samples of formation fluid of which samples are taken within 300 days. Each fractured interval was filled up with 10 tons of proppant marked with quantum dot marker-reporters. This case allowed the most complete implementation of technologies' monitoring function as it had an extended sampling schedule. As shown in Figure 9, all six intervals initially showed a suitable gas condensate inflow. Three months later, intervals 5 and 6 experienced rapid increase in water production. However, analysing the accumulated production during the entire period of conducting the research study, it can be concluded that all intervals contributed in the total production of the well are relatively uniform.

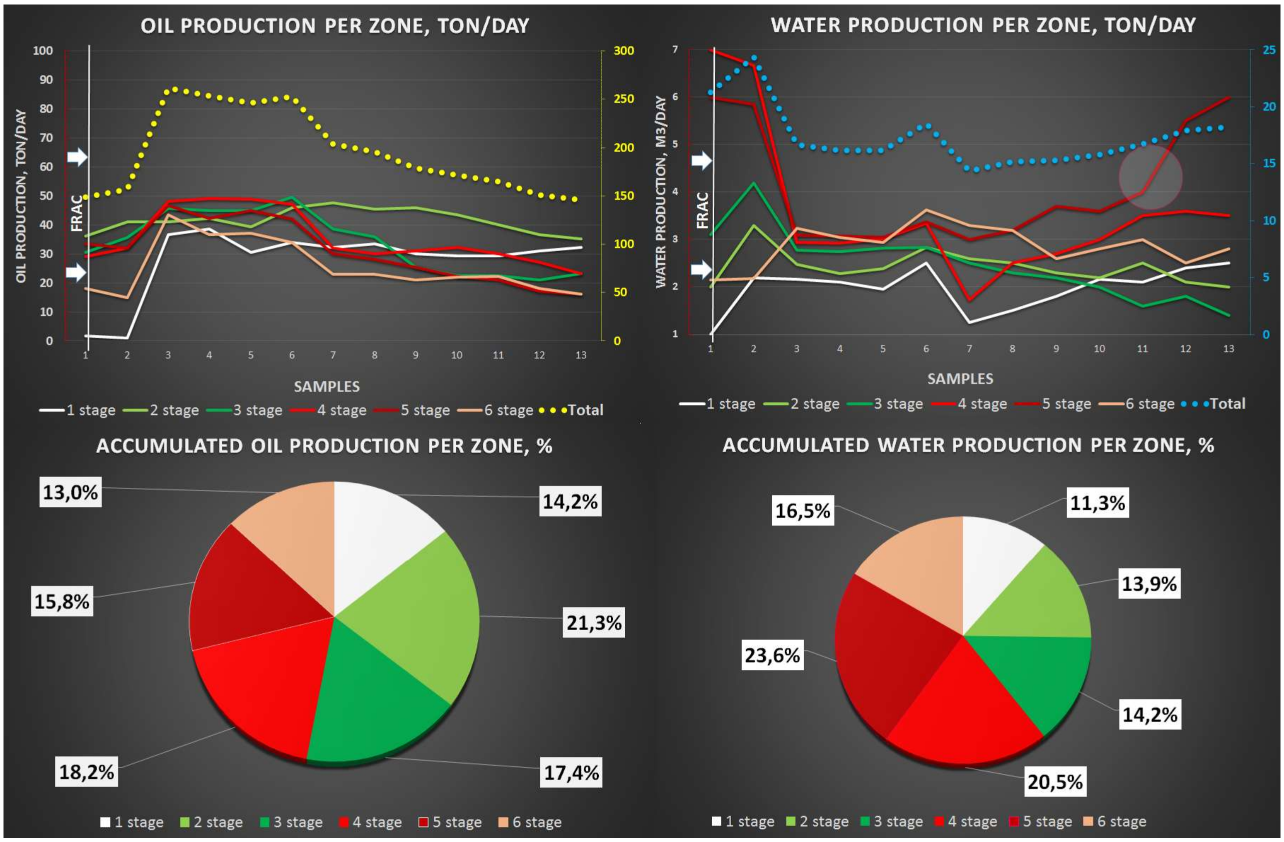

Figure 9. Intervals' production rates and cumulative production.

Conclusions

Based on the field implementation results, there are few modifications has been made to address lessons learned. The total number of marker-reporters in samples of formation fluid collected decreased over time in 7-10 months and influenced the accuracy of production logging data. To ensure the high accuracy of research throughout the declared period of one year, the developers of the technology doubled the concentration of markers in the polymeric coating of proppant while maintaining its physicochemical properties including the estimated reaction time with the formation fluid.

Qualitative and quantitative analysis of quantum dot marker-reporters in samples of formation fluid allows making informed conclusions about the performance of productive intervals of horizontal well. Application of the technology in the fields of the leading Russian oil and gas companies in 2016-2017 showed the following benefits:

- The possibility of monitoring inflows for a long period of time, in contrast to a one-time logging operation;
- A significantly lower resource intensity and cost;
- Confidence in conditions when the traditional downhole logging operations are complicated.

Quantum dot tracer technology allows solving a number of problems, such as:

- Post fracturing inflow profile evaluation extended in time;
- Assessment of each production interval in regards to water and oil production;
- Optimization of technical solutions for well completions in the early stages of field development, such as number of ports;
- Analysis of hydrocarbon extraction ratio;
- Detailed information in the analysis of mutual influence of neighbouring wells in the oilfield.

The application of the technology is particularly effective in the early diagnosis of water breakthrough. Timely and efficient identification of reasons and places of water breakthrough is a key factor as it allows enough time to choose the right technology for water shut off operation [15]. In Russia, only around 30% of wells reach designed volumes of oil production [16]. Less than 60% of all water shut off operations are successful as it lacks timely and cost-effective diagnostic instruments [17]. Ultimately, this fact reflects in declining production rates and increasing incurred costs.

The future development of production logging tracer technologies may happen in few directions. One of the alternative versions of the tracing technology is locating markers in the well completion equipment being deployed downhole. When markers are loaded to casing configuration, it is required to design and manufacture well completion components individually for each production interval. Such technical solution makes each well an individual project which implies multiple increases in the time and cost of the operation.

It is important to mention that as additional materials are placed in the casing design, the contact area between the formation and the wellbore is reduced, which can affect the production rate of the well. The space in the downhole equipment is limited and capacitate small amount of polymer inserts with markers. Thus the chemical composition of the polymer has to be changed in order to reduce reactivity with formation fluid. In this case, well production has to be stopped for 8-10 hours to accumulate suitable concentration of markers in the formation fluid.

Multi-stage fracturing is one of the widely used methods of stimulating horizontal wells. The second method is the acid stimulation of openhole laterals (or uncemented liners) in carbonate reservoirs with the aid of coiled tubing service. Acid stimulate creates a dendritic structure or wormholes in the near-wellbore area of the formation called "critical matrix". During acid stimulation, signatures of markers mixed with stimulation fluid penetrate through wormholes and stick on the rock surface. The entire length of the horizontal section is virtually divided into 20-30-meter intervals with corresponding signatures of markers gradually emitting into the formation fluid and indicating interval performance.

List of references:

1. SPE 120591, Horizontal Well Production Logging Deployment and Measurment Techniques for US Land Shale Hydrocarbon Plays, Duncan Heddleston, SPE, 2009
2. "Production logging in horizontal wells under condition of low unstable inflow", Kolesnikova A.A., Kremenetsky M.I., Ipatov A.I., Kovalenko I.V., Komarov V.S., Nemirovich G.M., Oil Industry Magazin, 2016
3. CDU TEK, Central Dispatching Department of Fuel Energy Complex, Completed wells in horizontal drilling, 2017
4. Rudnitsky S.V., Ananenko S.A., Kravets V.A., Market research report "The production logging and multistage hydraulic fracturing market in Russia". RPI Eastern Europe, 2017
5. CDU TEK, Central Dispatching Department of Fuel Energy Complex, Hydraulic Fracturing, 2017
6. CDU TEK, Central Dispatching Department of Fuel Energy Complex, Completed wells in producing drilling, 2017
7. "Keeping Producing Wells Healthy", Akhnoukh R., Leighton J., Bigno Y., Schlumberger Oilfield Review Magazin, 1999, Volume: 11, 30-48
8. SPWL-2005-A, Overview Of High-Angle And Horizontal Well Formation Evaluation: Issues, Learnings, And Future, Society of Petrophysicists and Well-Log Analysts, 2005
9. OTC-26414-MS, Integrated Wellbore Suveillance Techniques for Effective Reservoir Management Plan, Offshore Technology Conference Asia, 22-25 March, Kuala Lumpur, Malaysia, 2016
10. Gurianov A.V., Katashov A.U., Ovchinnikov K.N. "Production logging using quantum dot tracers", Coiled Tubing Times, Volume 60, 40-49.
11. Kawasaki et al. Nanotechnology, nanomedicine, and the development of new, effective therapies for cancer. Nanomedicine: Nanotechnology, Biology, and Medicine. 2005; Volum 1, 101-109
12. Alivisatos, et al. Quantum dots as cellular probes. Annu. Rev. Biomed. Eng. 2005, 55-76.
13. "Quantum size effect in the optical-spectra of semiconductor micro-crystals", Ekimov A.I., Onushchenko A.A., Soviet Physics: Semiconductors, 1982, 775–778.
14. Gao et al. In vivo molecular and cellular imaging with quantum dots. Current opinion in biotechnology. 2005, 63-72.
15. "Water control", Bailey B., Crabtree M., Tyrie J., Elphick J., Kuchuk F., Romano C., Roodhart L., Schlumberger Oilfield Review Magazin, 2000, Volume: 12, 30-52
16. "The future of oil recovery factor", Oil and Gas Vertical Rus, 2012, Volume 2, 60-63
17. Diagnostic and workover operations in oil and gas wells, Budnikov V.F., Makarenko P.P., Uriev, Nedra, 1997, 226