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Confirmed Effectiveness of Tracers' Production Logging in Comparison with Conventional Production Logging

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Abstract

Due to traditional oil and gas reserve depletion, the share of unconventional, hard-to-recover oil and gas reserves is constantly expanding. The cost of horizontal well stimulation used to increase oil recovery rate using multi-stage hydraulic fracturing is significantly higher. Addressing this requires the implementation of new technologies and services to facilitate optimal drilling, completion and stimulation returns, thus shifting the focus to analyzing well productivity increases. The use of developed production logging technology allows oil and gas producing companies to efficiently determine well productive intervals, thereby indicating high production rates and maintaining the profitability of operating wells by eliminating non-productive intervals. This data allows for planning field development with higher profitability by increasing the oil recovery rate.

Introduction

The development of unconventional hydrocarbon reserves, including the Bazhenov Formation, is an important strategic objective, not only in Western Siberia but throughout the country. The complexity of developing the Bazhenov formation arises from high risks associated with a small degree of reserves exploration - tight oil and gas reserves cannot be developed using conventional methods.

The complexity of Bazhenov formation development is primarily a result of the characteristics of the formation itself; oil and gas in this case are also associated with the presence of kerogen, hydrocarbon compounds physically associated with kerogen and the matrix of formations, as well as free hydrocarbon compounds forming mobile oil accumulations in interconnected isolated pores. This category of reserves requires implementation of non-standard approaches to prospecting, exploration and production. It also requires new methods and technological solutions. The technology of horizontal well drilling with multi-stage hydraulic fracturing is considered fundamental, however, the methods used in this case are also unconventional because of the resulting high pumping rates, significant volumes of pumped fluid, and complex equipment. These peculiarities distinguish MFrac technologies used in Bazhenov formation from those that have been successfully applied in conventional formations in the past.

In 2016, for the first time in the Russian Federation, Gazpromneft PJSC implemented a full cycle of oil development technologies for unconventional reserves of the Bazhenov formation. This was done under conditions of technological restrictions imposed by sanctions. In addition to the cumulative assessment of the resource potential of unconventional reserves on current assets, one of the primary challenges facing the oil producing companies is the selection and testing of technologies for the development of unconventional reserves. The development and completion strategy is largely based on geological prerequisites and involves the introduction of cost-effective production technologies and high-tech equipment.

Historically, the analysis of multi-stage hydraulic fracturing operations efficiency was based on geological and hydrodynamic modeling that considered petro physical features, including the analysis of reservoir characteristics such as porosity, permeability, mineralogy and total organic carbon. However, the determination of flow profiles in production wells serves as the basis for making technical decisions that seek to increase efficiency in field development and optimize well construction solutions or capital workover operations. In this regard, the interest of production companies in well production logging technologies is conditioned by the potential significant cost savings and increase in the quality of logging works.

Today, several conventional production logging methods are used:

1. Field and geophysical research with PLT
2. Using ICD, ICV couplings (smart well completions ICD, ICV)
3. Using fiber optic sensors and additional software
4. Tracer-based studies (marker technology)

Conventional PLT logging and marker-based studies can be distinguished among the methods listed above as they provide the most reliable production logging methods in terms of accuracy and reliability of the resulting data.

Undoubtedly, the adaptive smart completion system is an important tool for developing horizontal wells. This system can be adjusted independently considering the speed, phase composition and fluid pressure. In this case, production logging is carried out using fluorescent tracers placed in the filter. One part of the tracer dissolves when it comes into contact with water, and the other dissolves when it comes into contact with oil. The color of the tracers corresponds to the horizontal well interval, allowing for evaluation of the operation of a particular area. However, the inflow profile data obtained by analysis of the samples with tracers are most often ambiguously interpreted. In this case, fluorescent tracers are not monodisperse, i.e. their size varies greatly, introducing significant error into the model used for production logging and data interpretation. This method is more suitable for qualitative production logging, but not quantitative logging.

The production logging method that utilizes fiber optic sensors and specialized software also has its drawbacks. On the one hand, downhole temperature logging has visible advantages over traditional flow measurement methods for the quantification of low flow rates due to higher sensitivity. Despite this, the present method has limited measurement accuracy, and the simultaneous influence of several processes on the thermal field causes additional ambiguity during data interpretation. In addition, quantitative evaluation using temperature logging methods cannot be performed without obtaining reliable data. Since the informative capacity issues of production logging method using fiber-optic sensors, as well as processing and analysis of the obtained data remain open, the application of such sensors for well development cannot always be considered rational.

Difficulties with Conventional PLT

Production logging of oil, gas and water inflows is a key objective for establishing an optimal strategy for production and development, as well as for the purpose of planning repair and water insulation works in a well. However, conventional PLT methods do not always produce satisfactory results due to the horizontal wells with MFrac flow characteristics, which are traditional for the Bazhenov formation development.

Stratified fluid flow, the presence of gas bubbles, possible recycling of the heavy phase, and separation of the flow at different speeds impose serious restrictions on the use of standard logging tools. The dynamic characteristics of multiphase flows determine its variability along the well. Therefore, the measurements made in the well lateral center do not provide adequate measurement accuracy as the sensors of conventional tools are placed in the completion at a considerable distance from each other, further complicating the analysis.

The influence of these factors is exacerbated by the complex trajectory of the horizontal well. The presence of sections with both a descending and ascending path leads to the appearance of stagnant zones and traps for water and gas in the well. Under these conditions, mechanical flow measurement is not uninformative and sensor indicators primarily display not the formation operation, but the nature of the well filling. Temperature logging also does not allow for determining how the formation works. This is because the temperature varies uniformly over the entire length of the well and there are no clear anomalies.

Contemporary foreign developments have been able to solve some of these issues, enabling the performance of efficient horizontal well production logging. The specialized PLT complex involves the application of multi-sensor systems located along the horizontal section, which include highly sensitive mini-flow meters, and electrical and optical composition sensors. The design of the device allows users to better consider the multiphase nature of the fluid flow and register more relevant data to determine the well flow profile compared to conventional PLT logging.

However, modern tools also have a number of disadvantages that complicate the successful implementation of horizontal well production logging. In cases of slight well flow, the process's capacity to analyze well flow profile and composition is significantly reduced. When developing unconventional reserves of the Bazhenov formation, low flow rates are quite common. This reduces the chances of obtaining informative data using these tools. Another serious drawback is related to the comparative fragility of the equipment (mechanical flow meters, optical and electrical sensors). In the event of damage to one of the elements of this equipment, the obtained data is corrupted and must be discarded. It is also important to note that Bazhenov formation reserves are often characterized by low reservoir properties and, therefore, show low production profitability rates. In such conditions, the use of specialized foreign horizontal well production logging methods is significantly limited by their high unit cost.

Study Object

Complex evaluation of production logging technologies was conducted at one of the company sites, and several technological solutions were implemented at one of the fields in Russia. The study object is a production well where a 7-stage hydraulic fracturing was carried out using Slickwater frac technology. This well was commissioned in March 2018. Proppant containing markers was pumped into the well during MFrac, enabling the collection of valuable information on continuous well operation. Scheduled geophysical logging also allowed for evaluation of well operation, selection of the working intervals, and a determination of the composition and flow rate of the incoming fluid. When analyzing the informational content of the above-mentioned logging operations, it should be considered that risks of ambiguity in interpretation exist in both cases, and each of the methods aid in obtaining the general image of well operation parameters.

Marker Production Logging Technology

The production logging method is based on the injection of marker-reporters that contain quantum dots in the proppant polymer coating. Quantum dots (several nanometers in size) are injected inside the insoluble microspheres (one micron in size), then placed in the proppant polymer coating. Fifteen tons of marked proppant are injected as normal proppant, and the last proppant pack is used to ensure improved washing in the near-well zone (Ovchinnikov, 2019). Next, the markers are washed out of the coating and injected into the formation fluid. Samples are then taken from the wellhead and tested in the laboratory for analysis.

The analytical method for determining marker-reporters is based on the instrumental method - flow cytofluorometry or simply cytometry (Ovchinnikov, Buzin, Saprykina, 2017). The principle of operation is as follows: inhomogeneities in the sample line up exactly one after another with the help of a crimping fluid and a finely tuned hydrodynamic system. Next, they are irradiated using several lasers. After irradiation, the signals are recorded by various detectors. For each point, 15 different parameters are fixed, the most informative of which are fluorescence channels at different wavelength ranges. Marker-reporters are microspheres with quantum dots inside. These dots fluoresce in different colors, depending on the signature number or the marker code (Kawasaki, 2005). Each horizontal well production interval of a horizontal well is marked with a unique code, allowing users to evaluate the contribution of each interval to well operation. Each sample, divided into phases, is then analyzed using the analytical hardware-software complex GEOSPLIT. Based on the sample analysis results and their interpretation, the relative content of marker-reporters with various signatures was determined, allowing for switching to the percentage expression of inflows for each interval (Figure 1).

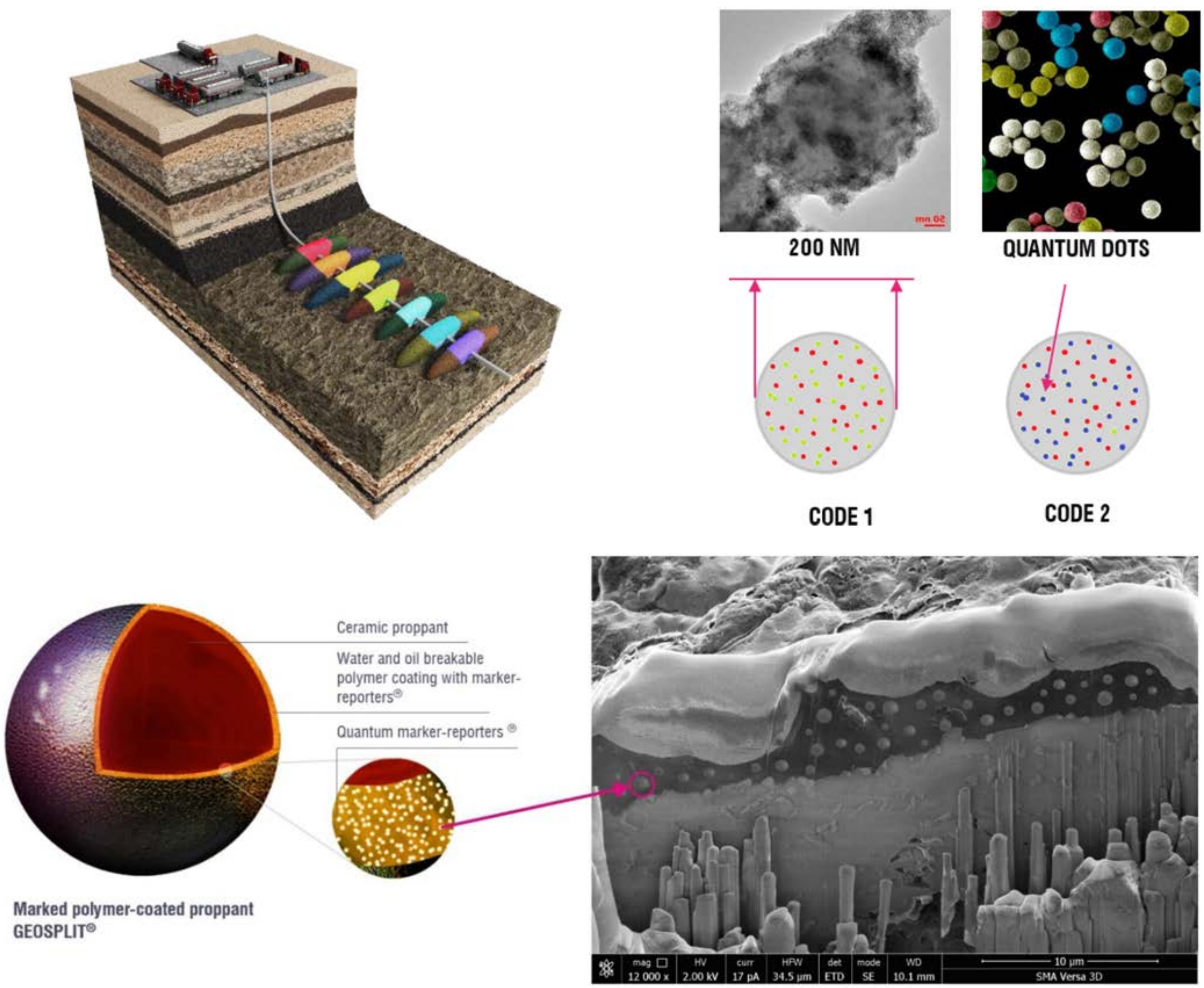

Figure 1—Marker Production Logging Technology

After conducting multi-stage hydraulic fracturing in March 2018, 44 formation fluid samples were analyzed for production logging using markers in the studied well. The well production logging lasted 6 months and included three sessions. Sample preparation activities were conducted for all formation fluid samples, and quantum marker-reporters were separately isolated from oil and water phases.

In general, according to the production logging results of the analyzed well, there is a tendency to change the stages' operation mode and the nature of well intervals operation within six months of production logging (Figure 2).

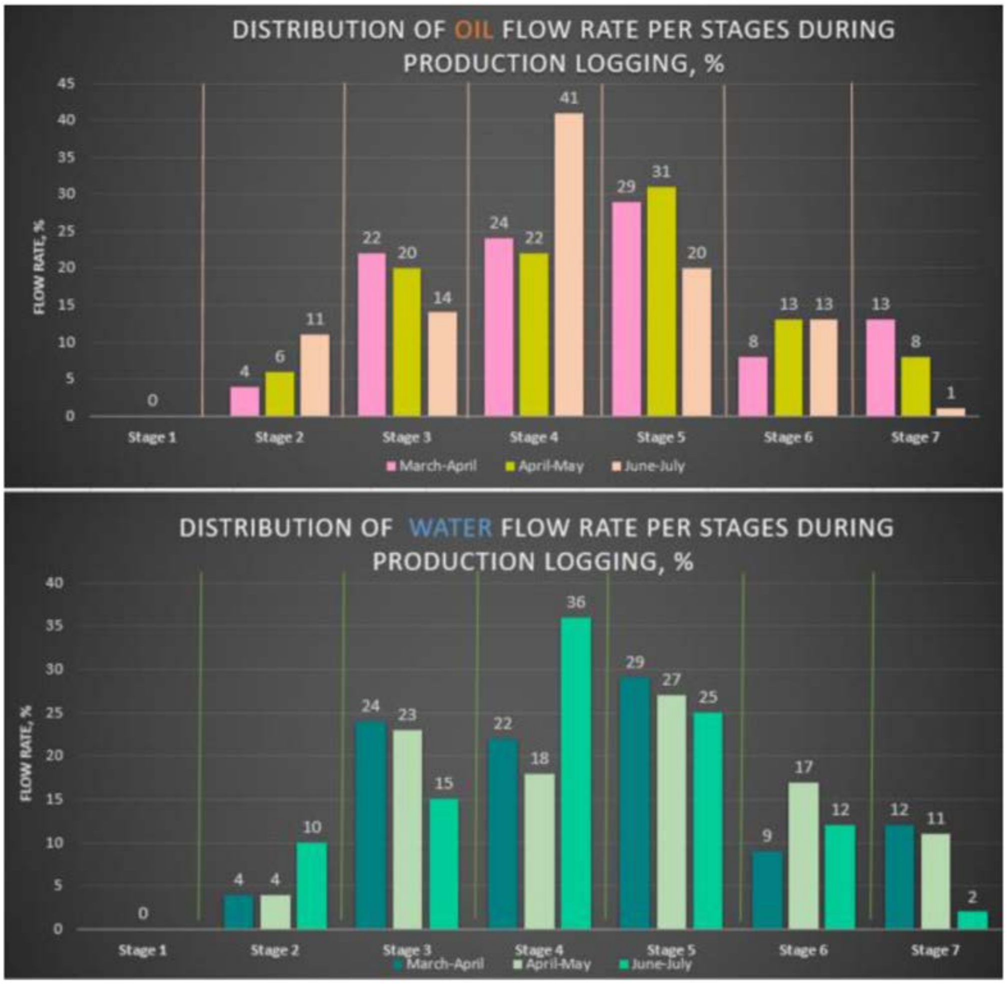

Figure 2—Distribution of oil and water flow rates by stages (data are rounded) during the period from 13.03.2018 until 26.07.2018

The fourth stage demonstrates the most positive dynamics of well flow, where the oil inflow indicators increased to 41% by the third test period. Stage 2 indicates low oil and water inflow parameters, and the contribution to the total well rate slightly increases closer to the final testing period. By the final testing period of Stage 3, there was a decreasing trend in the performance indicators, in which the oil inflow percentage decreased by 8% during the analyzed period. Stages 4 and 5 are marked as the most efficient periods, with maximum values of oil and water inflow. By the final sampling period, there was a significant drop in the performance indicators of Stage 7 - the percentage of oil flow decreased to 1%, providing the smallest contribution to the total well flow rate.

Production Logging Works

High-precision temperature and spectral noise logging (HPT-SNL) was performed from April 15 through April 20, 2018 in the idle well mode. The tools listed below were lowered into the well using coiled-tubing services.

1. Multi-sensor autonomous hardware complex GEO-2m6 (autonomous complex updated tool) - pressure - temperature - gamma logging - deep distance flow meter - moisture meter - collar locator - well thermo-conductive flowmeter	
2. GEO-MST - resistance meter - moisture meter - thermometer	
3. GEO-MBA - 6 distributed moisture meters - zenith angle sensor - device turning sensor	
4. SNL - spectral noise meter	
5. INDIGO - gamma logging - collar locator	
6. DMPT - temperature - pressure	

The studies were conducted on 3 flow modes (in spouting mode using 6 mm, 5 mm and 7 mm choke) during a brief well shut-in:

- 15.04.2018 - The records from the high-precision temperature and spectral noise logging were made in the well idle mode. The oil level in a stopped well is measured at a depth of 1170 m, and the level of the oil-water section is measured at a depth of 2695 m.
- 16-17.04.2018 - Measurements were taken in the inflow mode during a brief well shut-in using a 6 mm choke.
- 17-18.04.2018 - Measurements were taken in the flow mode using a 5 mm choke.
- 18-20.04.2018 - Measurements were taken in the inflow mode during a brief shut-in using a 7 mm choke.

The actual well operation parameters prior to production logging are indicated in the table below:

Q fluid, m3/day	Q oil, m3/day	Gf, m3/t	Pr, atm (20.03.2018)
52	24	274	243

Pressure curves were recorded during the tool lowering and descent in the interval of detailed studies for each mode. This demonstrated a discrepancy of more than 5%, serving as an indicator of the mode's instability.

Temperature Modeling

Temperature modeling was conducted while considering temperature perturbations (cooling anomalies) associated with previously injected fluid during hydraulic fracturing. According to the temperature modeling results, the total gas flow rate was 18 m3 / day, oil – 13 m3 / day, water – 9 m3/day for reservoir conditions. Fluid phase separation (hydrocarbons + water) is approximate, considering wellhead measurements from the beginning of operation and during the studies.

The primary fluid inflow falls in hydraulic fracturing Stage 4 (27% of the total volume), hydraulic fracturing Stage 7 (25% of the total volume) and hydraulic fracturing Stage 3 (22% of the total volume). In these intervals, activity is indicated according to spectral noise measurement data, and changes in the temperature gradient are recorded in the inflow mode (Figure 3).

The gas inflow falls during the following stages: hydraulic fracturing Stage 3 (28% of the total gas volume), hydraulic fracturing Stage 7 (27% of the total gas volume) and hydraulic fracturing Stage 4 (20% of the total gas volume). Water inflow is recorded from all hydraulic fracturing working stages. With a relatively low liquid flow rate (20 m3 / day), determining the intervals' most intensive water inflow is not feasible.

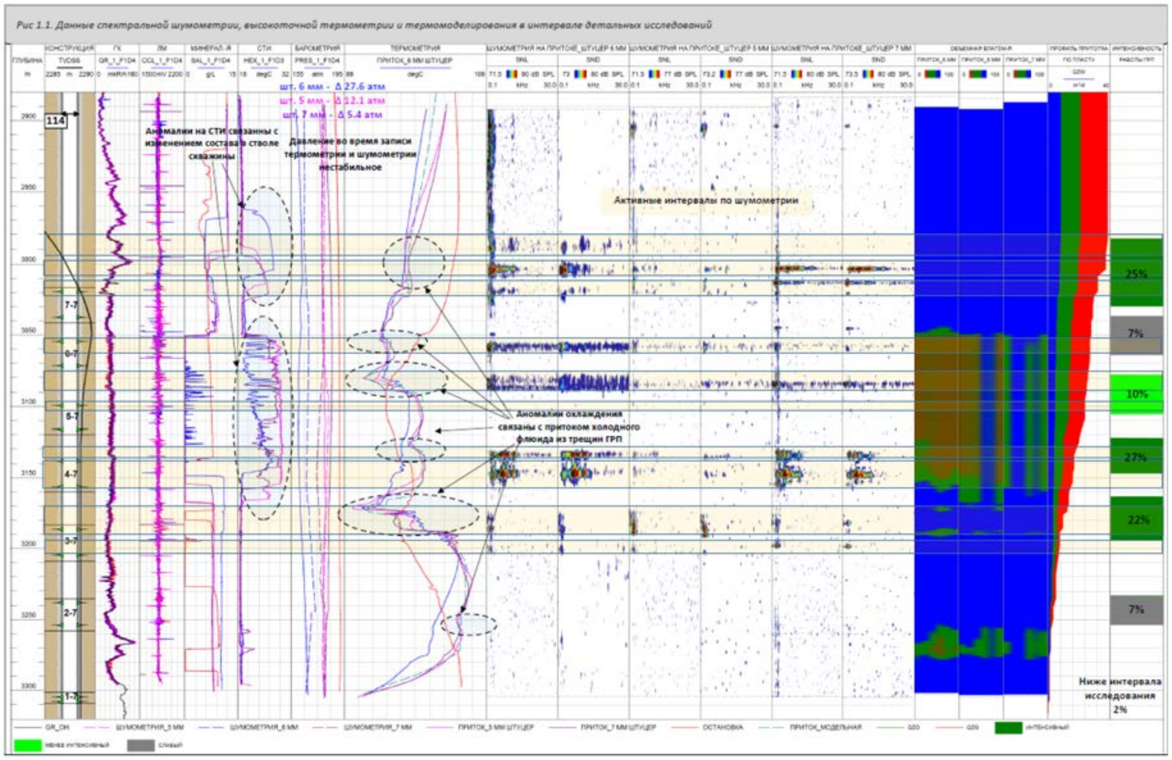

Figure 3—Geophysical logging results

Spectral Noise Logging

Spectral noise logging (SNL) is used to determine formation fluid flow intervals. Here, the noise spectrum is displayed on the color bar, and the noise amplitude is displayed in different colors: red indicates high-amplitude noise; yellow, green, blue represent low-amplitude noises (arranged in descending order); and white displays noise with an amplitude below the tool sensitivity threshold. The noise frequency diagram determines the flow components, such as the in-column flow, movement along the cement stone, flow associated with the well structure integrity, and distinguishing the inflows along the fracture.

Despite the unsteady production mode (according to wellhead measurements) and unstable well operation, the repeatability of noise measurement data is observed in all 3 modes of operation (choke = 6 mm, 5 mm and 7 mm). All chokes indicate the operation of hydraulics during fracturing Stages 3, 4, 5, 6 and 7. No additional fracturing intervals are observed on any choke, which could potentially be related to a minor, unstable depression during spectral noise logging.

Comparative Analysis of Production Logging Results

According to the complex of aggregate data and temperature logging results, the main fluid flow is associated with hydraulic fracturing Stage 4 (27% of the total volume), Stage 7 (25% of the total volume) and Stage 3 (22% of the total volume). These intervals show activity subject to spectral noise logging as well as changes in the temperature gradient recorded in the inflow mode:

- The most stable well operation for production logging was conducted with a 6mm choke.
- The presence of low-frequency noise is presumably associated with the movement of fluid along the broken cement.

Telemetry data indicates a potentially inaccurate interpretation:

- Data from Stage 7 indicates the maximum fluid heating, which cannot indicate the maximum fluid flow.
- Data from Stage 5 indicates the maximum fluid cooling, which cannot indicate the minimum fluid flow.

The results of the comparative evaluation of marker production logging and PLT logging are shown in Figure 4, where it can be seen that:

- 4 out of 6 analyzed well intervals indicate a high convergence of the results obtained by GEOSPLIT marker production logging and PLT logging.
- A discrepancy is observed during the evaluation of the contribution of Stages 5 and 7.

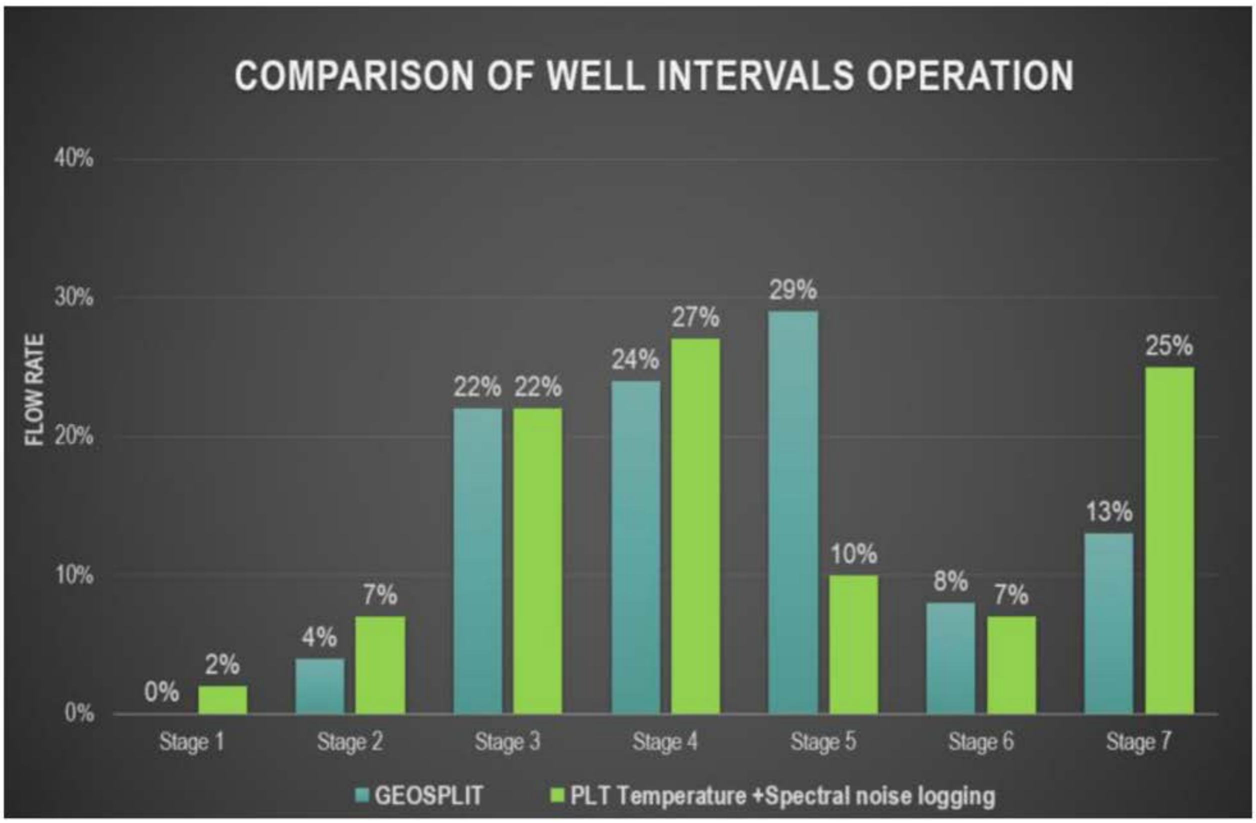

Figure 4—Results of the comparative evaluation of marker production logging GEOSPLIT with conventional PLT logging

The discrepancy seen in the results could have a variety of causes, notably that PLT and marker production logging data may characterize different periods of well operation, as the tests are not carried out simultaneously. It is also necessary to note the difficulties associated with conventional PLT logging under conditions of multi-phase fluid inflow. The mobile, light phase moves along the upper part of the horizontal well section, while the heavy phase located below, as a rule, moves at a significantly lower speed. The heavy phase can be occasionally filtered into the zone located on the lower absolute elevations, and this complicates the interpretation of the flow distribution along the well. Another potential cause for the discrepancy in the evaluation of Stages 5 and 7 is the gas zone. This is because the spectral noise logging records a significant influx, whereas the temperature logging results indicate only a moderate influx.

Conclusion

Conventional PLT logging methods, though well-proven in vertical wells, requires expensive technical solutions, including CT, specialized delivery tools for geophysical instruments (downhole tractors) and Y-tool bypass systems in horizontal wells. The accuracy of horizontal well logging data interpretation can also be diminished due to multiphase flow and changes in fluid flow velocity, and the CT effect on the pressure measurement accuracy and flow rates.

The obtained production logging and marker diagnostics results serve as important information related to the in-depth analysis of the data on the deposits in the working area. These methods and results enabled the successful evaluation of well operation. Obviously, contemporary PLT logging complexes and methods for delivering downhole equipment to the bottomhole can provide informative data on the horizontal well operation. However, analysis of gas and water breakthroughs will require non-stationary measurement techniques with periodic, multi-temporal measurements in order to determine the fluid composition in the well due to the inflows immediately after starting well operation.

Temperature logging requires the presence of contrasting temperature anomalies, but their absence in the well is rarely observed (for example, the temperature of the formation is often equal to the temperature of the formation fluid). For the Bazhenov formation, which is generally characterized by a relatively stable gas factor, contrasting anomalies in all ports allow for a reliable estimation of the inflow at all stages. Spectral noise logging aids in confirming the presence of flow stages and, in combination with temperature logging, provides a complete picture of well productive intervals operation. The disadvantage of this solution is that it is currently very complicated to generate a reliable quantitative interpretation of the incoming fluid.

Standard existing software products typically assume a uniform distribution of proppant, but they do not consider, for example, the vector of linear velocities and mechanisms of proppant movement. This means that marker production logging and its practical application at this stage are not supported by modeling the proppant injection area, which complicates the approach to the technology evaluation. In addition, in view of the uncertainties described above, not all proppant injected into the well may operate properly, and partial fractures or complete closures may occur.

Today, we cannot claim that production logging using markers can completely replace conventional PLT logging complexes, mainly because the fluid flow processes along the fracture have not yet been analyzed with a sufficient degree of certainty. However, the results of production logging using markers can significantly improve the final interpretation results as they allow oil producing companies to obtain and monitor dynamic information on the well productive intervals operation over long periods of time without well shut-in.

The authors of this article believe that at this stage of the complex technology's application, the comparison between these methods is inappropriate. In this case, different technologies can complement each other to ensure the quality of the information received. This is because the interpretation of the production logging using markers results and micro-seismic well monitoring data (MSM) will also be required to provide an accurate and effective interpretation for the oil producing company. These results are required for the estimation of the fixed component of the fracture when compared to the induced part.

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