Please fill in the name of the event you are preparing this manuscript for.	2019 SPE ATCE
Please fill in your 6-digit SPE manuscript number.	SPE-196172-MS
Please fill in your manuscript title.	Unleashing the Power of Smart Particles for Completion Diagnostics: Advancing the Production Flow Profiling Technology with Sub-atomic Fingerprints and Big Data Analytics

Please fill in your author name(s) and company affiliation.

Given Name	Surname	Company
Talgat	Shokanov	QuantumPro, Inc., USA
Pavel	Khudorozhkov	QuantumPro, Inc. USA
Adilkhan K.	Shokanov	Abai University, Kazakhstan

This template is provided to give authors a basic shell for preparing your manuscript for submittal to an SPE meeting or event. Styles have been included (Head1, Head2, Para, Fig, Caption, etc.) to give you an idea of how your finalized paper will look before it is published by SPE. All manuscripts submitted to SPE will be extracted from this template and tagged into an XML format; SPE's standardized styles and fonts will be used when laying out the final manuscript. Links will be added to your manuscript for references, tables, and equations. Figures and tables should be placed directly after the first paragraph they are mentioned in. The technical content of your paper WILL NOT be changed. Please start your manuscript below.

Abstract

Current multistage hydraulic fracturing operations in shale are costly, environmentally challenging and inefficient. Multistage hydraulic fracturing operations already represent close to 60% of the total drilling and completion cost for each shale well. The industry studies reported that based on data evaluated in multiple shale basins in North America alone that up to 50% of the clusters and stages do not produce in geometric completion design. Shale E&P operators need more accurate, cost-efficient, timely and actionable data on the performance of individual fracturing stages and intra-well communication to enable improved decision-making and optimization of multistage hydraulic fracturing and completion strategy, as well as overall field development.

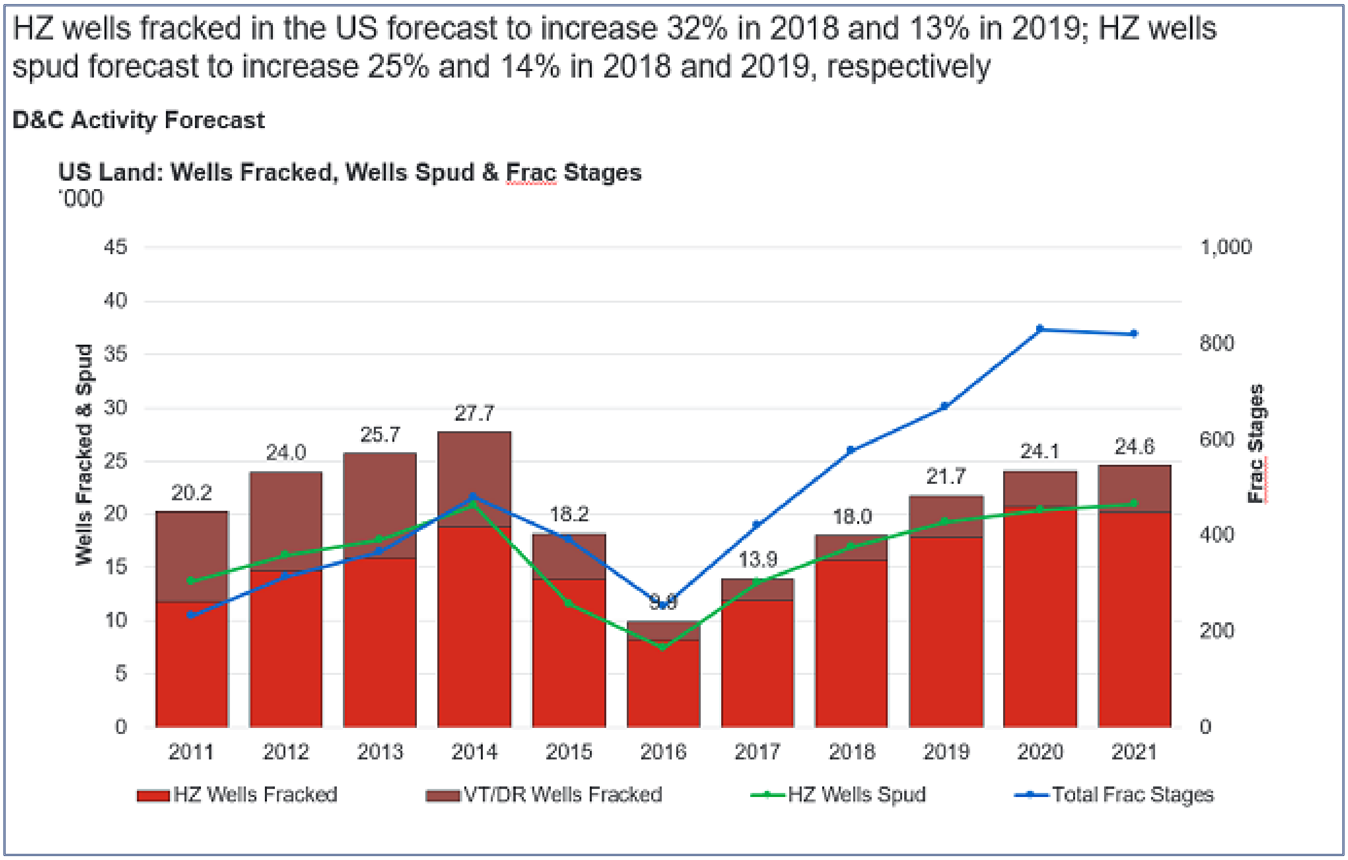
This paper will describe a revolutionary smart tracer portfolio testing and design for multistage hydraulic fracturing stimulation. The technology enables the next generation of smart tracers coupled with advanced sub-atomic measurements that significantly reduce the completion cost and double the efficiency of the hydraulic fracturing treatments. An automated process with stringent quality control assured precise tracer addition onsite and provided accurate and actionable completion diagnostics results at fraction of the cost for high-cost measurements (e.g., PLT, DTS & DAS).

The integration of smart tracer portfolio with intelligent-completion diagnostics for E&P customer enabled by performance-flow-profile data. This data used to optimize completion strategies, achieve optimal production per foot, and reduce completion cost. Follow-up big-data analytics and 3D fracture-modeling delivered accurate, calibrated, actionable, and cost-effective completion-diagnostics results. Since tracer data are captured over several months, E&P operators are captured access to continuous flow profiling data to optimize well performance routinely when new completion-diagnostics results are received. This will enable E&P operators to significantly reduce operating cost and optimize production in shale wells.

Introduction

The multistage hydraulic fracturing is a stimulation process that significantly increases the production of oil and gas from unconventional shale reservoirs and predominantly done in horizontal wells. The goal is to maximize reservoir contact by exposing vast quantities of surface area within the reservoir target by creating and interconnecting hydraulic and natural fractures. Horizontal wells now account for more than 90% of wells drilled in unconventional shale reservoirs.

The horizontal laterals extending from 5,000 up to 15,000 ft. The multistage hydraulic fracturing operations involve pumping from 10 to 50 hydraulic fracturing stages with cumulative volume per well from 4 to 15 million gallons of water and from 5 to 20 million pounds of proppant. It is estimated that from 500,000 to 750,000 fracturing stages completed around the world per year and 240 billion pounds of sand used per year in 2018. This represents the total completion cost (high-pressure pumping cost, proppant, and fluid costs) per well ranging from USD 2.9 million to USD 5.6 million in typical shale well in US land making up to 60% of well's total cost in 2018.


HZ wells fracked in the US forecast to increase 32% in 2018 and 13% in 2019; HZ wells spud forecast to increase 25% and 14% in 2018 and 2019, respectively

D&C Activity Forecast

US Land: Wells Fracked, Wells Spud & Frac Stages

Figure 1: Hydraulic fracturing activity and stage count in North America land

Increasing E&P spending in unconventional oil and gas reserves, especially in the shale basins, is expected to remain a key factor driving market growth. North America dominated the global demand and accounted for over 85% of total spending. The U.S. and Canada together accounted for the lion's share in the global hydraulic fracturing spending. The hydraulic fracturing activity is expected to witness considerable growth in countries such as Algeria, Argentina, Australia, Kazakhstan, Mexico, Poland, and Russia over the next decade on account of rising interest for developing the large available unconventional hydrocarbon reserves.

Although, industry studies reported that up to 50% of the hydraulic fracturing clusters and stages do not produce and up to 40% of the fracture networks do not produce based on measured data from production logging and fiber-optic measurements in stimulated shale wells. Also, with the current geometric factory mode completion approach with more fracturing stages and equal spacing, millions of frac sand and water pumped per well as well as longer horizontal laterals, it is estimated that up to 40% of the drilled and completed wells will be uneconomical in North America alone.

Besides, interactions between fractures in adjacent horizontal wells and their costly negative effects have become the focus of much discussion and debate within the hydraulic fracturing technical community. The impetus for this attention has been the impact of these interactions on productivity and the mechanical integrity of these parent wells. All that drive the needs for oil and gas operators to have more accurate, affordable, timely data on the performance of individual fracturing stages and measured intra-well communication and temporary and long-term frac/frac connection to enable improved decision-making and optimization of multistage hydraulic fracturing operations as well as overall field development.

Smart Tracer Technology

To control the effectiveness of multistage hydraulic fracturing stimulation treatments, it is essential to use special tracing methods. These methods are based on the addition of the labeled substance to the proppant, water or gas, and monitoring the release of tracers with flow back water and produced oil and gas from the current well or nearby observation wells. Currently, conventional water-soluble and oil-soluble chemical substances with fluorescent properties and ionic, organic materials, or radioactive isotopes are used as the tracers. Tracers with fluorescent properties, ionic and organic materials, characterized by their relatively high cost, limited only to chemical measurement techniques at a molecular level and often reported false positive results for long-term frac/frac communication. Moreover, environmental regulations in many countries prohibit the use of radioactive tracers (i.e., radioactive isotopes), as they pollute the environment and could contaminate with radiation subsurface layers.

The authors as part QuantumPro, Inc. R&D efforts and in collaboration with a strategic nanotechnology partner developed and commercializing the next generation of smart or intelligent tracers to improve the efficiency and productivity of multistage hydraulic fracturing operations. The technology is based on proprietary particles developed from low-cost materials and utilizes advanced sub-atomic spectroscopy measurement techniques to map the distribution of well production, the performance of each fracturing stage, cross-well interference and environmental containment. The smart or intelligent tracers are easily deployed with accuracy, efficiency, and detection capabilities well beyond current chemical and DNA sequencing products, enabling oil and gas operators to significantly reduce cost and optimize production in shale developments.

Figure 2: QuantumPro's patented smart tracer portfolio and frac/completion optimization workflow

The unique features of smart tracer for completion and hydraulic fracturing optimization portfolio entails:

- Deployment of first of its kind sub-atomic measurements

- Most rigorous smart tracer design for each hydraulic fracturing design
- Highly automated unit for precise smart tracer addition onsite
- Cutting-edge mobile data laboratory and QAQC workflows
- Real-time onsite sampling, tagging, analysis, and interpretation
- Secured cloud-based real-time data delivery and visualization

An automated process with stringent quality control assures precise smart tracer addition and provides accurate and actionable completion diagnostics results at fraction of the cost for high-cost measurements (e.g., production logging tool (PLT), fiber optics with Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS), DNA sequences).

All these combined created the critical value for oil and gas operators which entails the most accurate, affordable and actionable stage performance and production data, integrated workflow from smart tracer mapping to intelligent completion diagnostics, state-of-the-art sub-atomic measurements coupled with advanced geomechanics and onsite laboratory analysis with big-data analytics.

Lab Testing - Performance Analysis

To provide quantitative and qualitative interpretation, all smart tracers undergo a rigorous laboratory testing and validation process to ensure ultimate performance down-hole and within the complex fracturing network. Each smart tracer first tested for thermal and pressure stability, settling time, particle size distribution, reservoir static and dynamic adsorption, as well as other characteristics during a comprehensive testing process.

The next step is to align and refine each smart tracer design with pre-planned frac design and estimated well completion flow profile. This is required for performance testing of smart particles recovery efficiency for minimum and maximum flow rates at stage level. The oil and gas shale operator have provided the typical shale well completion design for performance verification testing for smart tracer at following down-hole conditions:

- Well production rate: 4,000 barrels per day
- Well frac stages: 40 stages per well
- Flow rates per stage: 100 barrels per day
- Perf clusters: 3 perforation clusters per stage
- Minimum flow rate (6 in. perf): 0.5 gallon per min
- Maximum flow rate (6 in. perf): 3.0 gallon per min
- Proppant pack: 40/70 frac sand

This is assuming under the above conditions ranged flow rates if shale well has averaged 1.5 open perforations per cluster and during the period while well is producing at 4,000 barrels per day or higher. In reality, the production rate may fall off quickly so long-term monitoring of smart tracer recovery would also rely on smart particles being able to move at a much lower rate. In addition, the performance of moving the smart tracer in the horizontal section of the shale well is considered. If the stage closest to the toe is producing 100 barrels of liquid per day (or 0.0486 gal/sec) with 4-1/2” liner, then the fluid is moving at 0.0814 ft/sec.

In order to accomplish such flow profiling and smart tracer recovery testing the special unit was designed, manufactured and deployed under strict R&D experts supervision for a dedicated study of each smart tracer flow profiling via simulated hydraulic fracture with frac sand and down-hole wellbore condition using different flow profile rates at each stage (see Figure 3). To enable the most efficient smart tracer recovery and collection from tested flow stream the variation of specifically designed filter cartridges from nanomaterials were deployed in the testing unit (see Figure 4). The basic requirements for the flow loop performance testing include the selection of appropriate measuring instruments, the need to ensure initial and boundary conditions. The basis of the choice was the flow performance parameters and methods of the theory of flow velocity and modeling smart tracers down-hole.

Figure 3: Testing unit for flow profile and recovery performance analysis

The frac flow loop performance testing was designed considering the possibility of testing not only each smart tracer under study but also the individual test instrument and component assemblies in the frac flow loop performance testing unit. The testing was conducted on the one hand to verify the results of the calculation using various methods and their subsequent refinement, and on the other hand to determine the effect of various design factors on the main parameters of each smart tracer.

Two poly composite IBC tote tanks are installed opposite each other on the horizontal surface. They, in turn, are connected by several circulations, bypass, and discharge lines. The unit also contains the self-priming circulation pump with adjustable rates, two sets of special nano filters lines, digital flow meter, suction, and discharge pressure gauges, isolation (diversion) ball valves, frac pack sand simulation tube and wellbore simulation tube. The unit is mounted in a controlled environment in the laboratory and equipped with a water supply system. Tanks are made of durable polymers, for even stronger construction are additionally strengthened with a metal grill for increased rigidity. The plastic tank is equipped with an orifice with a lid for pouring fluid and smart tracer, a drain flange ball valve with a diameter of about 11.8 inches (30 cm). The plastic container has incredible strength, and at the same time, lightness. It can sustain the most aggressive chemicals and successfully withstands almost any weathering.

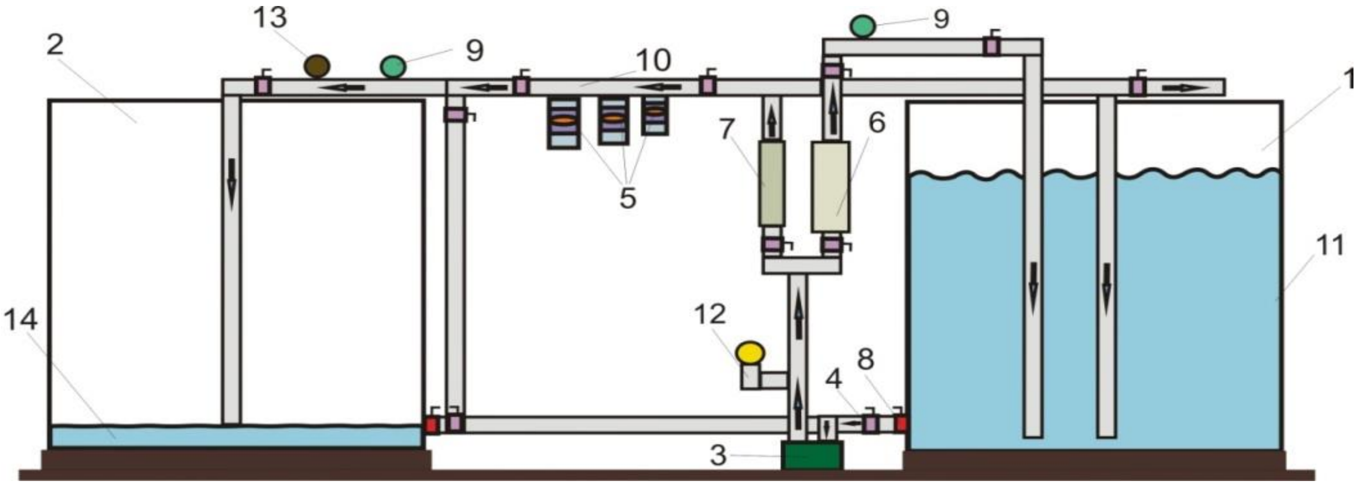


Figure 4: Schematics of the unit for flow profile and recovery performance analysis

The testing unit contains the following components: 1- intake poly composite IBC tote water tank; 2 – recipient poly composite IBC tote water tank; 3 - the self-priming circulation pump with adjustable rates; 4 – isolation ball valve; 5 – two stacks of nano-filters; 6 – wellbore simulation tube; 7 – frac pack sand simulation tube; 8 - ball valve at intake water tank; 9 – pressure gauge; 10 – flow loop pipe; 11 - liquid with smart tracer; 12 - protection / pressure release pop-off valve; 13 – high precision flow meter; 14 – discharge liquid.

The process of testing entails transferring of designed liquid volume with smart tracer from intake poly composite IBC tote tank (1) using the self-priming circulation pump with adjustable rates (3) through either through wellbore simulation tube (6) or frac pack sand simulation tube (7) using control valves and further to experimental area with two stacks of nano-filters (5). The liquid flows through the nano filters and the smart particles remain in the nano-cartridges, from where they will later be collected for sub-atomic analysis. From the experimental section, the liquid is directed to the second recipient tank (2). If needed a separated return line can fed back the liquid through the return line to the intake water tank, and the pressure in the return line can be released into the atmosphere using protection / pressure release pop-off valve. Each node of the experimental unit has its own purpose in the flow performance testing and analysis.

The flow loop performance testing conducted with variety of flow pressure ranging from 10 psi to 500 psi. The conventional plastic pipes with a diameter of 0.78 inch (20 mm) are used for the water supply system. The pipeline consists of control valves that open and close, depending on the progress of the test. Important elements of the flow loop performance testing unit are the main filters with a cylindrical body and designed to be installed a metal thread with various particles removal capacity. These filter cartridges are made from microwire using high-performance alloy and glass coating and mounted in the two lines (main and back-up lines). Connections are made in the form of threads and connected to pipes. The design of the filters is tailored for quick and easy replacement. The mesh cartridge aligned with smart tracer size and can efficiently remove all types of particles from the flow stream and send for sub-atomic analysis. Such analysis included Mössbauer spectroscopy and X-ray fluorescence (XRF) analysis. Mössbauer spectroscopy is a versatile technique used to study nuclear structure with the absorption and re-emission of gamma rays, part of the electromagnetic spectrum. The technique uses a combination of the Mössbauer effect and Doppler shifts to probe the hyperfine transitions between the excited and ground states of the nucleus. Mössbauer spectroscopy requires the use of solids or crystals which have a probability to absorb the photon in a recoilless manner, many isotopes exhibit Mössbauer characteristics. XRF is a non-destructive analytical technique used to determine the elemental composition of materials. XRF analyzers determine the chemistry of a sample by measuring the fluorescent (or secondary) X-ray emitted from a sample when it is excited by a primary X-ray source. Both Mössbauer spectroscopy and XRF having high accuracy, and considered as promising methods in the oil and gas industry, in particular for registration tracers (special indicators) in the samples during hydraulic fracturing and reinjection process.

The flow loop performance testing allowed us to obtain reliable data necessary for the study and analysis of smart tracers. The smart tracer recovery was tested using actual shale well completion design provided by oil and gas operator with assuming 400,000 pounds of 40/70 frac sand per stage. The projected flow velocity at the cluster level ranged from 0.1 – 3.0 GPM and detection limited up to 1 ppm from milligram sample collected from the testing as shown in Figure 5. The results indicated very good volume of smart tracer recover from the first run with 9.2% at 3 GPM and with 6% at 0.1 GPM respectively, which then after was tested using sub-atomic instruments for fingerprints identification.

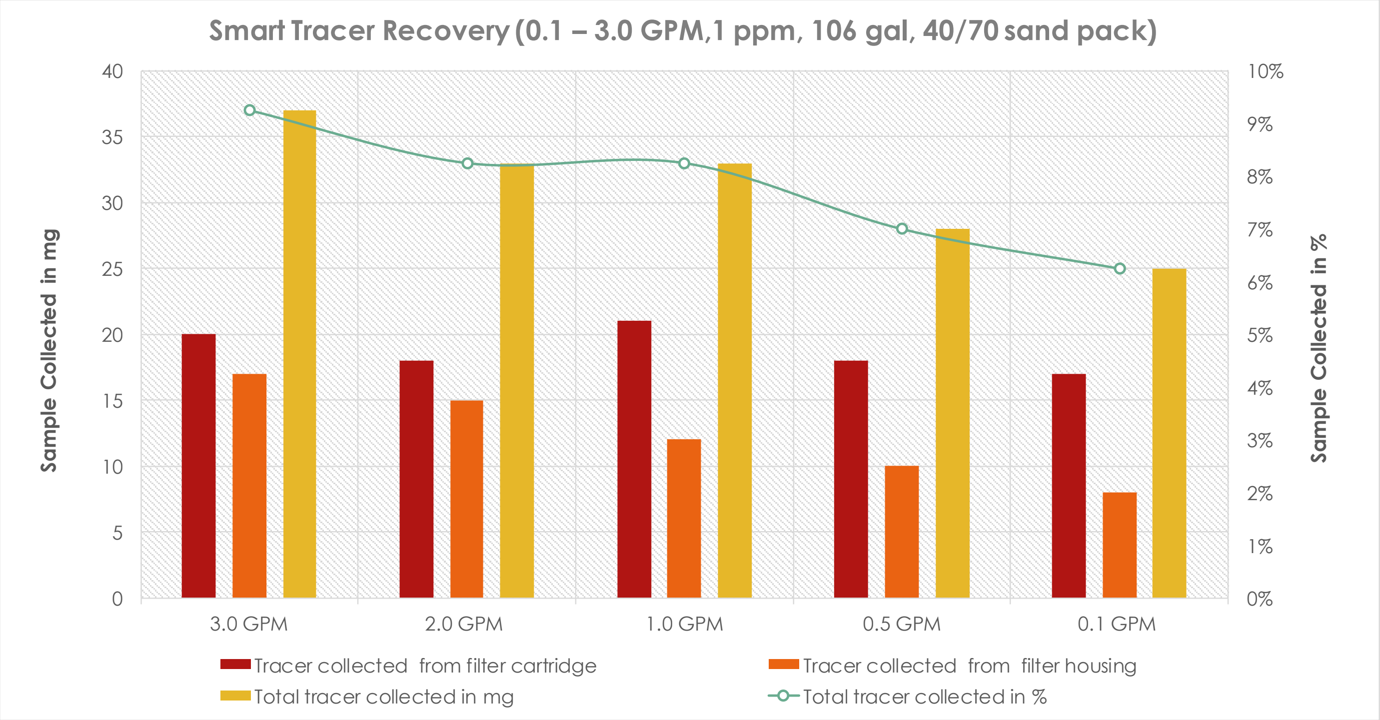


Figure 5: Smart tracer recovery using flow loop performance testing

Integration with Completion Diagnostics

Completion diagnostics is a complex multidiscipline task that requires knowledge in many different areas of oil and gas field development including formation evaluation, geologic and geomechanics modeling, reserves estimation, hydraulic fracturing pressure analysis, and dynamic simulation. It is required to identify the reasons for horizontal well stages good or poor performance determined through smart tracer diagnostics and to verify each stage contribution to the total well production rate.

Like in conventional fields, shale well stage production rate is defined by several main reasons – the presence of hydrocarbon in place, formation quality (brittleness, porosity, and permeability) and completion efficiency (perforation strategy and hydraulic fracturing treatment design). Hydrocarbon presence in shale formation can be characterized by organic content (TOC). Formation organic content is normally determined in the laboratory by kerogen extraction from the core sample and its further analysis. In the field, organic reach intervals can be found using resistivity, spectral gamma ray and mud logs.

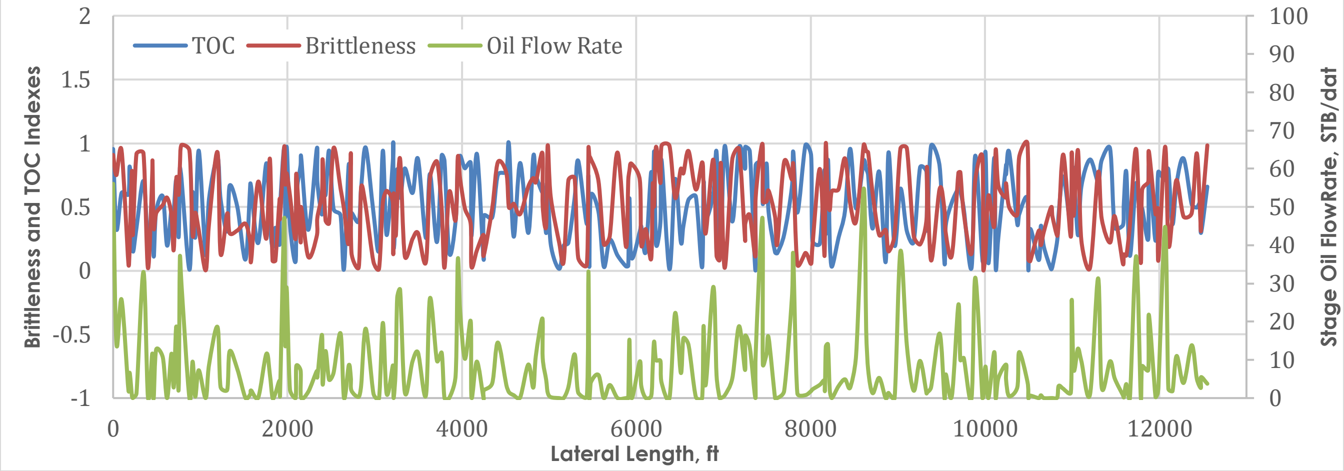


Figure 6: Prognosed oil flow rate profile across formation properties distribution

Unconventional fields are very often not well characterized by subsurface data needed for formation evaluation and limited modeling for accurate geological and geomechanical assessment. Nevertheless, over more than 100 years oil and gas industry accumulated a huge amount of subsurface data. More than 2 million wells were drilled in the United States alone and most of the currently developed basins are covered with seismic, well logging and core data, geologic and tectonic information. This legacy data is used to understand geology, correlations, and trends of rocks distribution in studied area to construct reliable models and predict further wells production potential.

Formation evaluation includes but not limited to the generation of rock properties profile along well lateral and creation of 3D geological models of the target reservoir. Wireline or MWD logs from target or nearby wells, core data, technical drilling data are used as inputs. Rock properties such as TOC, permeability, fracture intensity are the focus to estimate and primary drivers defining each stage performance.

Geomechanics analysis is intended to characterize the state of stress and mechanical properties that control fractures geometries and directions, fracturing pressures and propagation features, presence of natural fractures. Geomechanical properties govern the development of double permeability systems that include main plus secondary hydraulic fractures and natural fracture networks. Successful creation of the extensive fractured domain is another key factor defining stage production.

Legacy and new insightful learning gained different kinds of geologic information that need to be combined in one reliable solution but the correlations between that many types can be very complex and not always analytically clear. The future of shale formation characterization is deep machine learning and big data analytics employing different kinds of neural networks, a biologically inspired programming approach which enables computer to learn from observational data. All the tools are available—it is just a matter of knowing where to find the right tools.

DFIT and frac pressure diagnostics used to determine hydraulic fracture complexities during fracturing that can result in poor stage contribution to well production. Fracture height-growth outside of target zone or excessive lateral development towards parent well depleted area are clearly seen on the pressure curve, can be analyzed and prevented in the future. The results of detailed pressure analysis are also well used to calibrate stress values and other properties of geomechanical model. Hydraulic fracturing simulation is employed to verify fracture geometry and calibrate properties of geomechanical model through a pressure history match.

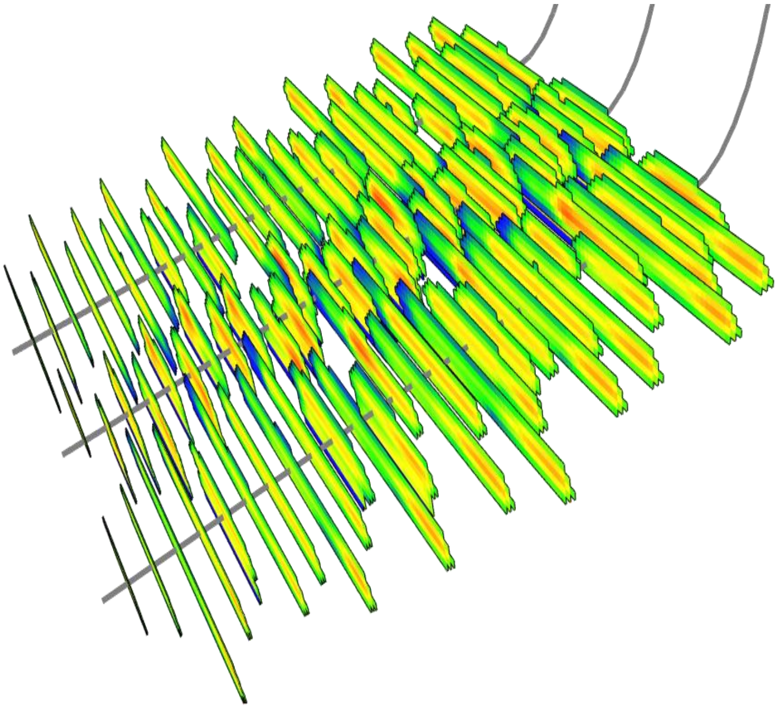


Figure 7: Hydraulic fracturing complexities modeling using geomechanical model

Combined results of completion diagnostics with extensive dataset from smart tracer using measured flow profile at the stage level and frac/frac connection enabled by neural networks for deep learning allow to optimize future horizontal wells designs, place the stages in right places with optimum distances and numbers of clusters as well as to perfect hydraulic fracturing design procedures. The entire process is intended to increase design efficiency, reduce cost and enhance well productivity. The final results of well completion design and production performance at the stage level will be published in subsequent papers upon approval from the client and QuantumPro's management.

Conclusion

This paper will describe a revolutionary smart tracer portfolio testing and design for multistage hydraulic fracturing stimulation for E&P customer. The technology enables the next generation of smart tracers coupled with advanced sub-atomic measurements that significantly reduce the completion cost and increase the efficiency of the hydraulic fracturing operations. Combined results of completion diagnostics with extensive dataset from smart tracer using measured flow profile at the stage level and frac/frac communication enabled by neural networks for deep machine learning allow to optimize future horizontal wells designs, place the stages in right places with optimum distances and numbers of clusters as well as to improve the hydraulic fracturing design procedures.

Acknowledgement

This work was supported by management and advisors of QuantumPro, Inc. Authors would like to thank Professor Adilkhan K. Shokanov, Head of Nano Technology Innovation Laboratory at Abai University in the Republic of Kazakhstan for competent assistance during XRF and Mössbauer analyses, and thankfully acknowledge all reviewers for their critical comments. The authors would also like to thank Houston Technology Center in the United States for assistance during experiments.

References

1. F. Fragachan, T. Shokanov, M-I SWACO; J. Ronderos, BP: "Cuttings and Waste Injection, Shale Fracturing Pressure Decline and Domain Mapping" SPE-147671 presented at the 2011 Canadian Unconventional Resources Conference in Calgary, Alberta, Canada, 15 - 17 November 2011.
2. A. K. Shokanov, K. M. Mukashev, F. F. Umarov: "Radiation-stimulated Bulk and Surface Effects in Materials"- San Bernardino, CA, USA, 2018. - 246 p. - ISBN 978-197-356-762-2.
3. A. Jamshidi: "Prediction of TBM penetration rate from brittleness indexes using multiple regression analysis", Modeling Earth Systems and Environment, 12 February 2018.
4. E.R. (Ross) Crain, H. Aharipour, M. Zeinali: "Characterization of Tight and Shale Unconventional Reservoirs from Logs" SPE-180961-MS, SPES AEPUR, Buenos Aires, Argentina, 1-3 June 2016.
5. E.R. (Ross) Crain, H Aharipour, Mohamad Mehdy Ahi, Amin Abbasi, Ayda Aharipour: "Shale Gas Log Evaluation for Gas Volume Calculations", International Field Exploration & Development Conference in Xi’an, China 18-20 September 2018.
6. V.C. Kelessidis: "Rock Drillability Prediction from In-situ Determined Unconfined Compressive Strength of Rock", The Journal of The Southern African Institute of Mining and Metallurgy Volume 111, June 2011.
7. A.K. Shokanov, M.F. Vereshchak, M.K. Kulbekov, I.A. Manakova, Sh.Zh. Hamraev, Y.A. Smikhan: "Mössbauer Research of Surface-Surface Concentric-Zonal Color Effects in Zoloceramic Materials" International Journal of Geography and Geology, Conscientia Beam, vol. 7(3), pages 45-55, 2018.