



Review article

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Comparative analysis of drilling technologies in tectonically disturbed carbonate reservoirs of Eastern Siberia

Ilya A. Yaroshchuk^{a✉}, Vladimir Yu. Panfilov^b, Pavel S. Pushmin^c

^{a-c}*Irkutsk National Research Technical University, Irkutsk, Russian Federation*

Abstract. The article presents a comparative analysis of modern drilling technologies used in the construction of oil and gas wells in tectonically disturbed carbonate reservoirs of Eastern Siberia. The relevance of the study is due to the high frequency of drilling complications associated with intense fracturing, fault-block structures, and heterogeneity of carbonate formations. The purpose of the study is to analyze the advantages, limitations, and areas of effective application of modern drilling technologies for challenging drilling. The study focuses on three main technological approaches: pneumatic hammer drilling, aerated and foam drilling systems, managed pressure drilling technologies. The methodological basis of the study includes comparative analysis and systematization of published domestic and international scientific and technical sources on drilling in challenging geological and technical conditions. It was established that the efficiency of drilling technologies is determined by the degree of rock fracturing, water cut level, borehole wall stability, and hydrodynamic control conditions. Pneumatic hammer drilling is shown to be the most effective when drilling through hard fractured carbonate formations, while aerated systems are efficient when drilling in severe lost circulation intervals, and managed pressure drilling technologies provide the highest efficiency under conditions requiring precise pressure control. It has been concluded that there is no universal drilling technology suitable for all geological conditions in Eastern Siberia. The most effective approach is the adaptive selection of technological solutions considering geological, hydrodynamic, and geomechanical features of a particular field.

Keywords: well drilling, Eastern Siberia, carbonate reservoirs, pneumatic hammer drilling, aerated drilling muds, managed pressure drilling; gas, oil, and water shows, mud losses

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Обзорная статья

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Сравнительный анализ технологий бурения в тектонически нарушенных карбонатных коллекторах Восточной Сибири

И.А. Ярошук^{a✉}, В.Ю. Панфилов^b, П.С. Пушмин^c

^{a-c}*Иркутский национальный исследовательский технический университет, Иркутск, Российская Федерация*

Резюме. В работе представлен сравнительный анализ современных технологий бурения, применяемых при строительстве нефтегазовых скважин в тектонически нарушенных карбонатных коллекторах Восточной Сибири. Актуальность исследования обусловлена высокой частотой осложнений при бурении в условиях интенсивной трещиноватости, разломно-блокового строения и неоднородности карбонатных пород. Целью работы являлся анализ преимуществ, ограничений и областей рационального применения современных технологий осложненного бурения. В рамках исследования рассмотрены три основных технологических направления: пневмоударное бурение, аэрированные и пенные буровые системы, технологии бурения с управляемым давлением. Методологическую основу работы составили сравнительный анализ и систематизация опубликованных отечественных и зарубежных научно-технических источников, посвященных бурению в осложненных геолого-технических условиях. Установлено, что эффективность технологий определяется степенью трещиноватости пород, уровнем обводненности, устойчивостью стенок ствола и условиями контроля гидродинамического режима. Показано, что пневмоударное бурение наиболее эффективно при проходке твердых трещиноватых карбонатных пород, аэрированные системы – в условиях интенсивных поглощений, а технологии бурения с управляемым давлением – при необходимости точного контроля давления в скважине. Сделан вывод о том, что универсальной технологии бурения для всех условий Восточной Сибири не существует. Наиболее эффективным подходом является адаптивный выбор технологических решений с учетом геологических, гидродинамических и геомеханических особенностей конкретного объекта.



Ключевые слова: бурение скважин, Восточная Сибирь, карбонатные коллекторы, пневмоударное бурение, азрированные буровые растворы, управляемое давление, газонефтеводопроявления, поглощения бурового раствора

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Introduction

Eastern Siberia is one of the most difficult regions of the Russian Federation in terms of the construction of oil and gas wells. A significant part of the promising objects in the region are confined to carbonate reservoirs, characterized by high faulting, intense natural fracturing, and an inhomogeneous distribution of porosity and permeability properties [1–3]. Additional difficulties are created by trap intrusions, cavernous zones, salt-bearing intervals and unstable geomechanical condition of the rock mass [4–6].

Drilling in such conditions is accompanied by challenges, among which the most common are circulation loss of drilling mud, wellbore wall instability, drilling tool sticking and gas, oil and water inflows. The occurrence of these challenges leads to an increase in non-productive time and an increase in the cost of well construction.

Fig. 1 shows a diagram of the main challenges that occur during drilling through tectonically disturbed carbonate reservoirs in Eastern Siberia.

The zones of intense fracturing and tectonic disturbances have the greatest impact on the stability of the drilling process, within which the

probability of circulation loss and flow of reservoir fluids into the wellbore significantly increases.

In recent years, low-pressure drilling technologies have become increasingly widespread to improve drilling efficiency in difficult conditions [7–10]. The most common technological areas are: pneumatic hammer drilling; aerated and foam drilling systems; managed pressure drilling (MPD).

The use of these technologies makes it possible to reduce the hydrostatic pressure on the formation, reduce the mud loss rate and increase the efficiency of bottom-hole cleaning. At the same time, the scope of their application is determined by the geological and technical conditions of drilling, the level of water cut and rock stability.

Table 1 provides a generalized description of the main challenges that occur during the construction of wells in tectonically disturbed carbonate reservoirs in Eastern Siberia.

The presented challenges are interrelated and significantly complicate the well construction process. In such conditions, drilling efficiency is largely determined by the correct choice of technology and the ability to adapt drilling parameters to changing geological and technical conditions.

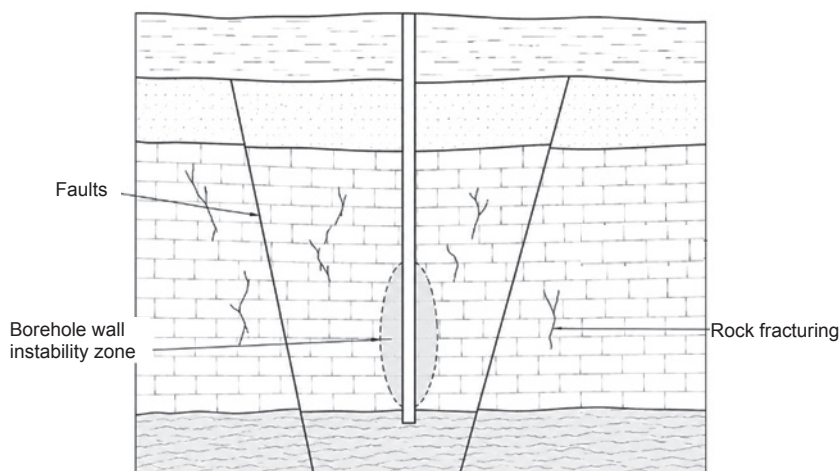


Fig. 1. Main challenges when drilling through tectonically disturbed carbonate reservoirs of Eastern Siberia

Рис. 1. Основные осложнения при бурении в тектонически нарушенных карбонатных коллекторах Восточной Сибири



Table 1. Main challenges when drilling through tectonically disturbed carbonate reservoirs
Таблица 1. Основные осложнения при бурении в тектонически нарушенных карбонатных коллекторах

Challenge	Main reason	Possible consequence	Main method of prevention
Drilling mud loss	Fracturing, cavernosity, fault zones	Circulation loss, increased non-productive time	Aerated systems, MPD, insulation materials
Gas, oil and water inflows	Reduction of hydrostatic pressure	Reservoir fluid inflow, emergency situations	Pressure control, blowout prevention equipment
Wellbore instability	Geomechanica instability	Rock falls, sticking	Geomechanical modeling, mud density control
Caving	Soft and salt-bearing rocks	Disturbance of wellbore geometry	Non-dispersing mud
Drilling tool sticking	Rock falls, differential pressure	Emergency work	Optimization of hydraulics and wellbore cleaning

The aim of the study was to conduct a comparative analysis of modern drilling technologies used in the construction of oil and gas wells in tectonically disturbed carbonate reservoirs in Eastern Siberia, as well as to identify their advantages, limitations, and areas of rational application.

As part of the study, three main technological areas of complex drilling, previously mentioned, were examined:

- pneumatic hammer drilling;
- aerated and foam drilling systems;
- MPD technology.

Materials and methods

The study is based on methods of comparative analysis, systematization, and critical generalization of published scientific and technical data devoted to drilling oil and gas wells in complex geological and technical conditions.

The work analyzes domestic and foreign publications devoted to pneumatic hammer drilling, aerated and foam drilling systems, managed pressure drilling technologies, as well as issues related to wellbore stability, elimination of mud loss, and prevention of gas, oil, and water inflows [11–21]. The main focus was on research related to drilling fractured carbonate reservoirs and complex intervals in Eastern Siberia.

Geological and technical features of drilling in Eastern Siberia

The geological and technical conditions of Eastern Siberia are characterized by a high de-

gree of tectonic disturbance, the development of natural fracturing, and significant heterogeneity of carbonate reservoirs [1, 14, 15]. A significant part of the promising objects of the region is associated with ancient Riphean and Vendian-Cambrian carbonate deposits, complicated by fault zones, cavernous structures, and trap intrusions.

When drilling wells in such conditions, the most common challenges are:

- intensive drilling mud losses;
- instability of wellbore walls;
- drilling tool sticking;
- cavern formation;
- gas, oil, and water inflows.

The occurrence of challenges leads to an increase in non-productive time, higher costs of well construction, and reduced efficiency of drilling operations. Additional complexity is created by the high heterogeneity of the rock massif. Within a single section, the following may coexist:

- hard carbonate rocks;
- fractured intervals;
- soft clay interbeds;
- salt-bearing deposits;
- cavernous zones.

Such conditions significantly complicate the selection of the optimal drilling technology and require adaptive management of circulation and pressure parameters.

A number of studies note that the use of traditional drilling muds under conditions of intense fracturing is accompanied by significant circulation losses and a deterioration in wellbore sta-



bility [17, 18]. In this regard, drilling technologies with reduced pressure are becoming increasingly widespread, as they allow for lowering the load on the formation and reducing the likelihood of challenges [22].

Pneumatic hammer drilling

Fig. 2 shows the schematic diagram of pneumatic hammer drilling. It displays the compressor equipment, the drill string, the pneumatic hammer mechanism, and the direction of movement of the working agent.

Pneumatic hammer drilling is based on a rotary percussion mechanism of rock destruction and is most effective when drilling through hard, fractured carbonate intervals. The use of percussion allows for increasing the mechanical penetration rate and improving the destruction of hard rocks [8, 9, 21, 23].

The main advantage of pneumatic hammer drilling is the high efficiency of destroying hard and abrasive rocks. An additional advantage of the technology is the reduction in the volume of the liquid phase in the circulation system, which can help reduce the intensity of drilling mud losses.

However, the use of pneumatic hammer systems is accompanied by a number of limitations. The effectiveness of the technology significantly decreases:

- in conditions of high water cut;
- when drilling soft rocks;
- in salt-bearing intervals;
- in unstable well walls.

Liquid penetration in the working zone of the air hammer leads to damping of the impact loads and worsens rock destruction. In addition, the use of air or nitrogen is accompanied by a decrease in hydrostatic pressure, which increases the likelihood of gas, oil, and water inflows.

Table 2 presents the main advantages and limitations of pneumatic hammer drilling.

Pneumatic hammer drilling is most effective in hard fractured rocks with relatively low water cut. In conditions of unstable rocks and intensive inflow of reservoir fluids, the use of technology requires increased control of circulation and pressure parameters.

Aerated and foam drilling systems

One of the most common ways to reduce circulation losses is to use aerated and foam drill-

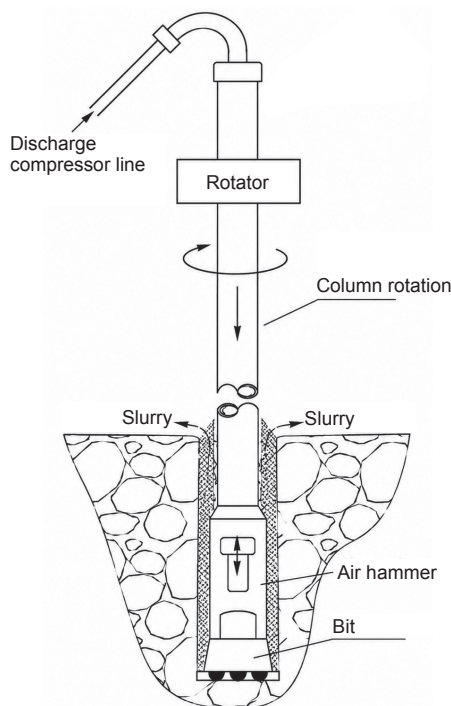


Fig. 2. Schematic diagram of pneumatic hammer drilling
Рис. 2. Принципиальная схема пневмоударного бурения



Table 2. Advantages and limitations of pneumatic hammer drilling
Таблица 2. Преимущества и ограничения пневмоударного бурения

Parameter	Advantage	Limitation
Destruction of hard rocks	High penetration rate	Reduction of effectiveness in soft rocks
Bottom-hole cleaning	Effective slurry removal	Dependence on circulation stability
Circulation loss	Reduction in the volume of the liquid phase	Limitations when there is high water cut
Hydrostatic pressure	Possibility of drilling with reduced pressure	Increased risk gas, oil and water inflows

ing systems. [3, 16, 24, 25]. These technologies are based on reducing the density of the drilling agent by injecting a gas phase, which reduces the hydrostatic pressure on the reservoir.

The following gas phases are usually used:

- air;
- nitrogen;
- gas-liquid mixtures;
- foam compositions.

Fig. 3 shows a drilling scheme using an aerated drilling fluid system, as well as the processes

of supplying a gas-liquid mixture and circulating a drilling agent.

The use of aerated systems makes it possible to reduce the equivalent density of drilling mud and reduce the intensity of circulation losses. A number of studies have noted an increase in the mechanical penetration rate and a reduction in non-productive time when using gas-liquid systems [3, 20, 25].

An additional advantage of aerated technologies is the reduction of drilling mud consumption and the volume of water consumed.

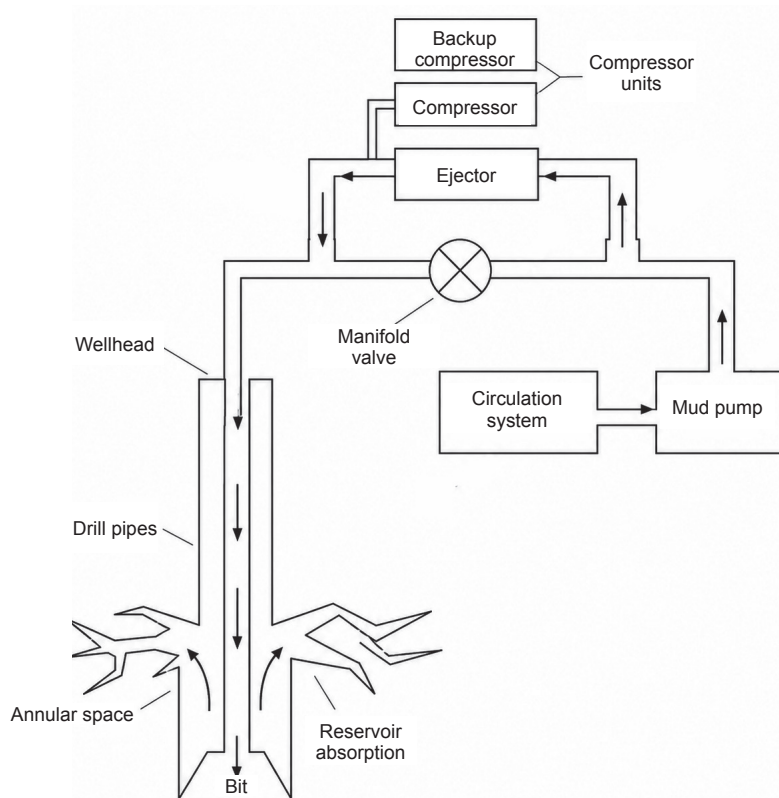


Fig. 3. Schematic diagram of drilling with an aerated drilling fluid system
Рис. 3. Схема бурения с использованием азрированной промывочной системы



However, the use of aerated and foam systems is accompanied by a number of limitations. The main risk factor is the likelihood of gas, oil and water inflows due to a decrease in hydrostatic pressure in the wellbore. In addition, instability of the gas-liquid mixture can lead to a deterioration in the bottom-hole cleaning and instability of the hydrodynamic regime.

Additional challenges are possible:

- with high water cut;
- in unstable rocks;
- in salt-bearing intervals;
- with intense inflows of reservoir fluids.

Comparative characteristics of aerated and foam drilling systems is given in Table 3.

Aerated and foam systems are most effective in conditions of intense mud loss, where a reduction in hydrostatic pressure on the reservoir is required. At the same time, the stability of the drilling process directly depends on the quality of control of the circulation parameters and the hydrodynamic regime [24, 25].

Managed pressure drilling technologies

Managed pressure drilling (MPD) technologies are one of the most promising areas for the development of complicated drilling [4, 17, 19, 24, 26]. The main objective of MPD is to maintain a managed pressure in the wellbore within a safe range between reservoir pressure and pressure of rock destruction.

MPD technology is particularly effective in the following conditions:

- intense fracturing;
- unstable rocks;
- a narrow range of permissible pressures;

- high risks of gas, oil and water inflows;
- partial and full mud loss zones.

MPD technologies make it possible to quickly adjust the equivalent circulation density and manage the pressure in the annular space of the well. This is especially important when drilling heterogeneous carbonate reservoirs, where even minor changes in the hydrodynamic regime can lead to challenges.

A number of studies have noted that the use of MPD contributes to:

- reduction of non-productive time;
- reducing the number of challenges;
- reduction of emergency recovery operations;
- improving the stability of the drilling process [4, 17, 19, 24].

However, the application of MPD is accompanied by high technological complexity and requires:

- specialized equipment;
- constant pressure monitoring;
- highly qualified personnel;
- operational management of circulation parameters.

An additional limitation is the increased capital and operating costs associated with the implementation of the technology.

A comparative assessment of the drilling technologies considered is presented in Table 4.

The presented data show that there is no universal drilling technology for all geological and technical conditions. Pneumatic hammer drilling is most effective when drilling through hard fractured rocks, aerated drilling systems are used in conditions of intense mud loss, while MPD technologies provide the highest level of hydrodynamic regime control [22, 24, 27, 28].

Table 3. Comparison of aerated and foam drilling systems
Таблица 3. Сравнение азрированных и пенных буровых систем

Parameter	Aerated drilling systems	Foam drilling systems
Reduction of hydrostatic pressure	High	High
Bottom-hole cleaning	Good	High when there is stable foam
Working in mud loss zones	Effective	Effective
Working in soft rocks	Limited	Limited
Risk of gas, oil and water inflows	Increased	Increased
Requirements for parameter control	High	Very high



Table 4. Comparative assessment of drilling technologies
Таблица 4. Сравнительная оценка технологий бурения

Criteria	Pneumatic hammer drilling	Aerated drilling systems	Managed pressure drilling technologies
Hard carbonate rocks	High effectiveness	Average effectiveness	High effectiveness
Zones of intense mud loss	Average effectiveness	High effectiveness	High effectiveness
High water cut	Low effectiveness	The application is limited	High effectiveness
Pressure management	Limited	Average	Maximum
Risk of gas, oil and water inflows	Increased	Increased	Decreased when correct configuration is used
Technology complexity	Average	High	Very high
Implementation cost	Average	Average	High

Results and discussion

The analysis shows that the effectiveness of complicated drilling technologies is determined by a combination of geological, hydrodynamic and geomechanical factors.

Pneumatic hammer drilling provides high mechanical penetration rate in hard carbonate rocks, however, its use is limited by high water cut and unstable geomechanical conditions. In such intervals, the effectiveness of the hammer mechanism is significantly reduced.

Aerated and foam drilling systems can reduce the intensity of mud loss and reduce the hydrostatic pressure on the reservoir. At the same time, the use of gas-liquid systems requires constant monitoring of circulation parameters and increased attention to the prevention of gas, oil and water inflows [29].

MPD technologies have the widest control capabilities for the hydrodynamic regime, but they are accompanied by high technological complexity and significant costs. MPD is most effective in conditions of a narrow range of permissible pressures and increased risks of challenges.

Comparative analysis shows that the choice of technology should be determined not only by the mechanical penetration rate, but also by the following parameters [30]:

- the stability of the wellbore walls;
- the probability of circulation losses;
- the risks of gas, oil and water inflows;
- the level of water cut;

– economic efficiency of the technology application.

Pneumatic hammer drilling provides maximum effectiveness in the destruction of hard rocks, however, it is inferior to MPD technologies in terms of control of the hydrodynamic regime. Aerated drilling systems occupy an intermediate position, combining the possibility of reducing hydrostatic pressure with a relatively lower cost of implementation.

An additional problem remains the limited amount of published field data on the objects of Eastern Siberia. Most of the studies are devoted either to individual technological solutions or to laboratory and model studies, which complicates the formation of universal engineering recommendations.

In this regard, further development of complicated drilling technologies should be aimed at:

- improving pressure management systems;
- development of combined drilling technologies;
- increasing the stability of gas-liquid systems;
- development of digital monitoring;
- collection of field data on objects in Eastern Siberia.

Conclusion

The comparative analysis of modern drilling technologies has shown that the construction of oil and gas wells in tectonically disturbed carbonate reservoirs in Eastern Siberia is accompanied by a complex of challenges, the main of which are



intensive loss of drilling mud, instability of wellbore walls and oil, gas and water inflows.

It is established that the effectiveness of complicated drilling technologies is determined by a combination of geological, hydrodynamic and geo-mechanical factors.

Pneumatic hammer drilling is most effective when drilling through hard fractured carbonate rocks, however, its use is limited by high water cut, soft and salt-bearing intervals, as well as the risks of the wellbore instability.

Aerated and foam drilling systems can reduce the intensity of circulation losses and reduce hydrostatic pressure on the reservoir, however, they require constant monitoring of circulation parameters and increased attention to the prevention of oil, gas and water inflows.

MPD technologies provide the highest level of control of the hydrodynamic regime and are most effective in conditions of a narrow range of permissible pressures and increased risks

of challenges. However, their application is accompanied by high technological complexity and significant costs.

It is shown that there is no universal drilling technology for all geological and technical conditions in Eastern Siberia. The most effective approach is an adaptive choice of technological solutions, taking into account:

- the degree of fracturing of rocks;
- the level of water cut;
- the stability of the wellbore walls;
- the nature of reservoir pressures;
- the likelihood of challenges.

Promising areas for further research are:

- improvement of managed pressure technologies;
- development of combined drilling systems;
- increasing the stability of gas-liquid solutions;
- development of digital monitoring;
- collection of field data on objects in Eastern Siberia.

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Information about the authors / Информация об авторах



Ilya A. Yaroshchuk,
Postgraduate Student,
Institute of Subsoil Use,
Irkutsk National Research Technical University,
Irkutsk, Russian Federation,
✉ ilya.yaroshuk@yandex.ru
<https://orcid.org/0009-0000-3955-8501>
Ярошук Илья Александрович,
аспирант,
Институт недропользования,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Российская Федерация,
✉ ilya.yaroshuk@yandex.ru
<https://orcid.org/0009-0000-3955-8501>



Vladimir Yu. Panfilov,
Postgraduate Student,
Institute of Subsoil Use,
Irkutsk National Research Technical University,
Irkutsk, Russian Federation,
panfilov_vu@mai.ru
<https://orcid.org/0009-0004-1248-5567>
Панфилов Владимир Юрьевич,
аспирант,
Институт недропользования,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Российская Федерация,
panfilov_vu@mai.ru
<https://orcid.org/0009-0004-1248-5567>



Pavel S. Pushmin,
Ph.D. in Engineering,
Associate Professor of the Department of Oil and Gas Engineering,
Institute of Subsoil Use,
Irkutsk National Research Technical University,
Irkutsk, Russian Federation,
pps@ex.istu.edu
<https://orcid.org/0000-0001-5127-849X>
Пушмин Павел Сергеевич,
кандидат технических наук,
доцент кафедры нефтегазового дела,
Институт недропользования,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Российская Федерация,
pps@ex.istu.edu
<https://orcid.org/0000-0001-5127-849X>

Contribution of the authors / Вклад авторов

Ilya A. Yaroshchuk – conceptualization, formal analysis, writing – original draft.
Vladimir Yu. Panfilov – conceptualization, formal analysis, writing – original draft.
Pavel S. Pushmin – supervision, writing – editing.
И.А. Ярошук – разработка концепции, формальный анализ, написание черновика рукописи.
В.Ю. Панфилов – разработка концепции, формальный анализ, написание черновика рукописи.
П.С. Пушмин – научное руководство, редактирование рукописи.

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