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On the selection of optimal drilling fluid formulations under HPHT constraints

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Abstract. Drilling deep and ultra-deep wells under high-pressure/high-temperature (HPHT) conditions is a strategic pathway for expanding Ukraine's resource base and requires a scientifically grounded approach to selecting optimal drilling-fluid formulations. The objective of this research was to establish, through an in-depth analysis of international and Ukrainian HPHT well construction practices, a methodology for selecting optimal formulations of high-performance water-based, clay-free drilling fluid systems (HT-HPWBF), which integrates both the hierarchy of optimality criteria and the system's key performance indicators. A systematic review and content analysis of more than 200 publications on HT-HPWBFs were performed, the field experience from Ukrainian assets was synthesised, and a comparative analysis versus international practice was conducted. The assessment reveals that Ukraine lags behind leading HPHT regions primarily due to continued reliance on conventional KCl and biopolymer-potassium systems rather than modern HT-HPWBFs. Based on importance-impact analysis of requirements, technological constraints, and performance indicators, the study demonstrated the feasibility of constructing a hierarchical framework of core criteria for selecting optimal formulations. A three-tier optimality hierarchy comprising α-criteria (well-control and safety), β-criteria (achievement

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of technological objectives), and γ-criteria (environmental-economic effectiveness) was proposed. A methodology for constructing composite key performance indicators that integrate field experience, laboratory testing, and risk assessment was developed. The study substantiated the combined use of advanced analytics of historical data, real-time monitoring of fluid parameters, and key performance indicators driven decision making for formulation selection. The results can be directly applied by drilling engineers and service companies to improve the efficiency of HPHT well construction in Ukraine

Keywords: drilling mud design; indicators of efficiency; drilling mud quality index; complex analysis; clay-free systems

Introduction

The energy security and prosperity of every country depends on the level of energy supply to industry and, consequently, on the level of hydrocarbon resource development. Given the contradiction between growing global demand for energy resources and their supply, drilling deep and ultradeep wells can be a strategic step towards expanding the hydrocarbon resource base. The main problems in drilling such wells are the high pressure and high temperature (HPHT) conditions at the bottom hole. The problems of producing hydrocarbons that lie in HPHT conditions are associated with significant risks of both a geological and technical-technological nature. For successful well completion in such conditions with simultaneous mitigation of complications or emergencies, special attention should be paid to the selection of the optimal mud formula. To select the optimal formulation, the advantages and disadvantages of existing alternatives in HPHT conditions should be evaluated, taking into account the technological features of use, expert assessment of possible risks (risk assessment), economic feasibility, and environmental acceptability of each formulation in particular. The complexity of implementing drilling programs under HPHT conditions is also related to the fact that several problems of different origins (geological, technical, technological, environmental, economic, etc.) usually need to be solved simultaneously.

According to J. Zhang *et al*. (2025), high formation pressure often leads to high risks of well control loss and low penetration rates due to the need for high-density mud systems, which can lose stability when exposed to high temperatures (170-240°C) for long periods of time. As noted by B. Miikor *et al*. (2025), water-based systems are less commonly used for high-temperature wells due to the stability (in particular, thermal degradation) issues of biopolymer thickening agents, water-shale control agents, and other components of drilling fluids under such conditions. However, the practical experience of T. Hasan Hamdan *et al*. (2020) has shown that, when it is necessary to obtain high-quality logging data to assess the prospects of new fields, water-based systems are a more desirable option. In addition, as noted by the authors Y. Freschi *et al*. (2025), with the growing emphasis on minimising the impact on the surrounding environment, high-quality HT-HPWBF (High Temperature-High Performance Water Based Fluid) systems will always be a priority. This is also facilitated by the development and deployment of the principles of "sustainable development" and "green transformation" of the Industrial Revolution 4.0 in the global oil and gas industry. The oil and gas industry is increasingly using HT-HPWBF systems whose main thermostabilising components are formates (Myslyuk & Zholob, 2023), polyamines or acetates (Liu *et al*., 2020a). Such systems have both high density (without the use of barite) and good thermal stability. The choice of organic salt solutions as the basis for drilling fluids helps minimise well control problems associated with barite settling, high rheology, poor rock stability, excessive casing corrosion, etc.

The mechanisms of biopolymer degradation in solutions at high temperatures include acid-catalysed hydrolysis and redox reactions. Therefore, the thermal stability of biopolymers can often be increased (up to 180°C) in three ways: using antioxidants (polyethylene glycols, magnesium oxide, formates) that inhibit oxidative reactions and react with free hydroxyl radicals, preventing polymer degradation (Myslyuk & Zholob, 2023); using oxygen scavengers (King & Rodrigue, 2025); and modifying by grafting monomers or functional groups (Kong *et al*., 2022). In order to maintain the operational and thermal stability of water-based drilling fluids at high temperatures when using xanthan biopolymer, the authors L. Quitian-Ardila *et al*. (2024) recommend increasing its concentration in the formulation.

According to research by N. Jameel & J. Ali (2023), the problem of controlling water loss and rheological properties in water-based systems can be effectively solved by using several types of polymers simultaneously. As noted by researchers J. Sun *et al*. (2024), despite the variety of systems developed that are resistant to high formation temperatures, a number of problems still arise in their practical application, such as insufficient stability in real well conditions, the complexity of controlling rheological and filtration properties, and insufficient compatibility with formations. This situation is most likely due to the complexity of selecting the optimal concentrations of reagents for each specific application (case or well). Significant attention has been paid to the development of heat-resistant reagents and equipment capable of operating in difficult HPHT conditions, which has made it possible to overcome the main technological challenges of developing ultradeep wells. However, issues related to the selection of optimal HT-HPWBF formulations, the criteria for the effectiveness of such systems, and ways to optimise them for specific mining and geological conditions have not been sufficiently studied. The aim of the study was to develop a methodological approach to selecting optimal formulations for highly effective water-based clay-free drilling fluids for HPHT well drilling. This was based on in-depth analysis of experience, taking into account the hierarchy of optimisation criteria and key performance indicators (KPIs) for such systems.

Materials and Methods

In accordance with the Law of Ukraine No. 4154-IX (2024), the development of mineral resources is one of the priorities. In order to improve the quality of deep and ultradeep well construction in complex mining and geological conditions, it is necessary to select the optimal drilling fluid formulations. To determine the criteria for optimality and form a system of restrictions for the main parameters of the fluids, the systematic review and content analysis of publications devoted to the selection of optimal formulations for water-based drilling fluids and their properties under HPHT conditions (more than 40 sources published in the period 2005-2025 as well as tenders from the Prozorro, n.d.) were carried out. The review covered all countries of the world, including Ukraine. The publications from peer-reviewed journals included in Scopus and Web of Since, as well as materials from the OnePetro digital library for the oil and gas industry (created and maintained by SPE) were taken into account.

To establish chronological links, trends or evolutionary changes in optimality criteria systems, all publications were grouped by year for further analysis. During the content analysis of publications, the main focus was on: the conditions in which the flushing systems were planned to be used (apart from HPHT, whether there are any other complications, such as unstable rocks, hydrogen sulphide, etc.); the objectives of developing or adapting the flushing fluid formulation; the parameters of the formulations under study; the criteria for optimality stated by experienced authors (usually practitioners); performance indicators (including KPIs) when testing formulations in both field and laboratory conditions and the methods for their development.

Based on the results of the analysis, sets of primary and secondary criteria for optimality were formed, with reference to the period of application (the degree of importance was indicated by the authors of the publications). Upon formation of the sets, a frequency assessment of the criteria was conducted and their average rank was determined for the construction of a hierarchy in the future. Based on a review of the requirements, technological limitations, and performance indicators of HT-HPWBF systems declared in publications, a hierarchical system was created. To develop recommendations for selecting a drilling fluid formulation for use in complex mining and geological conditions, a systematic and comprehensive approach was applied both at the design stage and at the subsequent stages of laboratory and industrial testing.

Important elements of the procedure for designing and selecting the optimal HT-HPWBF formulation were: assessment of predicted risks; determination of the main objectives of the formulation design; identification of the main problems and limitations imposed by HPHT conditions; formation of a list of alternative acceptable formulations in accordance with mining and geological conditions and a hierarchical system of requirements; selection of the criterion (criteria) of optimality or formation of a comprehensive indicator of the efficiency of the flushing system; implementation of the selected procedure for selecting the optimal formulation. Therefore, the paper considered the procedure for selecting optimal drilling fluids under HPHT constraints.

Results and Discussion

An analysis of publications and tenders (Prozorro, n.d.) showed that high-tech and complex HPHT wells are actively being constructed in Ukraine, and Ukrainian specialists have considerable experience in drilling such wells. Well drilling in Ukraine is steadily shifting from the normal pressure and normal temperature (NPNT) zone to the HPHT zone (Fig. 1). However, the share of modern clay-free HT-HPWBF systems in Ukraine is several times lower than in leading countries such as China or the United States.

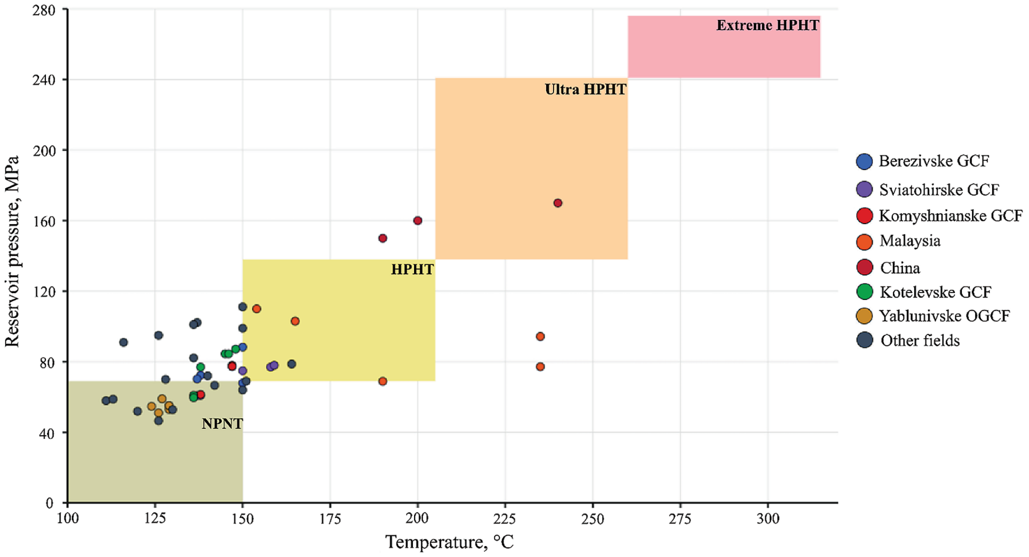


Figure 1. Comparison of HPHT well drilling trends in Ukraine with global practices

Source: created by the authors based on Prozorro (n.d.), O. Agwu *et al.* (2021), J. Zhang *et al.* (2025)

Among Ukrainian fields with HPHT conditions or conditions close to them are the Berezivske Gas Condensate Field (GCF), Shebelynske GCF, Stepove GCF, Solokhivske Oil and Gas Condensate Field (OGCF), Komyshnianske GCF, Sviatohirske GCF, etc. Although Figure 1 does not contain complete and comprehensive information on HPHT well drilling in Ukraine and worldwide, and only highlights a small part of it (available open data), it however, allows to see the general trend of lagging behind the world leaders in ultradeep well drilling (China, Malaysia, etc.). This statement applies to drilling fluids. According to the online public procurement platform Prozorro (n.d.), the most actively used fluids for HPHT drilling are chlorinated potassium-weighted HTHP solution and biopolymer-potassium HPHT solution. Although the use of these systems allows for the achievement of design depths, the total drilling time is much longer when compared to the time spent drilling with conventional HT-HPWBF systems. The increase in drilling time is associated with periods when the drilling rig or personnel are unable to perform planned productive operations due to various problems, such as waiting for the delivery of materials or specialists, or dealing with serious complications or accidents. Such time losses represent Non-Productive Time (NPT), i.e. time losses due to events or their absence, which are always officially recorded. This usually includes time lost on well control, delivery of drill string components, bits, downhole motors, cable logging, etc. In addition, during well construction, there is Invisible Lost Time (ILT), which is not always officially documented or recorded as downtime, but has a significant impact on overall work productivity and project cost. These include frequent short stops (which are not recorded as downtime due to their duration), time lost due to suboptimal decisions or lack of expertise (experience) among personnel, etc.

It should be noted that classic HT-HPWBF formulations are successfully used in Ukraine. For example, specialists from Geosynthesis Engineering used their own high-performance Biocar-TF system, which is stable at high temperatures, when drilling wells in the complex mining and geological conditions of the Semyrenkivske GCF (First utilization..., n.d.). However, the need for highly efficient clay-free HT-HPWBF systems is growing due to the trend of drilling wells over 5,500 m. In such conditions, reducing NPT and ILT during drilling by using HT-HPWBF-type drilling fluids is an important strategic decision for oil and gas companies. Another characteristic feature of the use of such systems is a significant reduction in NPT associated with loss of control over the well or stability of the wellbore (Biocar-TF biopolymer drilling..., n.d.). Since the main function of HT-HPWBF is to ensure safe working conditions while achieving maximum drilling efficiency at high bottomhole temperatures and the customer's specified consumption level, selecting the optimal formulation is a complex but crucial step in successful well drilling. To illustrate the variability of HT-HPWBF system alternatives and their component composition, Table 1 shows the characteristics of some commercial solutions developed and implemented by relevant service companies. All systems are environmentally friendly alternatives to non-aqueous-based solutions in terms of their effectiveness under HPHT conditions.

Table 1. Some commercial solutions for HT-HPWBF systems

System (Company)	Declared thermal stability, °C	Features and main components
PYRO-DRILL (Baker Hughes)	316	A highly effective system whose main components are Polydrill synthetic sulphated polymers and All-Temp and SSMA Mil-Temp interpolymers for regulating thermal stability, Chemtrol X AMPS/Aam copolymers, Kem-Seal, Pyro-Trol for controlling HPHT filtration, thickening and shale inhibition, Max-Guard™ Plus (clay inhibitor), Penetrex, Latilube™ (lubricating additives), Sulfatrol Xceed (HPHT filtration control), Max-Shield (sealing polymer).
BaraDrilN X (Halliburton)	232	A highly efficient clay-free well completion system based on synthetic polymers BDF-637 (for monovalent brines) or BDF-638 for divalent brines (CaBr2). If necessary, the system can contain corrosion inhibitors (Baracor 100) and oxygen absorbers (Oxygon™). Micromax or Mn_3O_4 can be used additionally to achieve the design densities.
BaraXtreme (Halliburton)	227	A highly efficient clay-free system based on synthetic polymer BDF-637 (BaraVis W-637), designed to control viscosity and filtration at high temperatures. The system also contains highly effective reagents that increase wellbore stability and reduce fluid loss, such as BaraFLC Nano-1 (nanocomposite suspension) and others.
VeraTherm (SLB)	205	The VeraTherm system, based on the synthetic polymer VeraVis, which is designed to regulate the rheological and filtration properties of the system, outperforms both formate and conventional polymer systems and demonstrates excellent performance at high temperatures. Depending on requirements, the system can be based on KCl, NaCl, NaBr, $CaCl_2$, $NaHCO_2$, $KHCO_2$, or $CsHCO_2$ brines.
Biocar-TF (Geosynthesis Engineering)	170	A highly efficient clay-free system based on xanthan gum, modified starch, and sodium and potassium formates. The system also contains the organo-mineral colloid Alevron, micro-marble, and other auxiliary substances.

Note: depending on drilling conditions, thermal stability can be increased or enhanced by changing the type or content of reagents; the composition of the system can be adjusted according to specific conditions or constraints

Source: created by the authors based on VeraTherm high-temperature water-based drilling fluid (n.d.), World's first application of BaraXtreme fluid in HTHP gas well (n.d.), BaraDrilN™ X fluid helps customer achieve well testing operation (n.d.), Patent No. 124224, (2020), J. Liu *et al.* (2020b)

Highly productive clay-free systems (Table 1) are based on specially developed synthetic polymers with various functional purposes that maintain their performance characteristics at the level specified in the design documentation under prolonged exposure to high temperatures. To solve the problems of controlling the filtration and rheological properties of water-based systems, the oil and gas industry most often uses supramolecular polyacrylamide, amphoteric polymers, comb-like polymers and thermo-associated polymers (Tchameni *et al.*, 2025), and nanopolymers (Karakosta *et al.*, 2021). The thermal stability of such synthetic polymers can be 200°C and above (Freschi *et al.*, 2025). As noted by H. Shi *et al.* (2024), most water-soluble polymers degrade at temperatures of 200-240°C, which complicates the control of rheological and filtration properties at high and ultra-high temperatures.

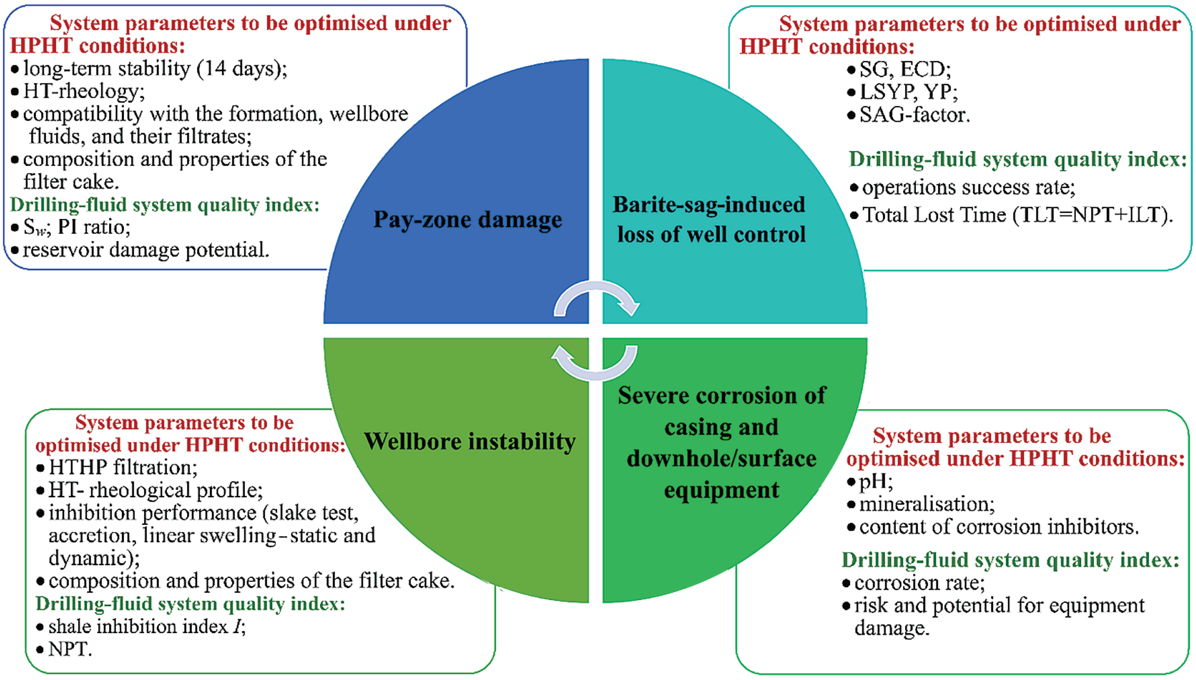
Therefore, with increasing drilling depths, there is a need to search for new, more temperature-resistant polymers with a heat resistance limit of 260°C, such as Pyro-Trol from Baker Hughes. In order to further increase the viscosity characteristics, a small amount of clay is added to such systems (Miikor *et al.*, 2025). However, according to A. Tchameni *et al.* (2025), high temperatures in the presence of clay materials (bentonite clay) in the solution formulation can cause thermally induced flocculation of clays and the formation of highly viscous gels. According to researchers S. Gautam *et al.* (2025), when developing a clay-free HPHT drilling fluid formulation, it is important to study the effect of polymer molecular weight and its distribution on the performance characteristics of the drilling fluid. This will largely solve one of the main problems of conventional water-based drilling fluids in HPHT conditions – barite ($BaSO_4$) sagging in both static and dynamic conditions, even during prolonged thermal ageing of the system.

Barite sagging can cause loss of well control (blowout), loss of fluid (due to hydraulic fracturing), problems with drill string mobility, etc. (Fakoya & Ahmed, 2023). J. Oseh *et al.* (2025) include the properties of the drilling fluid, the profile and geometry of the internal space of the well, and drilling parameters (rotation speed of the column, fluid flow rate, etc.) among the factors that most influence barite sagging. An effective measure to prevent barite sagging is to control the rheological properties of the system, among which Low Stress Yield Point (LSYP) should be noted. Another possible solution to the problem of weighting agent sagging is the correct choice of its type and particle size distribution. According to the authors, when drilling oil and gas wells in HPHT conditions, it is advisable to use nanoscale barite ($nBaSO_4$) and ilmenite ($nFeTiO_3$) due to the low susceptibility of such materials to sagging. The same opinion was expressed by researchers G. Soori *et al.* (2023), who proposed using Cerite (cerium oxide CeO_2) with a density of 6,000 kg/m^3 as a weighting agent, which would minimise the content of solid particles in the solution and, accordingly, pressure losses in the well.

According to O. Agwu *et al.* (2021), a cheaper alternative to barite in HPHT wells is manganese tetroxide (Mn_3O_4). The authors H. Mao *et al.* (2020) considered the possibility of combining barite with metal oxides, in particular iron (Fe_2O_3), and concluded that the rheological properties of HT-HPWBF largely depend on the type of weighting agents and their ratio in the formulation. Less commonly, zinc oxide (ZnO) (Ahasan *et al.*, 2021; Taghdimi *et al.*, 2023) or zirconium oxide (ZrO) (Medhi *et al.*, 2020) are used as weighting components. Laboratory studies and computer modelling are ongoing for these nanoscale weighting agents, without widespread industrial implementation. However, other nanodispersed oxides, such as Mn_3O_4 and CuO, are considered by A. Rana *et al.* (2024) to be an important element in the development of stable HPHT system formulations. Additionally, research by A. Shokry *et al.* (2024) shows that the use of nanoscale weighting agents can reduce the thickness of the filtration crust by 40% while simultaneously reducing the rheological properties and filtration of the solution system under HPHT conditions.

To solve the problems of sagging of weighting materials with a significant content (30-50%), optimise the rheological behaviour of drilling fluids and prevent absorption under HPHT conditions, researchers H. Mao *et al.* (2020) and H. Wang *et al.* (2022) proposed the use of sealing materials with the content, size, and particle size distribution selected using the ideal packing theory. This approach reduces sagging effects, problems with Equivalent Circulating Density (ECD), and changes in formation counterpressure. Depending on the profile and design of the well, the following methods can be used to assess barite sagging (Fakoya & Ahmed, 2023): test cell method; VST test (settlement test using a rotational viscometer); VSTT test (modified VST with a thermal cup); flow contour test; dynamic sag test at a large angle. The main principle in developing new or improving existing formulations for technological fluids is to minimise costs (time, resources, expenses) in the construction of oil and gas wells while ensuring their maximum productivity. A rational approach to selecting optimal formulations for technological fluids in HPHT conditions should also include an assessment of the risks associated with extreme environments in order to minimise them while achieving maximum operational efficiency (Fig. 2).

One of the main predicted risks associated with drilling mud under HPHT conditions is loss of control over the well due to both barite sagging and unsatisfactory filtration or rheological properties of the system. Damage to the formation or loss of wellbore stability can be the result of loss of well control, but can also occur due to other situational factors. Intensive corrosion of technical columns and equipment is also one of the main predicted risks associated with drilling fluid due to the characteristics of system weighting (inorganic and organic salts) and a significant increase in the activity of components under high temperature conditions. In such circumstances, in order to ensure maximum efficiency of the well deepening process while minimising the costs and risks associated with drilling fluid, the main objectives to be achieved through the use of HT-HPWBF should be set. The main objectives of designing highly efficient drilling fluid systems for HPHT conditions are shown in Figure 3.



System parameters to be optimised under HPHT conditions:
- long-term stability (14 days);
- HT-rheology;
- compatibility with the formation, wellbore fluids, and their filtrates;
- composition and properties of the filter cake.

Drilling-fluid system quality index:
- S_w; PI ratio;
- reservoir damage potential.

System parameters to be optimised under HPHT conditions:
- SG, ECD;
- LSYP, YP;
- SAG-factor.

Drilling-fluid system quality index:
- operations success rate;
- Total Lost Time (TLT=NPT+ILT).

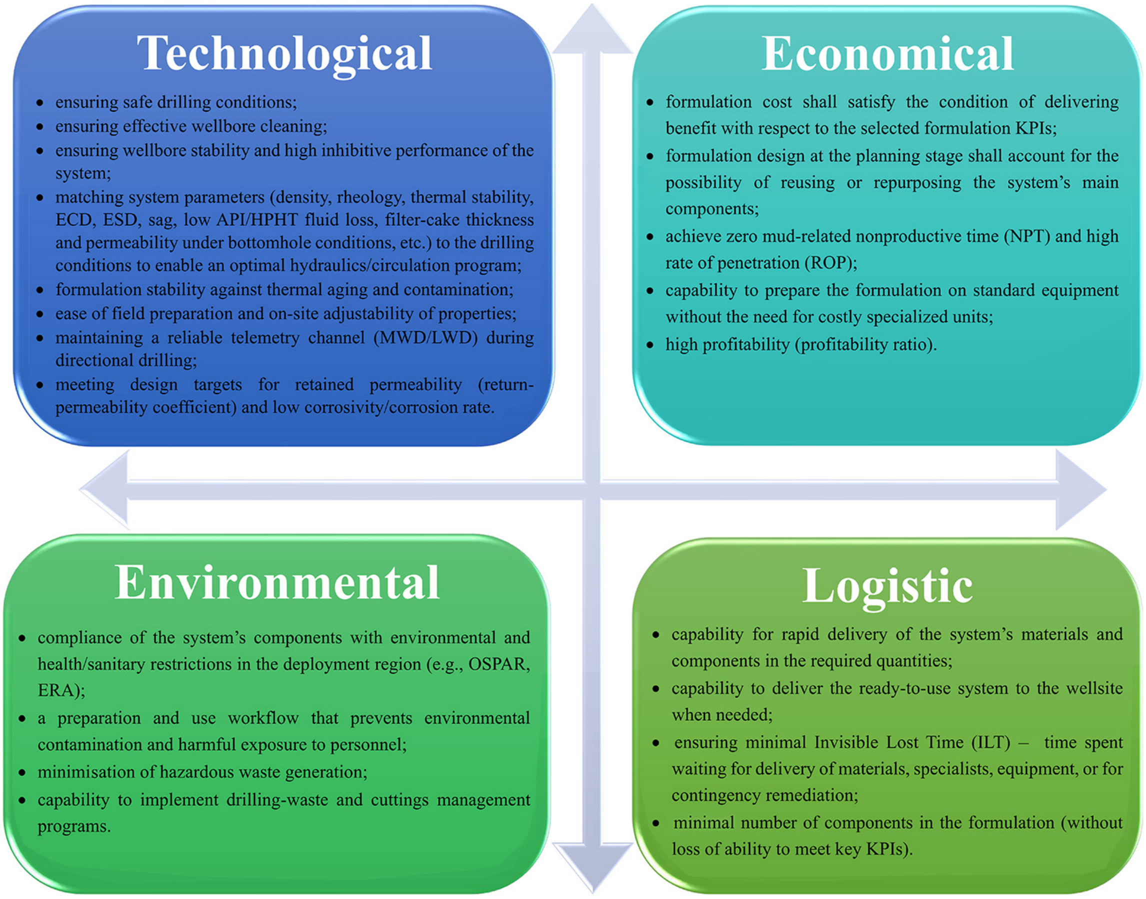
System parameters to be optimised under HPHT conditions:
- HTHP filtration;
- HT- rheological profile;
- inhibition performance (slake test, accretion, linear swelling-static and dynamic);
- composition and properties of the filter cake.

Drilling-fluid system quality index:
- shale inhibition index *I*;
- NPT.

System parameters to be optimised under HPHT conditions:
- pH;
- mineralisation;
- content of corrosion inhibitors.

Drilling-fluid system quality index:
- corrosion rate;
- risk and potential for equipment damage.

Figure 2. The main predicted risks associated with drilling fluid under HPHT conditions
Source: created by the authors based on information provided in the sources H. Mao *et al*. (2020), J. Zhang *et al*. (2025)



Technological
- ensuring safe drilling conditions;
- ensuring effective wellbore cleaning;
- ensuring wellbore stability and high inhibitive performance of the system;
- matching system parameters (density, rheology, thermal stability, ECD, ESD, sag, low API/HPHT fluid loss, filter-cake thickness and permeability under bottomhole conditions, etc.) to the drilling conditions to enable an optimal hydraulics/circulation program;
- formulation stability against thermal aging and contamination;
- ease of field preparation and on-site adjustability of properties;
- maintaining a reliable telemetry channel (MWD/LWD) during directional drilling;
- meeting design targets for retained permeability (return-permeability coefficient) and low corrosivity/corrosion rate.

Economical
- formulation cost shall satisfy the condition of delivering benefit with respect to the selected formulation KPIs;
- formulation design at the planning stage shall account for the possibility of reusing or repurposing the system's main components;
- achieve zero mud-related nonproductive time (NPT) and high rate of penetration (ROP);
- capability to prepare the formulation on standard equipment without the need for costly specialized units;
- high profitability (profitability ratio).

Environmental
- compliance of the system's components with environmental and health/sanitary restrictions in the deployment region (e.g., OSPAR, ERA);
- a preparation and use workflow that prevents environmental contamination and harmful exposure to personnel;
- minimisation of hazardous waste generation;
- capability to implement drilling-waste and cuttings management programs.

Logistic
- capability for rapid delivery of the system's materials and components in the required quantities;
- capability to deliver the ready-to-use system to the wellsite when needed;
- ensuring minimal Invisible Lost Time (ILT) – time spent waiting for delivery of materials, specialists, equipment, or for contingency remediation;
- minimal number of components in the formulation (without loss of ability to meet key KPIs).

Figure 3. Objectives of designing highly efficient drilling fluid systems for HPHT conditions
Source: created by the authors based on information provided in the sources A. Morrison *et al.* (2021), C. King & K. Rodrigue (2025)

The main objectives can be divided into four groups: technological, environmental, economic and logistic. Logistic objectives are listed separately from economic ones, since in complex HPHT conditions it is important to take into account the requirements for the delivery of materials in the shortest possible time, the problems of logistics of supply and storage of large volumes of scarce materials and their qualification. The criticality and completeness of the HT-HPWBF design objectives can be determined by the customer (or authorised responsible persons) taking into account the applicable industry safety requirements and environmental restrictions in force in the region where the flushing system is to be used. The planned objectives to be achieved at the final stage of HT-HPWBF formulation development are closely related to the problems imposed by HPHT conditions (Fig. 4), requirements for drilling fluids, and criteria for selecting optimal formulations to ensure KPIs.

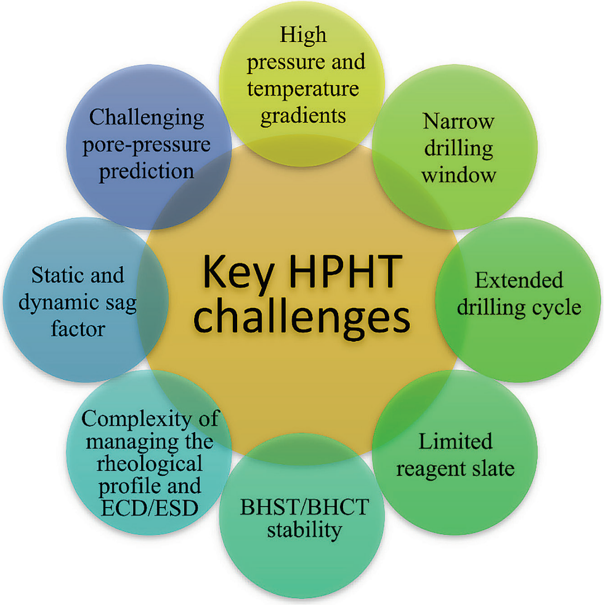


Figure 4. The main problems for drilling fluids related to HPHT conditions

Note: BHCT – Bottom Hole Circulating Temperature; BHST – Bottom Hole Static Temperature

Source: created by the authors based on information provided in the sources O. Agwu *et al*. (2021), A. Khalid *et al*. (2021), Y. Freschi *et al*. (2025)

The main problems in developing formulations for drilling fluids that must perform their functions under HPHT conditions, under technological, economic, environmental and logistical constraints, are primarily related to the limited range of acceptable materials. When selecting materials and components for highly heat-resistant formulations, it is necessary to take into account the operational, environmental, economic and logistic constraints that may arise in each specific case. The selection of drilling fluid components for high-temperature wells should be carried out in accordance with the temperature at the bottom of the well, with mandatory preliminary laboratory evaluation. Each individual component of drilling fluids has its own zero efficiency point – the temperature at which the reagents lose their productivity and effectiveness.

To develop and design a formula that is effective in HPHT conditions, regular preliminary laboratory studies must be conducted, which must include: static and dynamic ageing tests (24 and 72 hours), static and dynamic Sag Factor, including at BHST and BHCT; hot rolling for 16 hours at BHST, HPHT filtration, high-temperature rheological profile; zeta potential measurements, particle size distribution tests, etc. When optimising HPHT drilling fluid formulations, it is usually necessary to simultaneously address issues related to rheological control (rheological profile, yield point (YP), plastic viscosity (PV), LSYP, low shear rate viscosity (LSRV), etc.), filtration characteristics (application programming interface and HTHP filtration, thickness and properties of the filtration crust), as well as barite sagging. These parameters must be carefully monitored throughout the entire well construction cycle. The management of drilling fluid systems used in HPHT conditions must take into account the need to solve the problems shown in Figure 4, and also has some specific features in terms of engineering support.

According to J. Liu *et al*. (2020a; 2020b), due to the complexity of HPHT well design, extreme drilling conditions, and increased reactivity of rocks and reagents, water-based mud systems must have good inhibitory properties. In this case, the content of high-quality lubricating and antisticking additives is mandatory. This requirement is related to the need to minimise the problems of solid phase entering the mud system (Moroni *et al*., 2023). This will prevent an increase in ECD and rheological properties, prevent swelling of clayey rocks, and reduce problems associated with bit cleaning and loss of drill string mobility. As a result, when it is necessary to perform a roundtrip at significant depths, the frequency of drill string sticking and related technological downtime will decrease. With the deepening of high-temperature wells (and an increase in the temperature of the environment), the content of clay rock inhibitors should be increased and the inhibitory properties of the solution enhanced by introducing several types of inhibitors. According to X. Kong *et al*. (2022) and L. Moroni *et al*. (2023), a combination of KCl (6-12% content), amines (2-4%) and Partially Hydrolysed Polyacrylamide is effective for such purposes. According to H. Wang *et al*. (2022), polyamines are effective even at a bottomhole temperature of 235°C.

It should also be noted that water-based systems at high downhole temperatures are highly sensitive to treatment and prone to "depletion". Depending on the conditions and component composition, the "depletion" effect can manifest itself in evaporation, loss of activity, change in the pH of a particular reagent, and, accordingly, an increased need for re-treatment. Emulsifiers, wetting agents, active clay swelling inhibitors, and other surface-active substances are particularly sensitive to such depletion. Therefore, before adding any reagents to the active system, preliminary pilot laboratory tests should be conducted. When designing a hydraulic HPHT well cleaning programme, the solution behaviour model must take into account the PVT properties of the system. Having information about changes in the state of the drilling fluid depending on pressure and temperature allows timely and correct management decisions to be made when well conditions change. The requirements for HT-HPWBF drilling fluids must ensure the safe execution of planned work, personnel safety, and the desired result under the specified HPHT constraints.

An analysis of the use of drilling fluids for HPHT conditions (Erge *et al.*, 2020; Singh *et al.*, 2024) has made it possible to identify and summarise the requirements and criteria for selecting optimal HT-HPWBF formulations. It is necessary to ensure well control and full compatibility of the system and its filtrate with formation fluids and the reservoir. For this purpose, as noted by researchers S. Deshmukh *et al.* (2021), PV, ECD, Equivalent Static Density (ESD) and Sag Factor indicators must be low (including under BHST conditions). To ensure optimal rheology and keep the slurry in suspension, the YP should be within 12-25 (pounds/100 ft^2), and the LSRV at 6 rpm should be no more than 6 units on the scale. According to researchers, an HPHT filtration index of 2-7 cm^3/30 min at temperatures up to 300°F is quite acceptable for most wells. At the same time, the formulation should be resistant to sudden changes in the temperature profile (changes in solution parameters within acceptable limits, no salt crystallisation when the solution is brought to the surface, etc.) and static ageing at high (bottomhole) temperatures. At the same time, the stability of parameters under HPHT conditions must be maintained for at least 3-7 days and even several months (King & Rodrigue, 2025; Freschi *et al.*, 2025).

Excessive requirements or too strict requirements (extremely low parameter values that are difficult to achieve in real well conditions) can lead to a significant increase in the cost of the formulation, a reduction in the number of acceptable alternative formulations, or the absence of an optimal formulation. It should also be borne in mind that formulations that are effective in laboratory testing of technical and technological properties may not be competitive in industrial testing. The reasons for this are the balance between compliance with the requirements and the specific costs of materials, transportation, preparation, and health, safety and environment (HSE). Therefore, in such cases, it is advisable to use a hierarchy of functional requirements, technological constraints and performance indicators and to select a reasonable number of them according to the circumstances. As an example, Table 2 shows a developed version of a conditional ranking of these elements according to their importance and influence. It should be noted that the assignment of a particular element in Table 2 to the corresponding level of influence may be changed in accordance with specific drilling conditions (or changes therein) by providing such a recommendation (instruction) by experts, consultants (or expert advisory systems, such as Drilling Fluid Advisor), or the customer. The information in Table 2 may be supplemented in accordance with events, new circumstances or the absence of positive results from the use of a particular formulation.

Table 2. Hierarchy of requirements, technological limitations and performance indicators of HT-HPWBF systems

Functional requirements	Technological limitations	Performance indicators
Critical		
◈ thermal stability of the system; ◈ safe and efficient well control by ensuring low LSRV and LSYP values, Sag Factor < 0.5; ◈ maximum preservation of the reservoir properties of the productive formation; ◈ compatibility with the formation, other process fluids and their filtrates; ◈ explosion, eco and fire safety of the system and its components; ◈ compatibility with well completion and development technologies; ◈ stability of properties in HPHT environment at BHST throughout the entire period of prolonged downtime (during logging, especially in exploration wells); ◈ resistance of formulation components to hydrogen sulphide aggression; ◈ resistance of the formulation to contamination (cement, brine, etc.) and inflow of formation fluids.	◈ components resistant to high temperatures in static conditions; ◈ materials resistant to CO_2 and H_2S; ◈ delivery of system components of adequate quality in sufficient quantities may be difficult or economically unviable; ◈ problems with mixing and long-term storage of system components at the drilling site.	◈ maximum well productivity index (PI ratio); ◈ permeability recovery coefficient; ◈ maximum temperature stability retention time (days); ◈ technological efficiency coefficient and minimum number of incidents related to well control and safety; ◈ cuttings carrying index (CCI); ◈ maximum well integrity (stability) retention time; ◈ recipe profitability ratio (ROI).
Important		
◈ technological efficiency in preparation and use; ◈ low corrosion activity (all forms of corrosion) and abrasive impact on casing pipes and technological equipment; ◈ high inhibitory capacity; ◈ ability to effectively transfer hydraulic power; ◈ constant rheological properties under BHST and BHCT conditions, flat rheological profile over a wide range of temperatures and pressures; ◈ thin, low-permeability filtration crust.	◈ sulphur-containing corrosion inhibitors, commonly used in halide brines, decompose to H_2S at high temperatures; ◈ some amines used for pH control and inhibitors may react with acidic gases (CO_2, H_2S) to form harmful reaction products or lose their functional properties.	◈ drilling and completion time; ◈ ensuring maximum well life; ◈ low environmental footprint and impact; ◈ high accident-free drilling rate; ◈ well life and maintenance costs.

Table 2. Continued

Functional requirements	Technological limitations	Performance indicators
Additional		
◈ thermal stability in static conditions for a long time (more than 72 hours); ◈ high retention or carrying capacity; ◈ low chloride content (<70 mg/l) to minimise the impact on logging during drilling; ◈ the ability to conduct the most comprehensive set of high-quality geophysical surveys to assess the reservoir.	◈ some components of HT-WBDF may contribute to the formation of stable foam at high temperatures; ◈ degradation of chemical reagent properties during prolonged storage in field conditions (temperature, humidity, UV radiation).	◈ minimal costs for waste management and disposal of drilling sludge; ◈ minimal environmental footprint; ◈ environmental acceptability index; ◈ logistical efficiency index; ◈ technological feasibility index.
Specific		
◈ ensuring that there is no need to introduce corrosion inhibitors; ◈ stability of the Sag Factor over a long period of time (100 hours) in the absence of circulation; ◈ absence or low content of certain components (alkanes nC15 – nC35, aromatic hydrocarbons, etc.); ◈ absence or low content of biomarkers (terpenes, steranes, etc.).	◈ if hematite (Fe_2O_3) or ilmenite ($FeTiO_3$) are used as weighting agents, there is a problem of magnetic anomalies that distort MWD/LWD results; ◈ under HPHT conditions, metal ions (Fe^{3+}, Cu^{2+}, Mn^{2+}, etc.) can catalyse the degradation of polymers and the oxidation of organic components (by a factor of 10-100); ◈ when using nanomaterials (SiO_2, Al_2O_3, etc.), there is a risk of their aggregation and migration into the environment at pH <7 or >9.	◈ minimum volume of generated sludge (especially relevant for offshore drilling); ◈ cuttings carrying capacity index; ◈ corrosion inhibitor demand; ◈ biodegradability index of formulation components; ◈ strategic security coefficient; ◈ digital integration index.

Note: Wellbore Stability Index (WSI) is a comprehensive assessment of the ability of drilling fluid to maintain the mechanical integrity of the wellbore, preventing collapses, caving and other geomechanical problems; Recipe Profitability Ratio (ROI) – the ratio of economic effect (savings from reduced NPT, increased ROP, maintained productivity) to additional costs for premium components; Technological Efficiency Ratio is an integral indicator of successful drilling without complications, taking into account ROP, wellbore quality, and the absence of sticking and absorption, the coefficient depends on the synergy of components – HPHT rheology control, HPHT filtration, clay rock inhibitors, lubricating additives, etc., which work together; Cycle Economic Efficiency (Cost per BBL) – the total cost of the solution throughout the entire drilling cycle, taking into account treatments, refills and disposal, includes initial cost, treatments (10-30% of initial cost), losses (5-15%), disposal ($20-80/m3), logistics; Logistics Efficiency Index – the ratio of the formula's performance to the complexity of its delivery, storage and preparation in the field, takes into account the number of components (optimum 5-8), shelf life, the need for special equipment, and staff qualifications; Environmental Acceptability Coefficient – an integrated assessment of the environmental impact of formulation components according to OSPAR/EPA standards, including toxicity, biodegradability, and bioaccumulation; Hole Cleaning Efficiency – the quality of sludge removal and maintenance of hole cleanliness, assessed by cavernometer and analysis of sludge on the surface, depends on the optimisation of the rheological profile (YP/PV = 0.75-1.25) and the use of additional sludge carriers (fibres, spherical particles); Preparation Technological Index – simplicity and reliability of solution preparation in field conditions, including mixing time and quality stability, depends on the solubility of components, order of introduction, the need for special conditions (temperature, pH, hydration time); Strategic Security Index – independence of the ability to prepare the required volume of solution from critical imported components and the availability of alternative sources of supply, assesses the geographical diversification of suppliers, the availability of local analogues, and strategic reserves of formulation components; Digital Integration Index – compatibility of the formulation with automatic control systems, IoT sensors, and AI optimisation, requires stable rheological signatures, predictable behaviour, and the possibility of real-time correction

Source: compiled by the authors based on T. Hasan Hamdan *et al.* (2020), A. Rana *et al.* (2024)

The hierarchy shown in Table 2 links requirements and technological constraints with performance indicators. It is impossible to prepare an optimal HT-HPWBF formulation without meeting the functional requirements, constraints and performance indicators of the critical group. If important requirements such as the technological feasibility of preparation or the formation of a thin impermeable filtration crust (or others from the table) are violated, then the use of the formulation leads to a sharp increase in both costs and risks of complications, accidents, and an increase in drilling and completion time. This, in turn, reduces the profitability of the project. The fulfilment of additional and special functional requirements and restrictions as well as the provision of appropriate performance indicators is advisable in certain cases when required by the situation at the well or by the customer. The most common performance indicators for drilling fluids are the PI ratio and the permeability recovery factor. However, other indicators such as the Strategic Security Index, Digital Integration Index, etc. are also important for better formulation.

When developing a drilling fluid formulation for specific mining and geological conditions, each individual well should be assessed in advance for potential mechanisms of contamination of the bottomhole zone and risks of oil-water emulsion formation. This step will enable the correct choice of the base of the system (type of fluid), which will then be expanded with additional reagents to give the system the necessary technological properties. It is also important to take into account the existing practical experience of using certain formulations in specific (or similar) mining and geological and thermobaric conditions as fully as possible. Such experience is not just a database, journals or archives with poorly structured data, but intelligent systems that allow the accumulated knowledge and experience to be used as quickly and efficiently as possible.

To implement the procedure for forming a list of alternative acceptable HT-HPWBF system formulations, in addition to the hierarchical system of requirements, it is necessary to select an optimality criterion or form a system of criteria according to which the selection will be made. The main criterion for the optimality of the drilling fluid was the cost per unit volume of the formulation. Although the cost of the formulation in one way or another influences the choice of the base (type) of the drilling fluid and its component composition, it cannot be the main criterion when developing a new formulation or selecting the optimal variant among those proposed. In modern conditions, it is necessary to take into account the requirements for safety and control of the well, the technological efficiency of drilling, as well as environmental and economic aspects. At the same time, it should be noted that the selection of the optimal composition of HT-HPWBF is a multi-criteria task. The number of criteria, depending on the specific case (well, customer requirements, environmental and economic, or technological constraints), can range from 3 to 6 or more.

For example, authors A. Raptanov *et al*. (2021) mentioned drilling fluid density, HPHT filtration, pH, salinity, and water phase composition as key control parameters when selecting a drilling fluid. With the accumulation of practice and experience in drilling HTHP wells, the following combinations of optimality criteria have been implemented (compatibility, thermal stability and required density conditions are preserved for all options) (Deshmukh *et al*., 2021; Morrison *et al*., 2021; King & Rodrigue, 2025): Option 1 – HTH filtration, PV, YP; Option 2 – HTH filtration, PV, YP, Sag Factor; Option 3 – HTH filtration, LSRV, LSYP, ECD, Sag Factor; Option 4 – HTH filtration, LSRV, LSYP, ECD, ESD, Sag Factor, crust friction coefficient; Option 5 – HTH filtration, filtration crust parameters (density, permeability, thickness, friction coefficient), LSRV, LSYP, ECD, ESD, Sag Factor, inhibition capacity; Option 6 – HTH filtration, filtration crust parameters (density, permeability, thickness, friction coefficient), LSRV, LSYP, ECD, ESD, Sag Factor, inhibition capacity, high-temperature rheological profile.

With the accumulation of experience in the construction of HPHT wells, the system of criteria is constantly being supplemented and complicated. For this reason, service companies strive to ensure that at least 5-12 criteria are met simultaneously when developing highly effective formulations. Although the number of such criteria may be quite significant, for the purpose of selecting the optimal HT-HPWBF formulations, they can be presented in the form of a hierarchical pyramid (Fig. 5). The system of criteria for selecting HT-HPWBF recipes is based on a three-level hierarchical structure, in which: at Level 1 α – the criteria ensure well control and safe operation (typically, Sag Factor <0.5 and LSRV at 6 rpm ⩽6 units are acceptable); at Level 2 β – criteria ensure the achievement of design technological goals (usually acceptable values are HPHT filtration 2-7 cm^3/30 min, YP 12-25 pounds/100 ft^2; the rest are determined by the conditions of well construction and/or the customer); at Level 3, the combination of γ criteria allows balancing environmental safety and economic efficiency requirements (fully determined by the conditions of well construction and the customer).

It should be noted that Figure 5 does not show all possible criteria, but only those that are most commonly used for HT-HPWBF systems. Depending on the specific drilling conditions and restrictions imposed by these conditions and/or circumstances, environmental or legal regulations, or the project budget, the number of criteria may either decrease or increase. Moreover, the level of criteria can be raised from the second and third levels to the first, or from the third to the second, but the transition of α – criteria to a lower level or β – criteria to the third level is not possible. To adapt to the specific conditions of each situation, appropriate weighting coefficients can be introduced both within levels and for all elements of the criteria pyramid. Such weighting coefficients are often used (Khosravanian & Aadnøy, 2021) to simultaneously take into account several criteria and quickly assess the effectiveness of a formulation by using various criterion combinations (linear, additive, multiplicative, Nash combination, Min-Max combination, etc.).

Each of them has both advantages and disadvantages, but in general, such convolutions are not always sufficient in practice due to: the subjectivity of weights – even a small change in coefficients gives a different "optimum"; the problem is exacerbated when the criteria are correlated; the compensatory effect – "excellent" rheology can override "poor" ecology; scalarisation hides information about compromises: it is impossible to see how much worse/better a particular formulation is than its analogue (according to one or another individual indicator); non-linear and discrete constraints (e.g., "barite <4.2%" or "pH ⩾9") do not lend themselves well to smooth convolution – penalties or complex transformations are required; the number of criteria is growing (more than 25 indicators, including technological, environmental, economic, HSE, specific, etc.). It does not seem realistic to set the weights correctly for such a multidimensional task. Therefore, with the development of technology and the growth of computing capabilities, the following are used as alternatives to criterion convolutions: Pareto optimisation, evolutionary multi-criteria algorithms (NSGA-II, NSGA-III, SPEA2, PAES); machine learning methods: Gaussian Process Optimisation, Bayesian Optimisation, Random Forest; Fuzzy Logic methods: Fuzzy TOPSIS, Fuzzy AHP and many others.

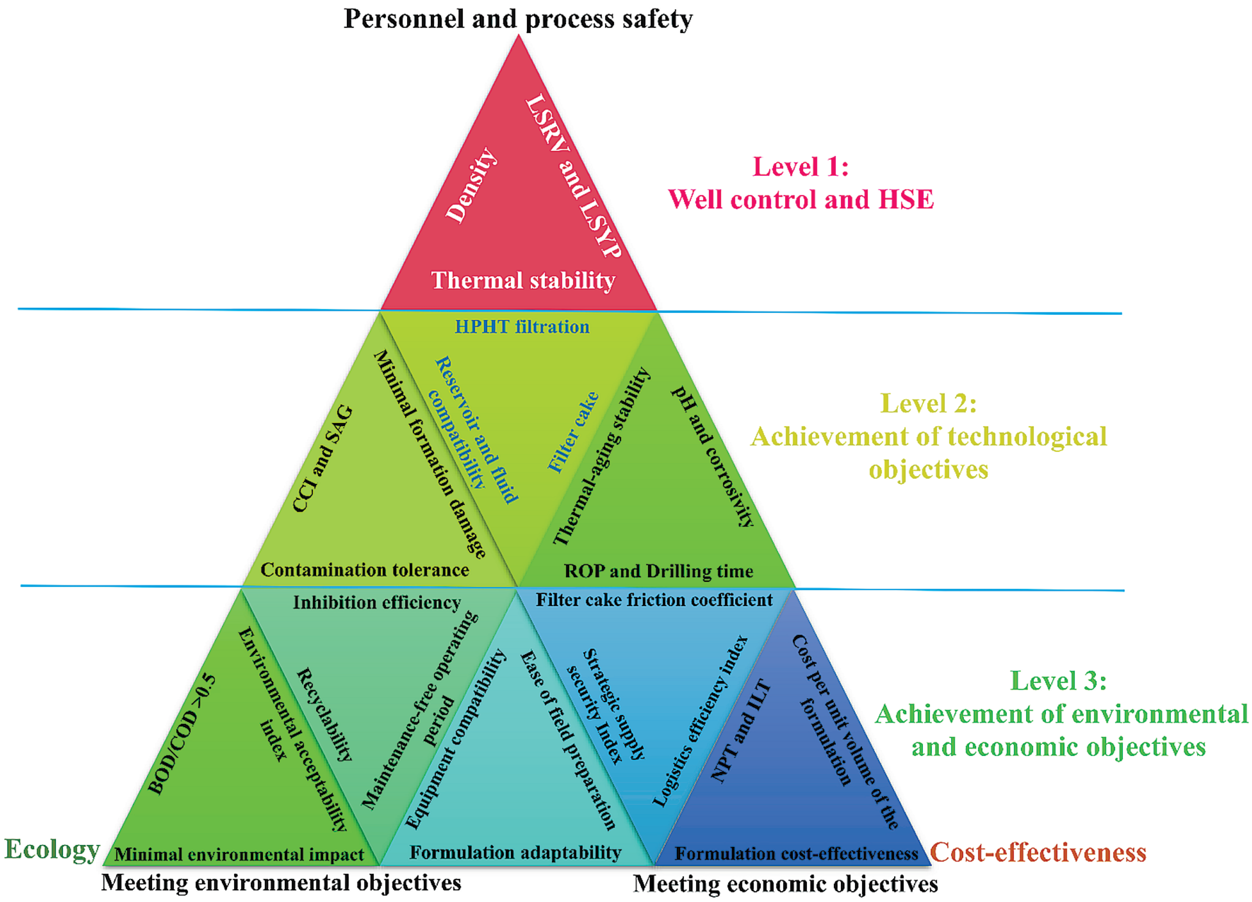


Figure 5. Illustration of the system of basic criteria for selecting HT-HPWBF formulations
Source: created by the authors

In order to make informed decisions regarding the composition of HT-HPWBF drilling fluid, it is necessary not only to identify the criteria that may influence the choice, but also to develop comprehensive KPIs that reflect the critical aspects of drilling fluid performance in terms of achieving the planned objectives. Such comprehensive KPIs provide a holistic view of the effectiveness of the formulation, taking into account the interrelationship between key parameters and performance indicators. KPIs can be developed through a weighted approach, where each individual KPI is assigned a specific weighting factor depending on its relative importance for specific drilling conditions. For example, in unstable clay formations, the weight of the clay inhibition indicator may be higher than that of the lubricity indicator. Indexing – creating an integral index by normalising and combining several KPIs. This approach provides a single numerical rating that reflects the overall effectiveness of the formulation. Matrix analysis – developing a matrix that displays the values of several core KPIs for different formulations. This allows for visual comparison and identification of optimal solutions based on trade-offs between different indicators.

The formation and correct analysis of industrial experience play a significant role in the formation of adequate predictive indicators of the effectiveness of fluid formulations used in similar or comparable drilling conditions. It should be noted that in order to form relevant KPIs, statistical, expert and big data analysis of industrial experience is performed provided that the data has been prepared in advance (systematisation, standardisation, noise component rejection, etc.). In addition to experience, i.e. accumulated knowledge and information, the proper implementation and functioning of KPIs also requires real-time monitoring and recording of flushing system parameters. Under such conditions, the actual optimisation of the formulation is carried out through laboratory testing, the design and logic of which is based on risk assessment and is adjusted in the event of significant changes in the well drilling process recorded by alert systems. This process is essentially an iterative selection of the component composition of the flushing system to achieve the design values of the system parameters, with maximum compliance with the selected optimisation criteria. Figure 6 shows the procedure for forming complex KPIs for the HT-HPWBF system.

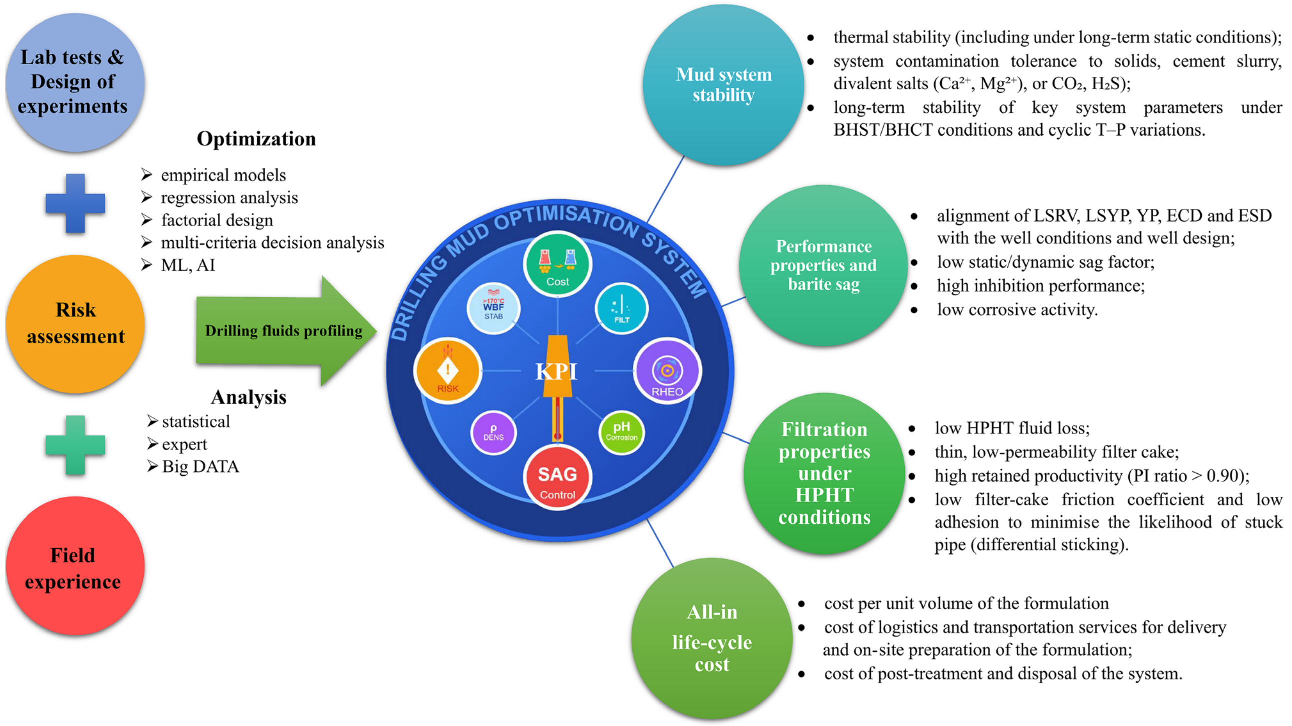


Figure 6. Formation of comprehensive KPIs for the HT-HPWBF system

Source: created by the authors

As can be seen in Figure 6, the comprehensive indicator is formed through an integrated combination of industrial experience, laboratory research, risk assessment, and drilling fluid profiling procedures. As a result, the following methodology for selecting the optimal HT-HPWBF formulation was developed: The process of researching and optimising the HT-HPWBF system involves several consecutive stages. The first stage involves collecting input data on the well and, if available, on neighbouring wells, as well as assessing technical, technological and environmental risks. In the second stage, design objectives are determined based on an analysis of key issues arising from the use of drilling fluids in HPHT conditions. The third stage involves the formation of a set of optimality criteria and their organisation into a hierarchical system, which allows the creation of a list of acceptable alternative HT-HPWBF system formulations. Finally, at the fourth stage, comprehensive KPIs are developed, which serve as the basis for the final selection of the optimal system formulation. The feasibility of using comprehensive KPIs in modern HPHT well drilling conditions is indisputable, given the increasing complexity of such projects.

For the successful application of HT-HPWBF in HTHP conditions, it is necessary to develop a set of KPIs that comprehensively reflect the suitability of the formulation. In challenging conditions of high bottomhole temperatures and pressures, to ensure maximum safety and efficiency of the drilling process, in addition to KPIs, it is recommended to simultaneously deploy and implement AI platforms for control and monitoring of the current state of well cleaning and deepening processes (such as AI-driller, Corva, etc.). The data obtained clearly correlates with the developed hierarchy of criteria. For example, indicators related to α-criteria (ensuring safe well control), such as the Sag Factor (0.45) and LSRV (5.8 units), confirm that all strict safety requirements have been met. At the same time, key technological indicators (filtration, shear stress) included in the β-criteria were achieved within the target ranges, demonstrating the high performance of the drilling fluid. Economic calculations reflecting γ criteria showed cost optimisation and high project profitability (ROI 1.6), confirming the environmental and economic efficiency of the decision.

Conclusions

The development and growth of Ukraine’s oil and gas industry is closely linked to the implementation of complex high-tech projects, including drilling wells in HPHT conditions. One of the problems encountered in the implementation of these projects is the scientifically sound selection of drilling fluid systems that would ensure fast, trouble-free well drilling with proper service support. This issue is particularly relevant when selecting the optimal drilling fluid formulations under HPHT constraints. The development and service support of drilling fluid systems in complex HPHT conditions critically depends on information support and accumulated practical experience.

The study confirmed the critical importance of a scientifically sound approach to selecting optimal HT-HPWBF drilling fluid formulations for the successful implementation of deep and ultradeep well drilling projects.

An analysis of more than 200 publications and drilling experience at Ukrainian fields (Berezivske, Shebelynske, Stepove, Solokhivske GCF, etc.) revealed a significant lag behind global practice, where the thermal stability of systems reaches 316°C compared to 170-200°C in Ukraine, and the share of modern clay-free HT-HPWBF systems is several times lower than in leading countries such as China or the USA. The developed three-level hierarchical system of criteria provides a comprehensive approach to evaluating the effectiveness of formulations: α-criteria guarantee safe well control (Sag Factor <0.5, LSRV at 6 rpm ⩽6 units), β-criteria ensure the achievement of design indicators (HPHT filtration 2-7 cm^3/30 min, YP 12-25 pounds/100 ft^2), γ-criteria optimise environmental and economic efficiency (ROI >1.5, NPT reduction by 30-40%). It has been established that successful commercial systems (PYRO-DRILL, BaraDrilNX, VeraTherm) use 5-12 criteria simultaneously, providing thermal stability of 205-316°C due to the synergy of synthetic polymers, formates and nanoscale weighting agents.

The proposed methodology for forming complex KPIs integrates three key components: analysis of industrial experience (with mandatory preliminary data preparation), laboratory research (including 24-72 hour ageing tests at BHST) and dynamic risk assessment. Further research should be aimed at developing unified methodologies for forming KPIs, taking into account the specifics of Ukrainian deposits, and creating a national database of HT-HPWBF formulation efficiency to accelerate technology transfer and achieve the strategic goal of increasing Ukraine's mineral resource base.

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Conflict of Interest

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References

[1] Agwu, O.E., Akpabio, J.U., Ekpenyong, M.E., Inyang, U.G., Asuquo, D.E., Eyoh, I.J., & Adeoye, O.S. (2021). A comprehensive review of laboratory, field and modelling studies on drilling mud rheology in high temperature high pressure (HTHP) conditions. *Journal of Natural Gas Science and Engineering*, 94, article number 104046. doi: 10.1016/j.jngse.2021.104046.

[2] Ahasan, M.H., Alahi Alvi, M.F., Ahmed, N., & Alam, M.S. (2021). An investigation of the effects of synthesized zinc oxide nanoparticles on the properties of water-based drilling fluid. *Petroleum Research*, 7(1), 131-137. doi: 10.1016/j.ptlrs.2021.08.003.

[3] BaraDrilN™ X fluid helps customer achieve well testing operation. (n.d.). Retrieved from https://www.halliburton.com/en/resources/baradriin-x-fluid-helps-customer-achieve-well-testing-operation.

[4] Biocar-TF biopolymer drilling fluid system was proposed. (n.d.). Retrieved from https://gse.ua/novini/1055-v-tannya-z-novim-rokom-p-dbittya-p-dsumk-v-2021-roku.html.

[5] Deshmukh, S., Motta, M.D., Prabhudesai, S., Patil, M., Kumar, Y., Mihalic, B.A., & Dey, R.S. (2021). Use of micronized weighting agents for high density completion fluids: A case study. In *IADC/SPE Asia Pacific drilling technology conference* (article number SPE-201065-MS). Yangon: SPE. doi: 10.2118/201065-MS.

[6] Erge, O., Sakaoglu, K., Sonmez, A., Bagatir, G., Dogan, H.A., Ay, A., & Gucuyener, I.H. (2020). Overview and design principles of drilling fluids systems for geothermal wells in Turkey. *Geothermics*, 88, article number 101897. doi: 10.1016/j.geothermics.2020.101897.

[7] Fakoya, M.F., & Ahmed, R. (2023). Experimental study on dynamic barite sag and effects of inclination and pipe rotation. *SPE Journal*, 29(2), 830-842. doi: 10.2118/217987-PA.

[8] First utilization of the clayless drilling mud "Biocar-TF." (2018). Retrieved from https://gse.ua/en/origins/how-it-was/806-first-utilization-of-the-clayless-drilling-mud-biocar-tf.html.

[9] Freschi, Y.L., Rincon Chavez, A.C., McCartney, R.M., Wenk, A., Manzoleloua, C., Li, D., & Derkach, E. (2025). An innovative water-based reservoir drill-in fluid solution customized to withstand the extreme thermal boundaries of the Perth Basin while minimizing formation damage. In *SPE/IADC international drilling conference and exhibition* (article number SPE-223723-MS). Amsterdam: SPE. doi: 10.2118/223723-MS.

[10] Gautam, S., Kumar, S., Kumar, A., Rajak, V.K., & Guria, C. (2025). Development of functional polymer-based clay-free HPHT drilling fluid: Effect of molecular weight and its distribution on drilling fluid performance. *Geoenergy Science and Engineering*, 246, article number 213616. doi: 10.1016/j.geoen.2024.213616.

[11] Hasan Hamdan, T., *et al*. (2020). New generation of HTHP water based drilling fluid changing conventional drilling fluids solutions. In *Abu Dhabi international petroleum exhibition & conference* (article number SPE-203439-MS). Abu Dhabi: SPE. doi: 10.2118/203439-MS.

[12] Jameel, N., & Ali, J.A. (2023). Field and experimental investigations on the effect of reservoir drill-in fluids on penetration rate and drilling cost in horizontal wells. *Gels*, 9(7), article number 510. doi: 10.3390/gels9070510.

[13] Karakosta, K., Mitropoulos, A.C., & Kyzas, G.Z. (2021). A review in nanopolymers for drilling fluids applications. *Journal of Molecular Structure*, 1227, article number 129702. doi: 10.1016/j.molstruc.2020.129702.

[14] Khalid, A., Ashraf, Q., Luqman, K., Hadj Moussa, A., Ghulam Nabi, A., & Umair, A.B. (2021). Precise bottom hole pressure management to reach target depth in a narrow windowed ultra HP-HT well: A case for automated managed pressure drilling. In *International petroleum technology conference* (article number IPTC-21410-MS). Kuala Lumpur: IPTC. doi: 10.2523/iptc-21410-MS.

[15] Khosravanian, R., & Aadnøy, B.S. (2021). *Methods for petroleum well optimization. Automation and data solutions*. Boston: Elsevier. doi: 10.1016/C2020-0-02224-3.

[16] King, C., & Rodrigue, K. (2025). Novel high temperature water-based reservoir drilling fluid to access depleted deepwater reserves. In *SPE/IADC international drilling conference and exhibition* (article number SPE-223705-MS). Amsterdam: SPE. doi: 10.2118/223705-MS.

[17] Kong, X., Chen, M., Zhang, C., Liu, Z., Jin, Y., Wang, X., Liu, M., & Li, S. (2022). Optimization of high temperature-resistant modified starch polyamine anti-collapse water-based drilling fluid system for deep shale reservoir. *Molecules*, 27(24), article number 8936. doi: 10.3390/molecules27248936.

[18] Law of Ukraine No 4154-IX "On Amendments to Certain Legislative Acts of Ukraine Regarding the Update of the Nationwide Program for the Development of the Mineral Resource Base of Ukraine for the Period Until 2030 and the Regulation of Certain Issues Concerning Minerals and Components of Strategic and Critical Importance". (2024, December). Retrieved from https://zakon.rada.gov.ua/laws/show/4154-20#Text.

[19] Liu, J., Dai, Z., Xu, K., Yang, Y., Lv, K., Huang, X., & Sun, J. (2020a). Water-based drilling fluid containing bentonite/poly (sodium 4-styrenesulfonate) composite for ultrahigh-temperature ultradeep drilling and its field performance. *SPE Journal*, 25(3), 1193-1203. doi: 10.2118/199362-PA.

[20] Liu, J., Li, G., & Xia, Y. (2020b). Technical progress on environmental-friendly, high-performance water-based drilling fluids. *Environmental and Earth Sciences Research Journal*, 7(3), 121-126. doi: 10.18280/eesrj.070305.

[21] Mao, H., Yang, Y., Zhang, H., Zheng, J., & Zhong, Y. (2020). Conceptual design and methodology for rheological control of water-based drilling fluids in ultra-high temperature and ultra-high pressure drilling applications. *Journal of Petroleum Science and Engineering*, 188, article number 106884. doi: 10.1016/j.petrol.2019.106884.

[22] Medhi, S., Chowdhury, S., Kumar, A., Gupta, D.K., Aswal, Z., & Sangwai, J.S. (2020). Zirconium oxide nanoparticle as an effective additive for non-damaging drilling fluid: A study through rheology and computational fluid dynamics investigation. *Journal of Petroleum Science and Engineering*, 187, article number 106826. doi: 10.1016/j.petrol.2019.106826.

[23] Miikor, B., Amadi, S.C., & Oriji, B.A. (2025). Performance evaluation of the types of polymers used as water-based mud viscosifiers for drilling operations in elevated temperature environment. In *SPE Nigeria annual international conference and exhibition* (article number SPE-228811-MS). Lagos: SPE. doi: 10.2118/228811-MS.

[24] Moroni, L., Fatkullin, K., & Tran Thanh, B. (2023). Evolution of a versatile HTHP water-based drilling fluid improved drilling efficiency offshore Vietnam. In *SPE/IATMI Asia Pacific oil & gas conference and exhibition* (article number SPE-215251-MS). Jakarta: SPE. doi: 10.2118/215251-MS.

[25] Morrison, A.C., King, C., & Rodrigue, K. (2021). First use of novel high temperature water-based reservoir drilling fluid to access depleted deepwater reserves. In *Abu Dhabi international petroleum exhibition & conference* (article number SPE-207825-MS). Abu Dhabi: SPE. doi: 10.2118/207825-MS.

[26] Myslyuk, M.A., & Zholob, N.R. (2023). To the assessment of thermal stability of biopolymer systems. *Journal of Hydrocarbon Power Engineering*, 10(1), 1-7. doi: 10.31471/2311-1399-2023-1(19)-1-7.

[27] Oseh, J.O., *et al.* (2025). Improvement of static and dynamic sag performance of water-based drilling mud using combined nano-barite and nano-ilmenite particles. In *SPE Nigeria annual international conference and exhibition* (article number SPE-228676-MS). Lagos: SPE. doi: 10.2118/228676-MS.

[28] Patent No. 124224. (2020). *Cement-free drilling mud*. Retrieved from https://sis.nipo.gov.ua/uk/search/detail/1608972/.

[29] Prozorro. (n.d.). *Contracts*. Retrieved from https://prozorro.gov.ua/uk/search/contracts.

[30] Quitian-Ardila, L.H., Garcia-Blanco, Y.J., Daza-Barranco, L.M., Schimicoscki, R.S., Andrade, D.E.V., & Franco, A.T. (2024). Improving the rheological and thermal stability of water-based drilling fluids by incrementing xanthan gum concentration. *Physics of Fluids*, 36, article number 103111. doi: 10.1063/5.0230214.

[31] Rana, A., Murtaza, M., Raza, A., Mahmoud, M., & Kamal, M.S. (2024). Application of high-density brines in drilling and completion fluids: Current insights and future perspectives. *Energy & Fuels*, 38(8), 6561-6578. doi: 10.1021/acs.energyfuels.3c04421.

[32] Raptanov, A.K., Ruzhenskyi, V.V., Kostiv, B.I., Myslyuk, M.A., & Charkovskyy, V.M. (2021). Analysis of the deep drilling technology in unstable formations at the Semyrenky Gas Condensate Field. *SOCAR Proceedings*, 2, 52-64. doi: 10.5510/ogp2021si200573.

[33] Shi, H., Yu, Y., Wang, Y., Ning, Z., & Luo, Z. (2024). Effect of ionic liquids with different structures on rheological properties of water-based drilling fluids and mechanism research at ultra-high temperatures. *Molecules*, 29(17), article number 4206. doi: 10.3390/molecules29174206.

[34] Shokry, A., Basfar, S., & Elkatatny, S. (2024). Evaluation of using micronized Saudi calcite in ilmenite-weighted water-based drilling fluid. *Scientific Reports*, 14, article number 12777. doi: 10.1038/s41598-024-63839-6.

[35] Singh, R., Sharma, R., & Rao, G.R. (2024). Investigation of the effects of ultra-high pressure and temperature on the rheological properties of a novel high-density clear completion fluids using magnesium bromide for applications in HPHT reservoirs. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, 10, article number 9. doi: 10.1007/s40948-023-00724-y.

[36] Soori, G.R., Mohd Alwi, M.A., Haniff Julian, Z., Tajudin, N., Zulkifli, S.A., & Abd Rahaman, N.A. (2023). Using cerium oxide (6.0 SG) as weighting material in HTHP drilling fluids. In *Gas & oil technology showcase and conference* (article number SPE-214171-MS). Dubai: SPE. doi: 10.2118/214171-MS.

[37] Sun, J., Yang, J., Bai, Y., Lyu, K., & Liu, F. (2024). Research progress and development of deep and ultra-deep drilling fluid technology. *Petroleum Exploration and Development*, 51(4), 1022-1034. doi: 10.1016/S1876-3804(24)60522-7.

[38] Taghdimi, R., Kaffashi, B., Rasaei, M.R., Dabiri, M.-S., & Hemmati-Sarapardeh, A. (2023). Formulating a novel drilling mud using biopolymers, nanoparticles, and SDS and investigating its rheological behavior, interfacial tension, and formation damage. *Scientific Reports*, 13, article number 12080. doi: 10.1038/s41598-023-39257-5.

[39] Tchameni, A.P., Nagre, R.D., Yin, S.-M., Wang, L.-Q., Wang, X.-Y., Zhou, S.-Y., & Wang, X.-D. (2025). A thermo-associating copolymer integrated with biogenic nanosilica as a novel viscosifier in low-solid drilling fluids. *Petroleum Science*, 22(7), 2884-2904. doi: 10.1016/j.petsci.2025.04.020.

[40] VeraTherm high-temperature water-based drilling fluid. (n.d.). Retrieved from https://www.slb.com/products-and-services/innovating-in-oil-and-gas/well-construction/drilling-fluids/water-based-drilling-fluid/veratherm-high-temperature-water-based-drilling-fluid.

[41] Wang, H., Huang, H., Bi, W., Ji, G., Zhou, B., & Zhuo, L. (2022). Deep and ultra-deep oil and gas well drilling technologies: Progress and prospect. *Natural Gas Industry B*, 9(2), 141-157. doi: 10.1016/j.ngib.2021.08.019.

[42] World's first application of BaraXtreme fluid in HTHP gas well. (n.d.). Retrieved from https://www.halliburton.com/en/resources/worlds-first-application-of-baraxtreme-fluid-in-hthp-gas-well.

[43] Zhang, J., Wang, H., Ji, G., Cui, M., Chen, L., Li, W., & Liu, L. (2025). Technologies and achievements for drilling and completion of onshore deep and ultra-deep wells in China. In *International petroleum technology conference* (article number IPTC-24918-MS). Beijing: IPTC. doi: 10.2523/IPTC-24918-MS.

До питання вибору оптимальних рецептур бурових розчинів в умовах HPHT обмежень

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Анотація. Буріння глибоких та надглибоких свердловин в умовах високих пластових тисків і температур (HPHT) є стратегічним напрямом розвитку мінерально-сировинної бази України, що потребує науково обґрунтованого підходу до вибору оптимальних рецептур бурових розчинів. Метою дослідження було формування на основі глибокого аналізу практики спорудження HPHT-свердловин методології вибору оптимальних рецептур високопродуктивних безглинистих систем бурових розчинів на водній основі (HT-HPWBF), яка б одночасно враховувала ієрархію критеріїв оптимальності і ключові показники ефективності системи. Проведено систематичний огляд та контент-аналіз понад 200 публікацій щодо застосування HT-HPWBF систем, узагальнено досвід використання таких систем на українських родовищах та виконано порівняльний аналіз з міжнародною практикою. Встановлено відставання України від світових лідерів у бурінні HPHT-свердловин переважно через використання традиційних хлоркалієвих та біополімер-калієвих систем замість сучасних HT-HPWBF. На основі аналізу важливості та впливовості вимог, технологічних обмежень і показників ефективності систем HT-HPWBF показано можливість формування ієрархічної системи основних критеріїв для вибору оптимальних рецептур. Розроблено трирівневу ієрархічну систему критеріїв оптимальності, що включає α-критерії контролю свердловини, β-критерії досягнення технологічних цілей та γ-критерії еколого-економічної ефективності. Запропоновано методологію формування комплексних ключових показників ефективності, що інтегрує промисловий досвід, лабораторні дослідження та оцінку ризиків. Обґрунтовано доцільність одночасного використання процедур інтелектуального аналізу історичних даних, моніторингу параметрів у режимі реального часу та впровадження ключових показників ефективності для вибору оптимальних рецептур. Результати дослідження можуть бути використані інженерами-технологами бурових підприємств та сервісних компаній для підвищення ефективності буріння HPHT-свердловин в Україні

Ключові слова: проєктування промивальної системи; індекс якості промивальної системи; критерії вибору; комплексний аналіз; безглинисті системи