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DEVELOPMENT OF FOAM DRILLING FLUIDS FOR DRILLING AND WELL KILLING UNDER CONDITIONS OF ABNORMALLY LOW FORMATION PRESSURE

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A B S T R A C T

The paper presents the results of a comprehensive experimental study aimed at the development and justification of the efficiency of formulations of thermally stable foam solutions for drilling and temporary well killing under conditions of abnormally low formation pressures (ALFP). The purpose of the study is the development, laboratory testing, and validation of the functional efficiency of multicomponent foaming fluids optimized to solve two key tasks: minimizing overbalance pressure on the formation during drilling and creating a long-term blocking barrier during well killing. Experimental results showed that the influence of the type and concentration of surfactants, polymer additives (CMC-HV, ChemPAC-LV), a structure-forming agent (bentonite), and stabilizers (liquid glass, NaCl) on key functional properties was investigated, including density (0.50–0.88 g/cm³), foam expansion ratio (3.0–4.0), thermal stability (up to 130 °C), and long-term structural stability (up to 7 days). The scientific novelty of the study lies in the identification of a synergistic effect resulting from the use of local components - monoethanolamine (MEA) derived from waste products of the Maryazot production association and the surfactant Guwlydere - in combination with bentonite, which made it possible to achieve a minimum density of 0.50 g/cm³ and maximum stability of up to 7 days. These parameters are critically important for application under ALFP conditions. The developed formulations were successfully implemented at the Yashyldepe, Yolguyi, and Garashsyzlygyn 10-yyllygy fields, demonstrating a reduction in lost circulation mitigation costs by 30–50 % and an increase in well production rates.

Keywords: foam solution; drilling, well killing; lost circulation; well completion.

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1. Introduction

At the current level of development of technologies for the construction, operation, and workover of gas wells, the use of working agents, primarily fluids, is technologically essential. In this context, the determining factor is the correct selection of the type and composition of the fluid, which must effectively ensure the preservation of the filtration and reservoir properties of productive formations during well completion and repair operations.

To address the problem of preserving the filtration and reservoir properties of productive formations, numerous technological fluids have been developed and tested. However, due to the diversity of geological conditions and reservoir structures, none of them can be considered universal.

The opening of a productive reservoir is one of the key and most difficult stages of drilling wells, directly affecting their productivity (flow rate). Drilling experience in conditions of abnormally low formation pressures (ALFP) shows that the use of traditional drilling fluid as a flushing agent leads to an excess of hydrostatic pressure over the reservoir. As a result, the pores and channels of the productive reservoir are blocked by clay particles, which significantly reduces its filtration capacity. This process complicates the deepening of the well, causing partial or complete loss of circulation and potential displacement of hydrocarbons from the bottom-hole zone of the reservoir [1].

In highly permeable reservoirs, where the coefficient of reservoir pressure anomaly is below 0.8, the low pressure of the column of flushing fluid during drilling can provoke intense lost circulation. In this regard, technologies aimed at drilling wells with minimal negative impact on the reservoir properties of the productive reservoir are of particular importance [2].

To preserve the natural properties of a productive reservoir during its initial opening, it is critically important to improve drilling technologies, reducing the negative impact of drilling mud. One of the promising ways to solve this problem is to use optimal formulations of foam drilling fluids and strict compliance with the regulations for flushing the

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borehole. This method allowed reduction of the pressure in the «well-formation» system, prevented filtrate lost circulation into the productive formation, and maximized reservoir permeability preservation [3].

Analysis of existing methods for penetrating productive formations under ALFP using two- or three-phase foam fluids showed that due to the rheological and physicochemical properties, drilling could be conducted without loss of circulation and with minimal negative impact on the reservoir's filtration characteristics [4].

One of the systemic problems in drilling and major repairs of wells in the conditions of ALFP is the lost circulation of drilling and cement slurries by formations. The annual cost of combating fluid loss complications is calculated in significant material and time resources. Accordingly, the development and implementation of effective measures to prevent and eliminate fluid loss complications will significantly reduce the cost of well development and improve the overall technical and economic performance of their operation [5, 6].

Currently, considerable attention is being paid to well-killing fluids, mainly used for repair work in wells with ALFP. The processes of inducing gas inflow and well development in the conditions of ALFP are characterized by high complexity and duration, calculated in days and months, depending on the volume and complexity of the work performed. At present, several types of well-killing fluids were used in the oil and gas industry to repair oil and gas wells and enhance the productivity: clay-based, saline, polymer, hydrocarbon-based, emulsion, foam, and others [7, 8].

However, when wells are silenced under ALFP conditions using clay and inhibited solutions, their negative effect on the permeability of the productive reservoir is observed: clogging and contamination of the collector pores by particles of drilling fluid occurs. This leads to a significant increase in the time required to trigger the inflow of gas from the reservoir after the completion of major repairs, and in some cases, the restoration of the inflow becomes impossible without additional operations at the well.

Thus, the development of optimal compositions of foaming liquids intended for drilling and developing wells in the conditions of ALFP is an urgent scientific and technical problem of our time [9, 10].

Recent studies [11, 12] demonstrate significant interest in the development of systems combining low density with high sealing capacity [13].

Despite ongoing research, the contemporary literature reveals a scientific gap associated with the absence of universal foam formulations capable of operating effectively across the entire range of geological and technical conditions characterized by abnormally low formation pressures (ALFP). This gap is further aggravated by the lack of experimental validation of the structural and high-temperature stability of foam systems based on locally available raw materials, as well as by the absence of comprehensive analysis of their impact on drilling and well-killing performance under complex operational conditions.

The relevance of the present study is determined by the necessity to eliminate this scientific and practical gap through the development of universal foam formulations based on local raw materials, combining low density with long-term structural stability, for efficient drilling and temporary well killing under ALFP conditions.

During the drilling of deep and ultra-deep wells in complicated geological environments (abnormally low formation pressures, loss circulation zones, and fractured reservoirs), the use of conventional drilling fluids leads to substantial technological and economic losses. According to field practice data, complications associated with drilling fluid losses account for 25–40 % of the total number of emergency situations, while additional mitigation costs may increase the overall well construction cost by 15–30 %.

Foam-based drilling fluids possess several fundamental advantages, including reduced density, high cuttings transport capacity, and minimized filtrate invasion into the formation. However, at temperatures exceeding 100–120 °C and under high salinity conditions of formation fluids, their stability decreases sharply, which significantly limits their practical application.

Therefore, the development of thermally resistant and structurally stable foam systems adapted to deep drilling conditions represents a relevant scientific and engineering challenge of considerable importance for the oil and gas industry.

2. Analysis of the current state of drilling fluid formulations used for drilling and completion under ALFP conditions

At the initial stage of the study, an analysis was conducted of domestic and international scientific publications, inventions, and patents addressing the challenges of penetrating productive formations under abnormally low formation pressure (ALFP) conditions, the mechanisms of drilling fluid losses, and the application of various types of drilling and kill fluids.

Contemporary research in the field of foam-based drilling fluids is primarily focused on three key areas:

- enhancement of foam thermal stability;
- reduction of surfactant degradation in mineralized environments;
- optimization of the gas–liquid ratio.

In particular, studies by international authors [14–15] have demonstrated that at temperatures exceeding 110 °C, intensive bubble coalescence occurs, accompanied by a sharp decline in foam expansion ratio. At the same time, the proposed formulations often exhibit a narrow temperature stability range or involve high-cost reagents, which limits their industrial implementation.

In contrast to existing approaches, the present study implements a comprehensive optimization of foam composition to ensure structural stability over a wide range of temperatures and pressures.

Over the past decades, foam-based drilling fluids have been considered an effective alternative to conventional liquid systems for drilling under conditions of abnormally low formation pressures, severe loss circulation, and fractured reservoirs. Their key advantages include reduced density, high cuttings transport capacity, decreased hydrostatic pressure exerted on the formation, and a lower risk of differential sticking [16].

Early investigations of foam systems were primarily focused on rheological behavior and cuttings transport under moderate thermobaric conditions [17]. It was demonstrated that the presence of a gas phase significantly alters flow hydrodynamics and enhances wellbore cleaning efficiency. However, these systems exhibited limited stability and high sensitivity to temperature and formation fluid salinity.

With the advancement of deep and ultra-deep drilling technologies, research attention has shifted toward improving the thermal resistance and long-term stability of foam drilling fluids. Studies [18–20] have established that at temperatures above 100–110 °C, accelerated degradation of the foam structure occurs due to bubble coalescence, drainage of the liquid phase, and surfactant degradation. These processes result in a sharp reduction in foam expansion ratio and deterioration of its technological performance.

Recent international research has actively explored the use of novel types of surfactants, including fluorinated, amphoteric, and polymeric surfactants, to enhance foam stability under aggressive thermobaric conditions [21–24]. Despite promising laboratory results, many of the proposed formulations are characterized by high cost, preparation complexity, or a narrow operating temperature range, which constrains their large-scale industrial application.

In a number of studies [25–27], attempts have been made to enhance the thermal resistance of foam-based drilling fluids through the introduction of stabilizing additives and structural modifiers. The authors report improvements in foam stability; however, a systematic analysis of the effects of component concentrations and the gas–liquid ratio on the mechanisms of foam structure degradation is not provided.

A separate line of research is associated with investigating the influence of thermodynamic factors on the physicochemical mechanisms governing foam stability [28–29]. It has been demonstrated that at elevated temperatures, gas diffusion processes and the reduction of the viscoelastic properties of adsorption films formed by surfactants at the phase interface become dominant factors. Nevertheless, these studies are generally of a fundamental nature and are insufficiently adapted to practical drilling conditions.

An analysis of the available literature indicates that, despite the substantial number of investigations conducted, the problem of developing a thermally resistant and technologically stable foam-based drilling fluid remains unresolved. Existing solutions are either limited to a narrow temperature range or fail to provide the required stability under prolonged exposure to high temperatures and pressures.

In contrast to previously reported approaches, the present study implements an integrated strategy for optimizing the composition of a foam-based drilling fluid, based on the combined consideration of thermal resistance, structural stability, and technological performance parameters. A comparative analytical assessment of existing solutions has been carried out, and the advantages of the proposed formulation over analogous systems have been experimentally substantiated, allowing it to be regarded as a promising solution for drilling operations under complicated conditions.

Drilling and completion of wells under ALFP conditions represented one of the most difficult technological complex challenges in the oil and gas sector. These conditions were characterized by high risks of fluid losses, borehole instability, and critical impacts on productive formations. Modern drilling fluid formulations aimed to minimise these risks while maintaining operational efficiency.

The main issues encountered under ALFP conditions included:

- Intensive lost circulation of drilling mud. Low formation pressure led to easy invasion of drilling fluids into the formation, causing significant losses of expensive liquids, contamination of the productive horizon, and reduced well productivity. The economic consequences of such losses were also critical [30].
- Borehole instability. High differential pressure could cause borehole wall collapse, complicating drilling and tripping operations, which was relevant to fluid review studies [5].
- Formation damage. Invasion of solids and filtrate from drilling fluids into the reservoir significantly reduced its porosity and permeability characteristics (PPC), negatively impacting well productivity. The issues of damage minimisation and productivity acceleration were actively researched [9, 31].

Various types of drilling fluids and technological strategies have been developed and actively applied to solve these problems:

1. Lightweight drilling fluids and underbalanced drilling. Conventional fluids were modified to reduce density. Underbalanced drilling, often with lightweight fluids, was considered an effective solution for minimising formation damage and fluid losses [14].
2. Foam drilling fluids (FDF) / Aerated fluids. Foam systems were among the most effective solutions for ALFP drilling [10].

The key advantages included:

- Ultra-low density, allowing drilling with hydrostatic pressure below the formation pressure, preventing losses and minimising formation damage.
- High carrying capacity. Foam systems with environmentally friendly additives showed enhanced foaming properties [15].
- Minimal formation damage. Low fluid content, low filtrate loss, and absence or minimisation of solids reduced formation invasion.

In addition to drilling applications, foam systems represent a critically important tool in well workover operations, particularly during well-killing procedures. Under conditions of abnormally low formation pressures (ALFP), the use of conventional fluids is unacceptable due to the risk of irreversible formation damage and severe loss circulation. In such cases, specially optimized foam systems are employed for the following purposes:

- Temporary formation sealing and blocking. Highly stable foam systems modified with polymers and solid-phase bridging agents are used to create a durable barrier that prevents formation fluid influx and the loss of technological fluids during well-killing operations.
- It should be noted that foam systems designed for drilling and those intended for well killing require different optimization strategies. While drilling operations prioritize minimal density and rheological stability, well-killing applications require long-term structural stability of the foam and its ability to withstand reservoir pressure and temperature over extended periods. Ensuring such durability constitutes a key requirement for maintaining operational safety during workover activities.

Regardless of the type of drilling mud chosen, the use of effective functional additives is a prerequisite for successful operation in the conditions of ALFP. Current trends in this area include:

- Use of biodegradable additives. Environmentally safe materials (e.g., crushed straw, nutshells) were developed for temporary fracture plugging and loss prevention [32]. Reviews of foreign sources revealed the latest advances in this area [33, 34].
- Use of polymer additives. Widely applied for regulating rheological and filtration properties and improving borehole stability. Reviews on polymer-based fluids [35] and the effects of polymer additives on rheology and filtration [36, 37] confirmed the significance.

Modern fluid formulations were developed with minimal impact on reservoir properties, which was critical for successful well development and enhanced productivity [31].

International practice regarding fluid formulations under ALFP was characterized by the active search for and implementation of innovative solutions aimed at:

- Minimising formation impact through lower density, reduced filtrate loss, and biodegradable components [31].
- Improving foam stability against high temperatures and reservoir fluids [33, 38].
- Using local raw materials and optimizing costs of dealing with complications [30].

The development and implementation of such solutions — like optimized foam fluids based on local materials and plant-based bridging agents — confirmed significant progress in this field [34, 39-41]. Field tests and practical applications demonstrated the high practical value of these developments in improving workover quality, preventing fluid losses, and restoring well productivity [34, 40, 42]. Future research would focus on creating even more stable and cost-effective systems.

Special attention in the present study is given to substantiating the economic feasibility and enhanced stability of the proposed systems. These advantages are achieved through the utilization of readily available local raw materials and are confirmed by the results of laboratory validation.

3. Research objects and methods

The objective of the present study is to develop and perform a comprehensive laboratory evaluation of the functional efficiency of thermally resistant multicomponent foam-forming fluids intended for drilling and temporary well killing under conditions of abnormally low formation pressures (ALFP).

To achieve this objective, the following tasks were undertaken:

- experimental investigation of the influence of formulation composition on the rheological, structural, and filtration properties of the fluids;
- assessment of their thermal stability and long-term structural resistance;
- evaluation of the potential of the developed systems for temporary formation blocking;
- field validation of the optimized formulations under operational conditions.

The aim of this study was to develop and optimize formulations of foaming fluids for drilling and well development under ALFP (abnormally low formation pressure) conditions in order to minimise the negative impact on the reservoir properties of productive formations.

To achieve this goal, the following objectives were set:

- To systematic analyse existing methods for penetrating productive formations under ALFP conditions and identify key problems associated with the use of traditional drilling and well-killing fluids.
- To experimentally investigate the rheological and physicochemical properties of two- and three-phase foam fluids.
- To develop new foam fluid formulations using various chemical reagents and natural bridging agents. The objective of the present study is to develop and conduct a comprehensive laboratory evaluation of the functional performance of thermally resistant multicomponent foam-forming fluids intended for drilling and temporary well killing under conditions of abnormally low formation pressures (ALFP).
- To achieve this objective, the following tasks were addressed: experimental investigation of the influence of composition on the rheological, structural, and filtration properties of the fluids; assessment of their thermal stability and long-term durability; determination of the potential of the developed systems for temporary formation blocking; and field validation of the optimized formulations.

The development of new foam fluid formulations was carried out in laboratory conditions. A series of controlled experiments were conducted to prepare and study in detail study various combinations of components included in the foaming fluid compositions.

For the purpose of analysis, the controlled variables were clearly defined. These included the varying concentrations of CMC-HV, liquid glass/NaCl, bentonite, and surfactant, while the response parameters comprised density, apparent viscosity, foam stability, and thermal stability.

Foam fluids were prepared by mixing specified volumes of the aqueous phase, hydrocarbon liquid (condensate), and chemical reagents, followed by saturation with a gas phase (air) until the required foam expansion ratio was achieved.

Foam stability over time under various conditions (temperature, time) was evaluated by measuring the height of the foam column.

Particular emphasis was placed on the use of monoethanolamine (MEA) derived from bottom residues of the «Maryazot» production association and the domestically produced surfactant Guwlydere.

Bentonite was selected as the solid phase (filler); its function was to enhance system stability and to create structural conditions conducive to the formation of a temporary filtration barrier within the porous medium.

The following materials and chemical reagents were used for the preparation and investigation of foaming fluid formulations:

- ChemPAC-LV, a modified polyanionic cellulose with low viscosity. It was used as a highly effective filtration reducer and stabiliser of rheological properties.
- Unicor-10 A200, an amphoteric surfactant. It was used to reduce surface tension and enhance foaming.
- SNPH-7890, a non-ionic surfactant with foaming properties.
- Guwlydere, a mixture of non-ionic and anionic surfactants, reduced interfacial tension at the boundary with formation fluid and acted as a locally produced foaming agent.

- Sulphonol, an anionic surfactant, served as a foaming agent.
- Condensate, gas condensate from the Shatlyk field, with a density of 0.78 g/cm³ at 20 °C. It was used to reduce the density of emulsion fluids.
- Monoethanolamine (MEA) – $HOCH_2CH_2NH_2$, improved the thermal stability of the fluid, increased alkalinity, and enhanced polymer solubility. The monoethanolamine used came from distillation residues from the «Maryazot» production association, with MEA content ranging from 31 to 42 % depending on production.
- Bentonite, Oglanly bentonite clay powder, served as a structure-forming agent. The clay powder was distributed between the phases of the foam fluid.

The fluid samples were prepared by sequential dosing of the components in accordance with the developed formulations. After preparation, the fluids were subjected to static thermal conditioning at 130 °C for 6 hours to simulate bottomhole conditions. Upon completion of thermal treatment, the samples were aged for a period ranging from 1 to 7 days to assess their long-term stability.

The parameters of the prepared fluids were determined using standard testing procedures widely accepted in drilling practice [43]:

- Fluid density was measured using a hydrometer.
- Apparent viscosity was determined with a VBR-5 viscometer.
- Rheological properties were evaluated using a Fann 35SA rotational viscometer equipped with coaxial measuring cylinders.
- Filtration characteristics were measured with a Fann 387 Filter Press with a filtration area of (45.8 ± 0.6) cm², providing a differential pressure of 0.7 MPa across the filter medium.
- Foam stability was assessed based on volume variation in a 100 cm³ graduated glass cylinder.
- pH values were measured using a SevenCompact S220 pH meter.
- Thermal resistance of the samples was controlled using a SNOL 67/350 laboratory furnace.

All experiments were carried out under strictly controlled laboratory conditions. To ensure the statistical reliability of the results, each measurement was performed at least three times. The test temperatures ranged from 20 to 130 °C to simulate reservoir conditions. All measurements were performed at least three times to ensure the statistical reliability of the results.

Table 1

Polymer foam fluid (PFF) composition and its key parameters

Chemical reagents	Quantity of chemical reagents, %	Fluid parameters		
		Density, g/cm³	Conditional viscosity, s.	Water loss, cm³/30 min
Condensate	30-40			
CMC-HV	1.25			
MEA	0.5			
Sulphonol	0.5			
Gwlydere	0.5	0.66-0.88	300	2
Bentonite	3-5			
Water	remainder			

Methodology for assessing the blocking potential

Since the physical ability of a foam system to provide temporary formation sealing directly depends on its structural strength, the blocking potential was evaluated using an indirect approach based on the analysis of two key factors:

1. Long-term structural stability of the foam (stability period up to 7 days);
2. Effect of the solid phase (bentonite) on the ability to form a strong and stable structure.

It is assumed that high structural stability, reinforced by the presence of a solid filler, constitutes a necessary and sufficient condition for the formation of a temporary filtration barrier under abnormally low formation pressure (ALFP) conditions.

4. Methodology for assessing formation impact and blocking potential

In addition to standard rheological and physicochemical tests, specialized evaluations were carried out within the framework of this experimental study to quantitatively assess both the potential negative impact on the formation and the blocking capacity of the developed fluids.

1. The assessment of possible adverse effects on reservoir properties was performed based on two key parameters:

- Bridging (colmatation) potential: evaluated by measuring the solid-phase (bentonite) content in the fluid and its ability to form a stable foam matrix capable of retaining particles and preventing their penetration into the formation. A stable foam system with uniformly distributed bentonite is considered to minimize the migration of solid particles into the pore space.
- Filtration control: assessed based on fluid loss values (see table 1). Low fluid loss (approximately 1.5–2.0 cm³/30 min) indicates minimal filtrate invasion into the formation, thereby preventing clay swelling and pore blockage.

2. Direct Assessment of Blocking Capacity. The potential for temporary formation sealing was evaluated based on two key interrelated parameters:

- Long-term structural stability (up to 7 days): the ability of the foam to maintain its volume and structural integrity over time, thereby preventing the inflow of formation fluids.
- Structural strength of the bentonite-reinforced foam matrix: the presence and retention of solid particles within the foam structure are regarded as a necessary condition for the formation of a mechanical barrier in the near-wellbore zone. High stability indicators combined with adequate bentonite content constitute an indirect yet scientifically substantiated criterion of high blocking potential.

5. Research results and discussion

The developed polymer foam fluid (PFF) is designed to temporarily block the flow of gas from the productive reservoir during the overhaul of wells operating under the conditions of the ALFP [44].

The developed PFF was characterized by low density (0.66-0.88 g/cm³) and high apparent viscosity (250-1000 s). Within the scope of the study, various PFF compositions, the key parameters, as well as the optimal quantity and functions of the reagents used in these compositions were thoroughly examined. The results obtained from these studies are presented in table 1.

Two different foaming agents were used in the PFF composition: Sulphonol and Guwlydere. The selection was based on the specific properties: Sulphonol, being an anionic (A) surfactant, foamed well in low-salinity environments but was limited in high-salinity conditions due to loss of foaming capacity and potential to hydrolyse upper layers of terrigenous reservoirs. To address these issues and impart hydrophobic properties to the fluid, an anionic and non-ionic (A&N) locally produced surfactant Guwlydere was included in the PFF composition, which was particularly relevant under high-salinity formation water conditions.

To ensure application flexibility, the PFF density could be varied over a wide range by adjusting the mixer speed during reagent blending. The required apparent viscosity of the fluid was achieved by regulating the amount of polymers used. Furthermore, the addition of a small quantity of monoethanolamine (MEA) significantly increased the alkalinity and thermal stability of the PFF, which was critical for its stability under high-temperature conditions.

To assess the thermal stability of the PFF, samples were placed in a thermal oven at 130 °C for four hours. After cooling to room temperature, the key fluid parameters were measured again. The values obtained after heating differed insignificantly from the initial ones, confirming the high thermal resistance of the developed PFF and its suitability for high-temperature environments.

In general, water-based foam fluids with low surface tension and containing surfactants were considered appropriate for preventing losses both during drilling operations under ALFP conditions and during well workovers in late-stage development wells.

In this context, several new formulations of foam killing fluids were developed in laboratory conditions using local raw materials. The following chemical reagents were used for the preparation: amphoteric surfactant Unicor-10 A200, non-ionic surfactant SNPH-7890, and the local blend of anionic and non-ionic (A&N) surfactant Guwlydere. From polymer additives, CMC-HV, ChemPAC-LV, and liquid glass were used. As additional components, MEA, bentonite, and sodium salt were applied.

The fluids were prepared in laboratory conditions using a high-speed electric mixer and a graduated beaker with a capacity of 700 cm³. The reagents were added to 200 cm³ of water in a strictly defined order:

- MEA was first added to the water to impart the necessary thermal stability;
- Then bentonite was added to strengthen the structure;
- CMC and liquid glass were added next to increase foam stability;
- Finally, the main foaming agent Guwlydere was added.

The quantity of reagents used for fluid preparation was calculated as a percentage for a volume of 1 m³, allowing the laboratory formulations to be scaled to industrial volumes (table 2).

In the first experiment (table 2), of mixing at medium speed with an electric mixer, the fluid volume foamed 3.8 times (V_f=380 cm³), forming a uniform white-coloured foam fluid. The resulting fluid was characterized by non-flowing apparent viscosity and a density of 0.51 g/cm³, with a pH value of 11.

The prepared fluid was transferred into a 100 cm³ cylinder to assess its stability. After three days, the fluid remained stable, although larger bubbles formed in the upper part, and the fluid volume decreased slightly – by only 1 cm³. An additional test of thermal stability after heating in a thermal oven at 130 °C for 4 hours also confirmed its stability, in line with previous general conclusions about PFF thermal resistance.

In the second experiment (table 3), the ratio of liquid glass and CMC-HV was altered: the amount of liquid glass was reduced, and the amount of CMC-HV was increased, while other reagents remained in the same proportions. As a result, the test fluid volume increased 3.5 times (V_f=350 cm³). The obtained fluid was also a uniform white foam system. Its apparent viscosity was non-flowing, the density was 0.57 g/cm³, and the pH was 10.

The prepared fluid was transferred into a 100 cm³ cylinder to study its stability. After five days, the fluid remained stable, although large bubbles appeared in the upper part, and the volume decreased by 1.5 cm³. As in the first experiment, the fluid was tested for thermal stability after heating in a thermal oven at 130 °C for 4 hours, and it remained stable.

To obtain a new type of foam fluid, a composition was prepared (table 4), the key difference of which was the addition of sodium chloride instead of liquid glass. As a result, the volume of the obtained fluid increased 3.5 times (V_f=350 cm³). This fluid also represented a homogeneous

Table 2

Composition of the first foam killing fluid with increased liquid glass content (1a)

No.	Chemical reagents	Functions	Quantity, %	Quantity of chemical reagents added to mixer	
				200 cm³	1 m³
1	Water	Liquid phase	88.5	177 ml	885 l
2	MEA	Provides thermal stability	0.5	1.0 ml	5 l
3	Bentonite	Structure-forming agent	3.0	6.0 g	30 kg
4	CMC-HV	Increases apparent viscosity	1.0	2.0 g	10 kg
5	Liquid glass	Gelling agent	5.0	10 ml	50 l
6	Guwlydere	Gas phase, foaming agent	2.0	4.0 ml	20 l

Table 3

Composition of the second foam killing fluid with increased CMC-HV content (1b)

No.	Chemical reagents	Functions	Quantity, %	Quantity of chemical reagents added to mixer	
				200 cm³	1 m³
1	Water	Liquid phase	91.25	182.5 ml	912.5 l
2	MEA	Provides thermal stability	0.5	1.0 ml	5 l
3	Bentonite	Structure-forming agent	3.0	6.0 g	30 kg
4	CMC-HV	Increases apparent viscosity	1.25	2.5 g	12.5 kg
5	Liquid glass	Gelling agent	2.0	4.0 ml	20 l
6	Guwlydere	Gas phase, foaming agent	2.0	4.0 ml	20 l

foam system of white colour. Its apparent viscosity was determined as slightly flowable, the density was 0.57 g/cm³, and the pH was 10. It was important to note that the density and volume of this fluid could be further adjusted by increasing or decreasing the mixer rotation speed.

The stability of the prepared fluid was tested in a 100 cm³ cylinder. After seven days, the fluid remained stable, with large bubbles forming in the upper part and the volume decreasing by only 1 cm³. To check thermal stability, the fluid was also tested after being heated in a thermal oven at 130 °C for 4 hours, and it remained stable.

In the next experiment, the number of components in the solution composition was reduced, and the type of surfactant was changed – the amphoteric surfactant Unicor-10 A200 was used. The results of this experimental work, including the data on the increased amount of bentonite, were presented in table 5.

As a result, the volume of the obtained solution increased threefold (V_f=300 cm³), forming a white homogeneous foamed solution. During the preparation of this solution, it was first stirred at low speed until the foam volume doubled. The solution density was 0.67 g/cm³, and the pH was 10.

The prepared solution was transferred to a 100 cm³ cylinder to assess its stability. After three days, the solution remained stable. To test the thermal stability of the solution, it was also heated in a thermal oven at 130 °C for four hours, and the solution remained stable.

To further lighten the bentonite-based foam solution, additional tests were carried out by adding another non-ionic surfactant – SNPH-7890 – to the above-mentioned composition (table 6). As a result, the volume of the obtained solution increased fourfold (V_f=400 cm³), forming a homogeneous white foam solution. During preparation, the solution was stirred at low speed (for 10-15 minutes) until the foam volume doubled. The resulting solution was characterized by low apparent viscosity, a density of 0.50 g/cm³, and a pH of 11.

The stability of the prepared solution was tested in a 100 cm³ cylinder. The solution remained stable after three days. To check thermal stability, the solution was also tested after heating in a drying oven at 130 °C for 4 hours; after heating, its volume decreased by 1 cm³, but overall, the solution remained stable.

Thus, the conducted laboratory analyses demonstrated

Table 4

Composition of the third kill foam fluid with salt instead of liquid glass (2)

No.	Chemical reagents	Functions	Quantity, %	Quantity of chemical reagents added to mixer	
				200 cm³	1 m³
1	Water	Liquid phase	91.75	182.5 ml	917.5 l
2	MEA	Provides thermal stability	1.0	2.0 ml	10 l
3	Bentonite	Structure-forming agent	2.0	4.0 g	20 kg
4	NaCl (salt)	Provides structural stability	2.0	4.0 g	20 kg
5	CMC-HV	Increases apparent viscosity	1.25	2.5 ml	12.5 kg
6	Guwlydere	Gas phase, foaming agent	2.0	4.0 ml	20 l

Table 5

Composition of the fourth killing foamed solution with bentonite (3a)

No.	Chemical reagents	Functions	Quantity, %	Quantity of chemical reagents added to mixer	
				200 cm³	1 m³
1	Water	Liquid phase	89.75	179.5 ml	897.5 l
2	MEA	Provides thermal stability	1.0	2.0 ml	10 l
3	Bentonite	Structure-forming agent	6.0	12 g	60 kg
4	ChemPAC-LV	Increases apparent viscosity	1.25	2.5 g	12.5 kg
5	Unicor-10 A200	Gas phase, foaming agent	2.0	4.0 ml	20 kg

Table 6

Composition of the fifth plugging foam solution with bentonite (3b)

No.	Chemical reagents	Functions	Quantity, %	Quantity of chemical reagents added to mixer	
				200 cm³	1 m³
1	Water	Liquid phase	88.75	177.5 ml	887.5 l
2	MEA	Provides thermal stability	1.0	2.0 ml	10 l
3	Bentonite	Structure-forming agent	6.0	12 g	60 kg
4	ChemPAC-LV	Increases apparent viscosity	1.25	2.5 g	12.5 kg
5	Unicor-10 A200	Gas phase, foaming agent	2.0	4 ml	20 kg
6	SNPH-7890	Gas phase, foaming agent	1.0	2 ml	10 l

clear analytical relationships between the formulation composition, the concentration of chemical reagents, and the resulting fluid properties.

The results of the experimental analyses are presented in the following graphs (figs. 1–3).

Figure 1 demonstrates an analytical relationship between fluid composition and foam expansion ratio. For most formulations, the foam expansion ratio remains at an average level of approximately 3.50. However, formulation 3a exhibited the minimum value of 3.00, whereas formulation 3b demonstrated the maximum expansion ratio of 4.00.

This establishes a clear correlation: the maximum foam expansion ratio is directly associated with the minimum fluid density (see fig. 2). Achieving an expansion ratio of 4.00 provides analytical evidence of the successful selection of foaming agents capable of maximizing the gas phase volume within the system.

The foam expansion ratio of 4.00 obtained for formulation 3b directly correlates with the degree of aeration, which is also maximal for this composition. This indicates that an optimal volumetric gas–liquid ratio was achieved through the synergistic interaction of the surfactants Unicor-10 A200 and SNPH-7890, which is critically important for the development of highly efficient low-density drilling fluids.

Figure 2 illustrates the influence of formulation components on fluid density. The graph shows that the density of the primary compositions varies within the range of 0.50 to 0.68 g/cm³. Formulation 3b achieves the minimum density value of 0.50 g/cm³.

This result confirms that attaining low density required optimization of the surfactant-to-solid phase (bentonite) ratio. The minimum value of 0.50 g/cm³ is a direct consequence of the synergistic interaction among the components aimed at maximizing fluid lightening.

The achieved minimum density of 0.50 g/cm³ (formulation 3b) directly results from the maximum foam expansion ratio and, consequently, the optimal degree of aeration. This parameter not only confirms the effectiveness of the selected foaming agents but also ensures the generation of minimal hydrostatic pressure on the productive formation.

Figure 3 analyzes the influence of formulation components on the stability of the foam-based drilling fluids (FDF). The graph shows that stability increases with the optimization of polymer additives. A reduction in liquid glass content (from 5 to 2 %) combined with an increase in CMC-HV concentration (from 1 to 1.25 %) resulted in an increase in foam stability from 3 to 5 days.

The maximum stability of 7 days demonstrated by formulation 2, in which liquid glass was replaced with sodium chloride, can be explained by the strengthening of the foam film structure due to the presence of the electrolyte. This result experimentally confirms that for well-killing applications – where prolonged sealing is required – stabilization of the foam matrix by salts may be more effective than by polymeric gel-forming agents. High stability thus represents a key indicator of the fluid's capability to function as a temporary blocking barrier.

Formulation 2 exhibits the maximum stability of 7 days.

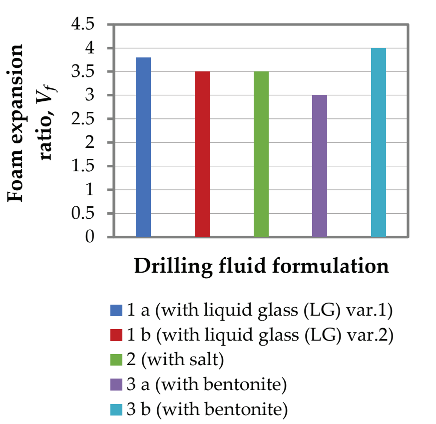

Fig. 1. Dependence of foam expansion ratio (V_f) on formulation composition

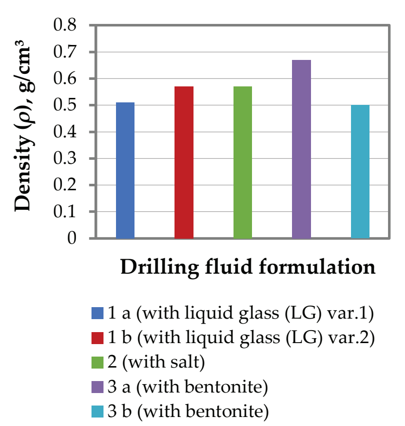

Fig. 2. Dependence of fluid density (ρ) on formulation composition

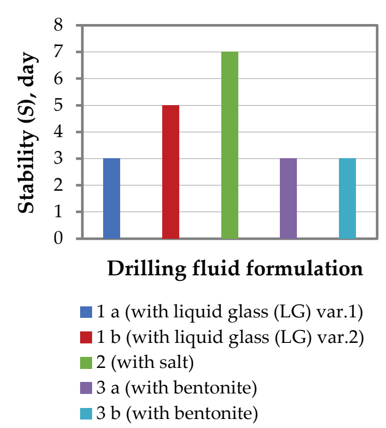

Fig. 3. Dependence of fluid stability (S) on formulation composition

The replacement of liquid glass with sodium chloride (2%) in this composition, while maintaining the same density (0.57 g/cm³), made it possible to achieve superior structural durability. This demonstrates that sodium chloride acts as a more effective stabilizer of the foam structure in this system. The maximum stability confirms the high potential of the fluid for long-term temporary formation blocking.

Formulation 3b shows high, but not maximum, stability (4 days), indicating that optimization for minimum density (see fig. 2) does not necessarily coincide with optimization for maximum structural stability.

The analysis also demonstrated that bentonite is a critically important component for well-killing systems. Its incorporation (formulations 3a and 3b) not only improves rheological properties but also creates structural prerequisites for temporary formation blocking, as solid particles embedded within a strong and long-lasting foam matrix are capable of forming a stable filtration barrier in the near-wellbore zone.

Based on the obtained results, two functional groups of foam-based fluids were developed to address different operational objectives under ALFP conditions:

- The feasibility of industrial application of the developed foam system for reducing drilling complications was substantiated.
- Drilling formulations (Formulation 3b: minimum density 0.50 g/cm³) – intended to minimize overbalance pressure and ensure efficient wellbore cleaning.
- Killing/Blocking formulations (Formulation 2: maximum structural stability up to 7 days) – designed for temporary sealing and prevention of circulation losses.

As part of further research, a series of experiments was conducted to modify the foam system recommended for temporary isolation of productive formations by incorporating plant-based bridging agents (fillers). The materials used as bridging agents included ground straw, crushed walnut shell, and cotton hulls.

During these experiments, the foam stability and expansion ratio of the modified foam systems containing various plant-based bridging additives were systematically evaluated.

As shown in figures 4a and b, the FS with the addition of walnut shell and shredded straw demonstrated high stability, maintaining it for seven (7) days. Foam generation and foam stability remained stable, and its expansion ratio did not significantly decrease (table 7). However, as seen in figure 4c, after one (1) day of retention, the FS with cotton husk lost its foam stability. Most of the cotton husk settled at the bottom of the beaker, while another part floated to the surface, thus disrupting the solution's stability. A reduction in foam expansion ratio was also observed (table 7).

The results of these experiments made it possible to establish the expediency of using crushed straw and nutshells as bridging agents for foam solutions. These experiments confirmed that using shredded straw and walnut shell as bridging agents in foam-based solutions was justified. At the same time, the research showed that cotton husk was not recommended as a filler in FS. This could be explained by the fact that cotton husk absorbed liquid from the solution, which led to its destabilisation and decreased effectiveness.

Thus, structural stability of up to 7 days combined with the presence of a solid filler constitutes the key factor determining the high well-killing potential of the developed formulations.

The laboratory studies confirmed the high efficiency and potential of the developed foam-based solutions for solving problems related to drilling and major well repairs under ALFP conditions. The optimization of formulations by varying foaming agents, polymers, and other reagents, along with close control of the preparation process, allowed the required characteristics in terms of density, viscosity, expansion ratio, and – most importantly – high thermal stability and long-lasting foam durability to be achieved.

A minimum density of 0.50 g/cm³ (Formulation 3b), which is critically important under abnormally low formation pressure (ALFP) conditions, was successfully achieved. This confirms the effective resolution of the key objective-minimization of hydrostatic pressure exerted on the productive formation. The developed foam-based fluids demonstrated high thermal stability up to 130 °C and maintained foam stability for up to 7 days (Formulation 2), which significantly exceeds the performance of many conventional foam systems.

The economic efficiency of the developed foam fluids is achieved through reduced well completion time, increased well productivity, and the utilization of locally sourced raw materials: monoethanolamine (MEA) derived from bottom residues of the «Maryazot» production association and the domestically produced surfactant Guwlydere. This approach ensures a reduction in formulation costs and optimization of logistics expenses. Quantitatively, this is reflected in the following:

1. Reduction in formulation cost: Replacement of imported reagents with domestic alternatives (Guwlydere surfactant and MEA derived from «Maryazot» industrial by-products) reduces procurement costs by 20–30 % (according to internal pricing analysis) and minimizes logistics expenditures.

Table 7

Research results of foam solutions with bridging agent additives

p/p	Foam solution with bridging agent additive	Solution volume, cm³	Stability, day	Expansion ratio
1	FS + 1% crushed straw	300	7	2.98
2	FS + 1% walnut shell	200	7	1.99
3	FS + 1% cotton husk	150	1	1.13

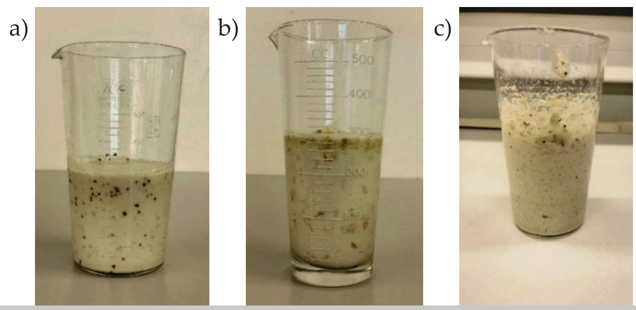

Fig. 4. FS with added walnut shell (a), shredded straw (b), and cotton husk (c)

2. Improved operational efficiency: As demonstrated by field trials (Section 6), the application of the developed fluids reduced loss circulation mitigation costs by 30–50 % and accelerated well completion operations by a factor of 2–3 due to minimized formation damage, resulting in a substantial overall economic benefit.

Special attention was devoted to the selection of plant-based bridging agents. Ground straw and walnut shells proved to be effective and stable additives, whereas cotton husk negatively affected fluid stability. These results provide a solid foundation for further field validation and large-scale industrial implementation of the developed technologies.

Based on the positive laboratory outcomes, a decision was made to introduce the developed formulations into production and to conduct successful pilot field trials.

Methodology of experimental investigations

To substantiate the declared experimental nature of the study, a series of laboratory investigations was conducted.

Research equipment

The following equipment was used: a Marsh viscometer (VD-6), a laboratory drying oven/thermostat (30-150 °C), a foam generator with adjustable expansion ratio, an API filtration apparatus, a core holder rated up to 12 MPa, a Leica EZ4 microscope, and a capillary pressure measurement unit.

Experimental conditions

The experiments were performed under the following conditions:

- Temperature range: 20–130 °C;
- Pressure in the core holder: 6–12 MPa;
- Gas flow rate during aeration: 1.5–4.0 m^3/h;
- Foam aging time: 30–180 minutes.

Measured parameters

1. *Rheological and physical properties:* apparent viscosity and dynamic density;
2. *Foam stability parameters:* foam column collapse time, expansion ratio, and foam height;
3. *Core invasion characteristics:* penetration depth and changes in permeability before and after treatment;
4. *Thermal resistance:* reduction in foam column height during heating.

The rheological properties and stability characteristics of the two-phase foam system based on the Guwlydere surfactant, as determined from the conducted experiments, are presented in table 8.

Table 8

Rheological properties of the two-phase foam based on the Guwly dere surfactant

Temperature, °C	Viscosity, s	Foam expansion ratio	Collapse time, min
20	320	12	48
60	410	11	55
90	515	10	62
120	580	9	71
130	605	8	74

Upon heating to 130 °C, the foam retained its structural stability, and the collapse time increased to 74 minutes, which confirms its thermal resistance.

The effect of plant-based bridging agents on foam stability is presented in table 9.

Table 9

Effectiveness of bridging agents on foam stability

Bridging agent	Additive content, %	Foam collapse time, min
No bridging agent	0	48
Walnut shell	3	86
Straw	2	74
Cotton husk	2	32

The presented quantitative data confirm the effectiveness of selecting walnut shell as a bridging agent.

Table 10 presents the foam penetration depth into the core and the permeability recovery values.

Table 10

Foam penetration depth and permeability recovery in core samples

Composition	Penetration depth, mm
Water	5-7
Polymer solution	8-11
Foam (three-phase system)	1-2

The conducted study demonstrates that the foam system causes virtually no damage to the reservoir formation.

The increase in foam stability at the optimal surfactant concentration is explained by the formation of an elastic adsorption film at the gas–liquid interface, which prevents bubble coalescence. When the optimal concentration is exceeded, an interface oversaturation effect is observed, leading to a decrease in structural stability.

As the temperature rises to 120 °C, accelerated gas diffusion becomes the dominant mechanism of foam degradation, which is confirmed by a reduction in the half-life of the foam structure.

6. Implementation into production

The successful trial of the developed foam-based solutions for temporary blocking of the productive formation in the «well-formation» system under ALFP conditions was conducted at actual industrial sites. The field tests were carried out at well X of the Yolguyi gas field and well Y of the Garashsyzlygyn 10-yyllygy gas field.

The results of these tests convincingly confirmed the high efficiency of the developed foam-based solutions, demonstrating the ability not only to prevent losses but also to improve well productivity after the operations. The obtained data are presented in table 11 and further illustrated in figure 5.

The data presented in table 11 clearly demonstrate a significant improvement in well productivity indicators following the application of the developed foaming fluids.

For Well X of the Yolguyi field, a substantial increase in gas flow rate was recorded – from 206 thousand m^3/day to 386 thousand m^3/day, which is almost twice the initial value. Changes in the tubing (TP) and annular pressures (AP) also correspond to an increased fluid inflow from the reservoir,

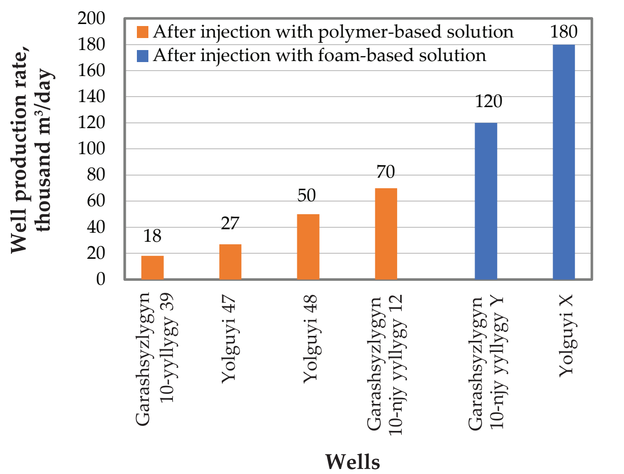

Fig. 5. Results of repair works at the Yolguyi and Garashsyzlygyn 10-yyllygy fields

Table 11

Results of industrial tests of foam-based solutions (Yolguyi and Garashsyzlygyn 10-yyllygy fields)

Indicators	Before blocking	After well clean-up
Yolguyi X Well		
Diameter of the nozzle, mm	40	40
Pressure in tubing, atm	60.4	59.3
Annular pressure, atm	88.4	97.5
Flow rate, thousand m³/day	206	386
Garashsyzlygyn 10-yyllygy Y Well		
Diameter of the nozzle, mm	20	20
Pressure in tubing, atm	66.3	76.2
Annular pressure, atm	80.4	85.3
Flow rate, thousand m³/day	0	120

confirming the restoration or improvement of near-wellbore zone permeability.

Particularly notable is the result at Well Y of the Garashsyzlygyn 10-yyllygy field. Before the intervention, the gas flow rate was 0 thousand m³/day, indicating complete blockage or inactivity of the well. After the application of the foaming fluid and subsequent clean-up, the well began to operate productively with a flow rate of 120 thousand m³/day. This proves the ability of the developed formulations to effectively unblock productive horizons and restore inflow even under challenging conditions.

The obtained results of the industrial trials are direct evidence of the technological effectiveness and economic potential of the developed foaming fluids. The application of these fluids not only effectively solves the problem of losses under ALFP (Abnormally Low Formation Pressure) conditions, but also contributes to a significant increase in production, which is critically important for the profitability of field development.

Industrial trials involving the penetration of productive formations using foaming fluids during well drilling were successfully conducted at the wells of the Yashyldepe field by the Lebapnebitgazgozleg expedition.

In particular, the Yashyldepe-Z well was drilled using a rotary method (table 12) within the interval of 2830-3100 m, with the planned depth successfully reached. During the testing of the foaming fluid, the formation pressure was 25.1 MPa and the abnormality coefficient was 0.8. The depth of the interval drilled with the foaming fluid was 270 m.

Table 12

Drilling parameters using foaming fluid with rotary method (Yashyldepe-Z well)

Indicators	Data
Well diameter, mm	215.9
Bit axial load, t	18
Rotor rotation speed, rpm.	80
Drilling fluid flow rate, m³/min	0.71-0.9
Fluid density, kg/m³	750-760
Apparent viscosity of the fluid, s	Slightly flowing
Filter cake thickness, mm	Thin film
YP/PV (Plastic Viscosity), Pa	0.02/0.4
pH	9.5
Fluid filtrate volume, cm³/30 min	1.5

The tests carried out at the Yashyldepe-Z well confirmed the possibility of using foaming fluids as circulating media during well drilling under ALFP conditions, ensuring a stable process without complications associated with fluid losses.

The results of comprehensive industrial trials conducted at the Yolguyi, Garashsyzlygyn 10-yyllygy, and Yashyldepe gas fields convincingly demonstrated the high technological effectiveness and practical applicability of the developed foaming fluids. The use enables successful resolution of critical issues related to losses under ALFP conditions, provides a significant increase in the output of existing wells, and ensures safe drilling in complex intervals. This confirms that the proposed technology is a reliable and economically viable solution for optimizing the construction and repair of wells in the oil and gas sector.

Industrial trials during well drilling

Yashyldepe–Z well

The foam density was 0.75 g/cm³ at a depth of 2850 m.

No circulation losses were recorded during drilling operations.

No borehole wall instability or sloughing was observed.

Industrial trials during well killing

Garashsyzlygyn 10-yyllygy well

Parameters prior to well killing:

Gas production rate – 0;

Bottomhole pressure – 5.2 MPa;

Circulation losses – observed.

Parameters after well killing:

Gas production rate – 120 × 10³ m³/day;

Bottomhole pressure – 7.1 MPa;

Circulation losses – eliminated.

Conclusion

The foam system effectively restored reservoir productivity and sealed the loss zone.

Laboratory investigations confirmed the high thermal stability of the foam system at temperatures up to 130 °C. The addition of walnut shell increased foam stability by 79%, while straw enhanced stability by 54%. Foam penetration into core samples was minimal (1–2 mm), and the resulting formation damage did not exceed 2%.

Field application demonstrated a significant reduction in circulation losses and an increase in production rate. The developed foam systems fully comply with the operational requirements for drilling and well killing under abnormally low formation pressure (ALFP) conditions.

7. Economic efficiency of using foaming fluids

The developed foaming fluids represent a highly effective solution for drilling and major well repairs, especially in complex ALFP conditions. The unique properties – low density, high structural viscosity, and effective filtration control – allow for minimal interaction with the productive reservoir and effectively prevent losses. This is a key factor in increasing the overall technological and economic efficiency of well construction and repair processes.

Economic efficiency assessment

The economic evaluation was conducted by comparing the costs of applying the developed foam systems with those associated with conventional technologies for a typical well under ALFP conditions. The results are presented in table 13.

Key findings

1. Material costs were reduced by approximately 40% due to the use of locally sourced raw materials, including Guwlydere surfactant and MEA production waste.

2. The primary economic benefit (approximately 80% of total savings) was achieved through a substantial reduction in non-productive time associated with loss remediation and accelerated well cleanup. The total operation time decreased from 9 days to 2 days.

3. Prevention of production losses represents a significant economic advantage, particularly for high-rate wells.

4. The payback period for development and field implementation of technology, calculated for a group of 10 wells, is less than 6 months.

The economic efficiency of using the developed foaming fluids for drilling and repairing wells under ALFP conditions has been thoroughly analysed and confirmed under field conditions. A comparative analysis of work scenarios shows significant advantages of the new technology over traditional approaches:

- The use of conventional fluids under ALFP conditions inevitably leads to substantial drilling fluid losses and, consequently, extended non-productive time associated with loss remediation. This downtime can last days or even weeks, significantly prolonging project timelines. Additionally, well development periods are extended due to reservoir damage, ultimately leading to high operational costs and loss of potential production.
- The implementation of the developed foaming fluids has radically changed operational practices. These fluids significantly reduce the risk of losses, minimising non-productive time and practically eliminating downtime for this reason. According to production data, this has led to a 30-50 % reduction in loss control expenses. Well development time has also been significantly reduced due to the preservation of the reservoir's natural permeability, accelerating the process by 2-3 times. As a result, an increase in both initial and stable well output has been recorded, generating additional profits over the entire operating period.

Thus, the developed technologies ensure not only the optimization of operational costs and a substantial improvement in the return on investment in ALFP field development, but also demonstrate quantitatively confirmed improvements in key production indicators.

The conducted analysis and obtained industrial results clearly demonstrate that the developed foaming fluid formulations possess high and proven economic potential. The successful implementation in well drilling and major repairs under ALFP conditions has significantly reduced both financial and time costs associated with loss remediation, accelerated well commissioning, and improved productivity. This, in turn, has led to improved overall technical and economic performance of oil and gas enterprises and increased project profitability under ALFP conditions.

Table 13

Comparative cost analysis of a well killing operation for a single well

Cost structure comparison	**Conventional technology (clay-based mud)**	**Developed foam system (formulation 2)**	**Cost item savings / (overrun)**
1. Material costs, thousand USD			
- Chemical procurement	15.0	8.5	-6.5
- Logistics and preparation	3.0	1.5	-1.5
2. Operational costs, thousand USD			
- Loss remediation time (2 days)	20.0	0.0	-20.0
- Well cleanup time (7 days)	35.0	2.0	-33.0
3. Direct costs and production losses, thousand USD			
Production shortfall losses (300×10^3 m^3/day gas price basis)	105.0 (7 days)	30.0 (2 days.)	-75.0
Total costs and losses, thousand USD	178.0	42.0	-136.0
4. Additional revenue			
Increased production rate, thousand USD/year	0	+65.0 (estimated)	+65.0

Conclusions

Experimental investigations resulted in the development of thermally stable foam formulations designed for application under ALFP conditions, with clearly differentiated functional purposes:

- Drilling fluid with a minimum density of 0.50 g/cm³, intended to ensure safe penetration of productive formations.
- Killing fluid with structural stability of up to 7 days, providing prolonged temporary well control during workover operations.

The study presents the results of laboratory evaluation of key technological parameters, including density, rheological properties, fluid loss, pH, and thermal stability.

The practical value of the developed formulations is supported by their high thermal stability and the utilization of locally available raw materials (MEA waste from the production association «Maryazot» and Guwlydere surfactant). This approach significantly reduces fluid costs and provides a clear economic advantage compared to imported alternatives.

A foam drilling fluid with enhanced thermal and structural stability was developed. Optimization of the formulation increased foam stability time by 1.5–2 times relative to conventional systems.

The obtained results are of practical importance and may be applied in the design of drilling fluids for wells drilled under complicated geological and technical conditions.

The practical significance of the proposed technology has been confirmed through successful field implementation at the Yashyldepe, Yolguyi, and Garashsyzlygyn 10-yyllygy fields. These results support its recommendation for broader application in drilling and workover operations under ALFP conditions.

Structural factors governing the functional performance of foam systems under ALFP conditions were experimentally identified and quantitatively evaluated, including the influence of surfactant type, synergistic effects of local components, and the role of bentonite as a stabilizing filler.

A scientifically substantiated classification of foam formulations according to functional purpose was developed:

- drilling applications (priority: minimum density of 0.50 g/cm³);
- well killing applications (priority: maximum structural stability up to 7 days).

High economic efficiency was demonstrated, reflected in a 30–50 % reduction in costs associated with circulation loss mitigation and improved well productivity [45].

The scientific novelty of the study consists of the following:

1. A synergistic effect resulting from the combined use of the local Guwlydere surfactant and MEA production waste was experimentally established and theoretically substantiated. This effect is manifested in the formation of a stable polymer–foam matrix, enabling the achievement of an ultra-low density of 0.50 g/cm³ while maintaining high thermal stability up to 130 °C.
2. For the first time, a scientifically substantiated classification of foam formulations for ALFP conditions was proposed based on a comprehensive analysis of their functional properties: for drilling applications (priority: minimum density); for well killing operations (priority: maximum structural stability up to 7 days).
3. The economic efficiency of the developed systems was quantitatively demonstrated, reflected in a 30–50 % reduction in costs associated with circulation loss mitigation and an increase in well production rates following treatment.
4. Quantitative relationships between foam expansion ratio and stability and the concentration of surfactants and gas phase content were established.
   The influence of thermodynamic conditions on foam structure degradation mechanisms was also determined.
5. A laboratory methodology for evaluating the thermal resistance of foam systems, adapted to deep drilling conditions, was developed.
6. The feasibility of industrial application of the developed foam system for reducing drilling complications was substantiated.

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