SOCAR Proceedings

Drilling & Completion

journal home page: http://proceedings.socar.az

METHOD OF INCREASING THE STRENGTH OF WELL CASING STRINGS UNDER PLASTIC FLOW OF SALTS BY ACTIVE RESISTANCE METHOD

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A B S T R A C T

The research is aimed at developing a new method of active resistance of deep well casing strings to increase their strength and durability under conditions of plastic salt flow. This study used methods of systematic analysis of geological conditions, design of well structures and evaluation of the effectiveness of fastening technologies aimed at solving problems related to drilling and operation of wells in difficult geological conditions of Turkmenistan. The conducted experiments have shown that the use of this method allows for reducing deformations and minimizing the risk of string damage in complex geological conditions. The data analysis showed that the applied method is able to increase the operational life of strings, which is a significant achievement in the field of drilling technologies. In addition, a comparative analysis with traditional methods confirmed the economic feasibility of the new approach, as it reduces maintenance and repair costs. Additionally, the results of the study revealed that the use of the new method leads to a 25 per cent reduction in the probability of cracking and fracture formation in casing strings compared to conventional approaches. It was also found that the method actively influences drilling dynamics by reducing the time it takes to raise and lower the string into the well, which improves the overall efficiency of drilling operations. Finally, the findings open up prospects for further study of the influence of different geological conditions on active drag efficiency, which may contribute to the creation of more adaptive and sustainable technologies in drilling practice.

Keywords: geological conditions, operational life, drilling technologies, active resistance, strength characteristics.

Date submitted: 12.08.2024 **Date accepted:** 03.03.2025

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Introduction

In today's drilling environment, improving casing string strength is one of the key challenges, especially in difficult geological conditions where plastic salt flows are observed. These conditions can lead to deformation and damage of the casing strings, which not only increases maintenance costs but also reduces their service life. Therefore, there is a need to develop effective methods to help strengthen columns and ensure their reliability. One of such methods is active resistance, which allows significantly improving the strength characteristics of casing strings, reducing the risk of fracture and cracking. This article is devoted to analysing the possibilities of using the active resistance method to improve the strength of casing strings, as well as its impact on the efficiency of drilling operations in conditions of high plasticity of salts. The results of the study open new horizons for the introduction of adaptive technologies in drilling practice, contributing to the optimization of drilling processes and increasing their economic feasibility.

The actual problem in the field of casing strings strength increase at plastic flow of salts is insufficient efficiency of traditional methods of deformation and fracture protection. O. Zvirko et al. [1] emphasize the influence of physical and mechanical properties of salts on casing performance. They stress that understanding of these properties allows more accurate prediction of casing behaviour under difficult operating conditions. R. Zhang et al. [2] investigate the effectiveness of using antifriction coatings to reduce friction between the string and the salt formation. In their findings, they note that the use of such coatings can significantly reduce the risk of deformation and extend the service life of casing strings. G. Fu et al. [3] consider the use of multilayer pipe structures, which can significantly improve their strength and resistance to deformation. They also point out that the correct choice of materials for each layer plays a key role in ensuring string reliability. J. Shen et al. [4] investigate methods for monitoring the condition of columns to promptly detect damage and extend their service life. They argue that the integration of modern sensors and monitoring systems can significantly improve the level of safety when working with wells. T. Rousakis et al. [5] emphasize the role of compensating insulation layers in load distribution on the string, which reduces stress concentration. Their study shows that the use of these layers can significantly increase the durability of strings in aggressive environments.

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http://dx.doi.org/10.5510/OGP20250101040

P. Kumari et al. [6] analyses corrosion processes occurring in aggressive media and suggests ways to minimize them. They note that an integrated approach to column protection can significantly reduce the risks associated with corrosion. M. Malik et al. [7] investigate the effect of temperature and pressure on physical and mechanical properties of casing strings. They conclude that these factors have a significant effect on the strength and durability of the pipes, which requires taking these parameters into account in the design. L. Dunn et al. [8] conduct an experimental study confirming the high efficiency of protective coatings. Their work demonstrates that the use of such coatings reduces wear and damage on casing strings, especially under high load conditions. G. Mubarak, et al. [9] emphasize an integrated approach to solving the problem, combining different methods of casing protection. They highlight that the integration of different technologies can significantly improve the reliability and durability of casing. A. Ihnatov et al. [10] point out the need for innovative materials to improve the durability of casing under difficult operating conditions. They note that such materials can be a decisive factor in ensuring the effective operation of wells for a long period of time. However, despite the advances, some questions remain unresolved. More in-depth analysis of the interaction of new technologies with various geological factors is needed, as well as an assessment of the long-term effectiveness of active resistivity in complex plastic flow conditions. It is also necessary to study the influence of different drilling modes on the strength characteristics of drill strings, which will open new perspectives for the development of adaptive technologies in drilling practice.

The aim of the study was to create a new method to improve the stability of casing strings in deep wells exposed to plastic salts.

Objectives of the paper are:

1. Studying the geological factors that influence the efficiency of new technologies and their interaction with drilling conditions.
2. Considering the physical and mechanical properties of salt formations and their influence on pipe performance.
3. Evaluating different approaches to column condition monitoring and their impact on timely damage detection.

Materials and methods

In this study, the problem of drilling wells in salt-bearing sediments was considered, with emphasis on the complex geological conditions observed in Turkmenistan. The geology of this region is characterized by the presence of thick Cimmerian-Titonian salt deposits, which creates significant difficulties in drilling and well operation. Given these characteristics, an attempt has been made to systematically analyse methods that can help to deal with the potential risks associated with such conditions.

In this regard, special attention was paid to the design and selection of well support technologies, both at the drilling stage and during operation. The study focused on improving wellbore strength, which proved critical to extending the productive life of the well. Unfavourable geological conditions, such as the presence of salt deposits, require the implementation of innovative solutions that can ensure the stability and safety of wells throughout their life cycle.

As an example, the situation at the Galkynysh oil horizon, located in the eastern part of Turkmenistan, was analysed. This location was chosen because of its characteristic problems with casing deformation. Drilling productive formations within these thick salt deposits required the development of effective methods to prevent or minimize deformation and its consequences.

During the operation of wells located at a depth of about 2200-2800 metres, buckling of casing strings was recorded, which led to the need for a detailed analysis of this phenomenon. The study included an examination of the causes and consequences of buckling, as well as its impact on well performance. One of the key aspects of the work was the identification of relationships between geological conditions and casing condition, which helped to form a more complete picture of the problem.

As part of the study, a well design was developed that included information on borehole diameters, casing run intervals and cement lift heights. This allowed optimizing the design and significantly improving the technical performance of the wells, ensuring their longevity and reliability.

For more in-depth analysis, data from 28 wells in the studied field were studied. Casing deformation was observed at depths ranging from 35 to 76 metres below the upper boundary of the salt deposits. These data, together with the results of stratigraphic analyses, have contributed to a better understanding of the field structure and associated risks. The plastic flow of salt deposits within the well is one of the causes of casing buckling.

A new method known as the «active resistance method» has been proposed to address the problem of casing buckling. This method aims to create an internal pressure greater than the equivalent rock pressure, which is a key element in combating casing deformation. Achieving the required pressure is accomplished by using the hydrostatic pressure of the drilling mud. The drilling mud pumped into the well pressurizes the casing, which helps to neutralize external loads that can lead to buckling. Thus, when the pressure inside the string exceeds the pressure of the surrounding rock, it creates conditions for string stability and prevents deformation.

The study investigated the feasibility of using downhole string isolation systems such as REPACKER by BAKER HUGHES and SHELLPACKER by HALLIBURTON to simplify the cementing technology. This study is aimed at optimizing the well-cementing process, which may help to improve its reliability and efficiency. The choice of these packers is due to their ability to provide tightness and protection of the downhole zone, which, in turn, allows for minimizing risks associated with leaks and other problems arising during well operation.

Results

Drilling wells in salt-bearing sediments is a challenge that has been observed in all parts of the world. One of the major complications of this process is the inelastic deformation of salt deposits. These deformations can lead to various problems such as narrowing of the wellbore diameter and loss of casing. The most serious and dangerous complication is casing buckling, which can lead to drilling stoppages and increased operating costs.

The problem associated with the plastic flow of salt

deposits requires special attention to well support, both in the process of drilling and during their operation. This situation is especially relevant for Turkmenistan, where large salt deposits are developed in the east of the country [11]. In this context, the need to improve wellbore strength, which in turn extends the productive life of the well, is considered. The oil horizon in the Galkynysh field in eastern Turkmenistan is used as an example.

Drilling productive reservoirs within thick Cimmerian-Titonian (Upper Jurassic) salt deposits is an important challenge. These sediments are prone to inelastic deformation, which exacerbates the risks and difficulties encountered during drilling and well operation. Therefore, it is necessary to develop effective methods aimed at preventing or minimizing deformations and their consequences, which will ensure the safety and efficiency of drilling in such conditions.

During operation of wells located in the intervals of salt deposits at a depth of about 2200-2800 m, gradual buckling of casing strings is observed. This phenomenon becomes especially pronounced after standard well casing support. As a rule, in most cases there is simultaneous buckling of several casing strings: 244.5 mm diameter intermediate string, 168.3 mm diameter production string and tubing string. This problem is relevant, as string buckling can negatively affect well operation and, ultimately, production efficiency [12]. A well design was developed for the field, the details of which are summarized in table 1. This information is critical for understanding the well design and possible causes of string buckling, which will allow more effective management of the drilling and operating process in conditions associated with salt deposits.

Thus, the casing buckling situation highlights the need for careful design and technology selection to ensure well stability and longevity in challenging geological conditions.

The cause of casing buckling in wells located in salt deposits is the plastic flow of these deposits inside the well. Under standard conditions, casing strings are designed to take into account the effect of biaxially balanced weight on external buckling pressure. However, during the flow of salt deposits, unbalanced weight is applied to the anchored casing string, resulting in a loss of stability.

The most dangerous for casing strings is the impact of uniaxial weight at an angle of 50 degrees [13]. This effect contributes not only to string buckling, but also to the deterioration of the overall well condition. An important aspect of the study is the lack of data on the deformation process in the anchored casing strings, such as profilometry, time to onset of deformation and lower limit of deformation. In this regard, it is accepted to consider the above critical condition associated with weight impact on the casing strings as the most dangerous scenario in the well conditions.

When the salt deposits lose stability and flow plastic, the external pressure on the anchored casing strings is restored to the rock pressure level. This corresponds to the equivalent of a pressure gradient of 2.3 g/cm^3 for the platform region, a large island relatively stable section of the continental crust characterized by a relatively calm tectonic regime.This corresponds to an equivalent pressure gradient of 2.3 g/cm^3 for the platform area, a large island relatively stable section of the continental crust characterized by a relatively calm tectonic As a result, the field where the downhole casing is installed has significant external crushing pressures in the salt intervals: at a depth of 2200 m the pressure is 50.6 MPa and at a depth of 2800 m it is 64.4 MPa.

The geological cross-section of the field, based on data from drill holes X1 and X2, is detailed in table 2. This infor-

Table 1

Project-oriented design of wells

Name	Barrel diameter, mm	Casing interval, m		Length, m	Cement lifting height, m
		upper	lower		
Guide shaft	720	0	5	5	Cyclopean concrete
Elongated direction	508	0	50	50	50
Conductor	323.7	0	1000	1000	1000
Intermediate column	244.5	0	2832	2832	2832
Operating column	168.3	0	3100	3100	3100

Table 2

Stratigraphy, lithology and possible sedimentation during drilling in the field

Stratigraphy upper	Assignment lower	Depth of descent, m		Thickness, m	Rocks	Possible complications
		upper	lower			
Fourth+Neogene system	Q+N	0	60	60	Sand and clay	Absorption, collapses
Perm system	P2+P1	60	285	225	Sand and clay with an admixture of gravel	Absorption, collapses
Lime system	K2+K1	285	2230	2005	Chalk, clay, limestone, marl	Landslides
Upper Yura	J3	2230	2830	600	Anhydrite, solid anhydrite, salt, rapa	Manifestation, occurrence of salts and brine
MiddleYura	J2	2830	3100	270	Oily limestone, dolomite	Karst and voids, absorption, sulphur release

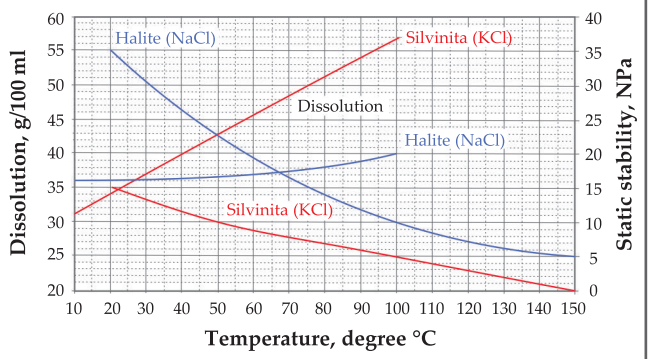

Fig. 1. Temperature dependence of solubility and static stability of salts (in grams of anhydrous salt per 100 ml of water)

Table 3

Information on production wells of the field

Well number	Depth, m	Filter, m		Gas inlet point, m
		upper	lower	
X2a	2996	2972	2982	2158
		2988	2996	
X3	2986	2974	2984	2134
X4	2962	2944	2954	2864
X25	3003	2982	2988	2852
X6	3038	2970	3031	2783

mation provides a better understanding of the structure and characteristics of the field, which in turn facilitates more effective management of drilling and well operations in complex geological conditions.

From the Jurassic sedimentary rock section (from bottom to top), the deposit terminates in a five-layer Cimmerian-Tithonian salt-and-anhydrite sequence, which is clearly visible in most of the deposit and provides the possibility of interrelationship (correlation). The Middle Jurassic carbonate sediments host a thick assemblage of salt deposits, which alternate from straight salts (halite), anhydrite, limestone and thin layers of clay [13]. The presence of potassium salt beds (2-9 m) in the upper part of the salt deposits is noted. The total thickness of the Upper Jurassic Cimmerian-Titonian sediments varies from 525 to 878 metres.

In the process of analysing casing deformations in the field under study, data from 28 wells were scrutinized. Of these wells, in 26 wells, it was recorded that casing deformation occurred at depths from 35 to 76 metres below the upper boundary of salt deposits. In one of the wells, deformation occurred at a depth of 2754 metres, which corresponds to the XX-P plastic, and in another well it occurred 86 metres above the upper boundary of the salt deposit, at a depth of 2278 metres.

It is important to note that a thick layer of potassium salts is observed in the upper part of the section. When comparing the thickness of salt deposits, the properties of halite (NaCl) and potassium salts (sylvine), it can be argued that potassium salts have higher solubility, which depends on temperature, and lower statistical stability [14]. Sylvin is a mineral of the halide class with the formula potassium chloride (KCl).

Silvinite is a sedimentary rock consisting of alternating layers of halite and silvin (nNaCl+mKCl) and some impurities (hematite, etc.). The ratio between potassium and sodium chlorides in silvinite is unstable. In the form of impurities, it usually contains a little anhydrite, gypsum, etc. This property is confirmed by the given figure 1.

Consequently, it can be assumed that one of the causes of buckling of the secured casing strings is the presence of potassium salts in the cross-section, especially under real well temperature conditions exceeding 60 °C. This conclusion is consistent with the above analysis of the deformation of the secured casing strings, confirming the influence of potassium salts on the stability and integrity of the casing strings during well operation. This finding is consistent with the above analysis of casing strain, confirming the effect of potassium salts on casing stability and integrity during well operation. Thus, the results of the analysis emphasize the need for further study of the interaction of different types of salts with casing to improve the reliability and efficiency of drilling operations in saline conditions.

For objective reasons, it is difficult to accurately determine the time of deformation of casing strings at wells in the field. The time that passes from the beginning of well operation until the emergency situation occurs, i.e. until the moment when buckling in rocks occurs in the secured casing strings, can vary from 3 to 13 years [15]. In addition, the occurrence of deformation in the string is significantly affected by a drop in the internal hydrostatic pressure gradient below 1.0 g/cm³. For reference, the average density of oil in this field is 0.86 g/cm³. This means that during well operation, especially when the pressure drops, the risk of column deformation increases. In the field in question, the wells are operated using the gas lift method, but without a gas lift valve. This means that gas is supplied exclusively through special entry points, which can also have an impact on pressure and thus on casing stability.

For clarity and more detailed analysis, table 3 provides information on some operated wells, including their characteristics and operating parameters. This will help to better understand how various factors affect the well operation process and the time of deformation occurrence in well casing.

As can be seen from table 3, in some cases the lower boundary of well emptying during operation is below the salt deposits. In such cases, the gas pressure supplied to the inter-casing space does not exceed 60-65 kg/cm². This creates additional risks for casing stability.

In conventional wells, the external overpressure is counteracted only by the string stiffness and hydrostatic pressure in the casing (fig. 2). However, considering the numerous repeated cases of casing buckling, it becomes obvious that the counterbalancing effect of the string stiffness is insufficient to counteract the string buckling under the action of equal rock pressure [16]. For example, in the subsurface of salt deposits in well No. X3, a special steel string of type P-110 x TP-110 TT with a diameter of 250.8 mm and a wall thickness of 15.88 mm was installed. However, after three years of operation, this casing was also subjected to wear.

In response to the problem of casing buckling, temporary solutions were proposed for different types of well designs that could resist the softening action of salts. One

Table 4

Proposed well design

Name	Barrel diameter, mm	Bit diameter, mm	Descent interval, m		Length, m	Cement lifting height, m
			upper	lower		
Guide shaft	630	—	0	5	5	Cyclopean concrete
Elongated direction	426	490	0	50	50	50
Conductor	323.7	393.7	0	1000	1000	1000
Intermediate column	244.5	295.3	0	2830	2830	2832
Shank	193.7	—	2150	2830	680	680
Operating column	139.7 (127)	165.1	0	3100	3100	3100

of these solutions was a well-drilling design that was prepared. As part of this project, two wells were drilled in the field. The design of these wells is summarized in table 4, which provides a closer look at the proposed modifications and their potential to improve casing stability in the salt-affected environment.

At present, the mechanism of rock pressure formation in the formation, as well as the influence of unstable and rigidly deformable salt deposits on the wellbore are insufficiently studied. This creates certain difficulties in assessing the stability of the casing string. The casing in the proposed design can temporarily counteract the plastic deformation of salt deposits, prolonging the service life of the well. However, the effect of unstable salt rocks on the borehole requires further research.

Considering the above factors, it is obvious that to improve the long-term reliability of the wellbore, it is necessary to apply new, unconventional and more flexible methods to combat the effects of downhole pressure on casing buckling.

One effective way to counteract varying rock pressure is to create a counterbalancing effect of hydrostatic pressure from the borehole fluid column or excess internal pressure that equals or exceeds the equivalent rock pressure gradient in the borehole ($R_{int}>R_{rock}$). This method has been called «the method of active resistance of casing» [17].

«Active Resistance Method» is an approach to wellbore strengthening that aims to counteract casing buckling and deformation of salt deposits by creating an internal pressure greater than the equivalent rock pressure. The basic idea of the method is to use the hydrostatic pressure of the fluid column in the well to neutralize external loads acting on the string. This is achieved by cementing two sections of casing: the first section is set at the design depth and the second section can be set with or without a packer, creating a separation between the two parts of the string. Once the packer is installed or the second section is cemented, the density of the drilling fluid increases to the design value, which creates additional hydrostatic pressure to resist buckling. An important element of the method is the creation of an inter-column zone, which is filled with drilling mud that has the necessary physical properties (heat resistance and thixotropy) to prevent sludge formation and maintain system stability.

The advantages of the method include increased string reliability, as this approach creates two independent casing strings that work together to provide reliability under increased external pressure. Increased pressure in the annulus helps extend the life of the well, as it reduces the likelihood of string buckling and emergencies. The flexibility of the method design allows the use of different types of packers (hydraulic, swellable) and materials, adapting it to the specific conditions of a particular field. The method also provides improved control, as it allows for more precise control of internal pressures and drilling fluid properties, which significantly reduces the risks associated with operation. The use of special packers and drilling fluids resistant to high temperatures makes the method relevant for wells in salt deposits, where temperatures can exceed 60 °C.

The use of the «active resistance method» is appropriate in conditions where conventional well-support methods fail to cope with the problems arising from the plastic flow of salt deposits. In conditions of significant external pressure and unstable salt deposits, this method demonstrates its effectiveness, ensuring long-term well operation and minimizing the risk of accidents. Thus, this approach, combining modern technologies and design principles, opens new horizons in the field of oil and gas field development, especially in complex geological conditions. Its application is not only justified, but also represents a necessary step to improve the efficiency and safety of drilling operations.

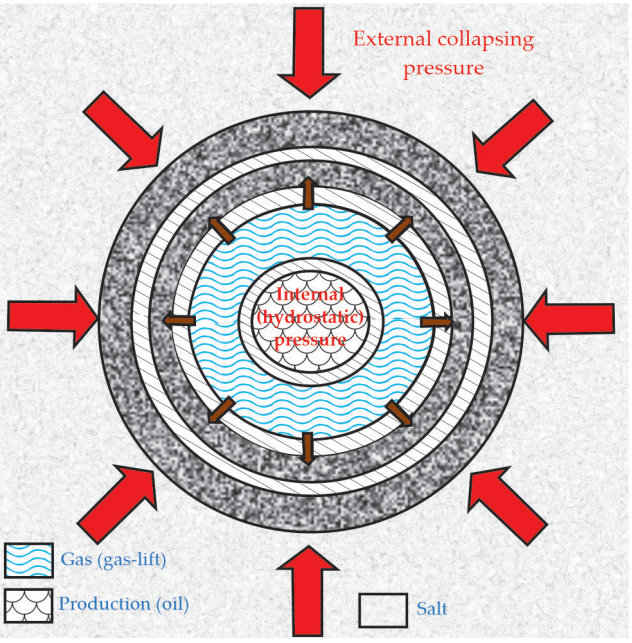

Fig. 2. Condition of wells during operation period secured by conventional technology between salt deposits

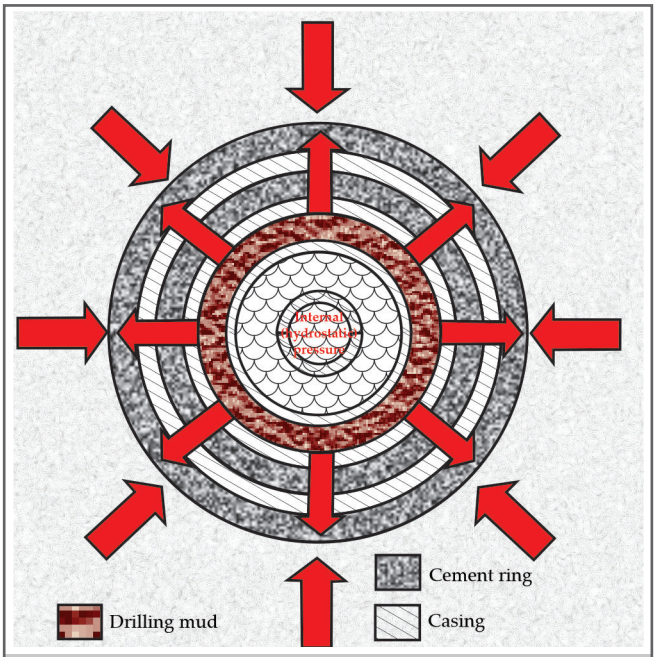

Fig. 3. Condition of wells during the operation period fixed by the proposed technology between salt deposits

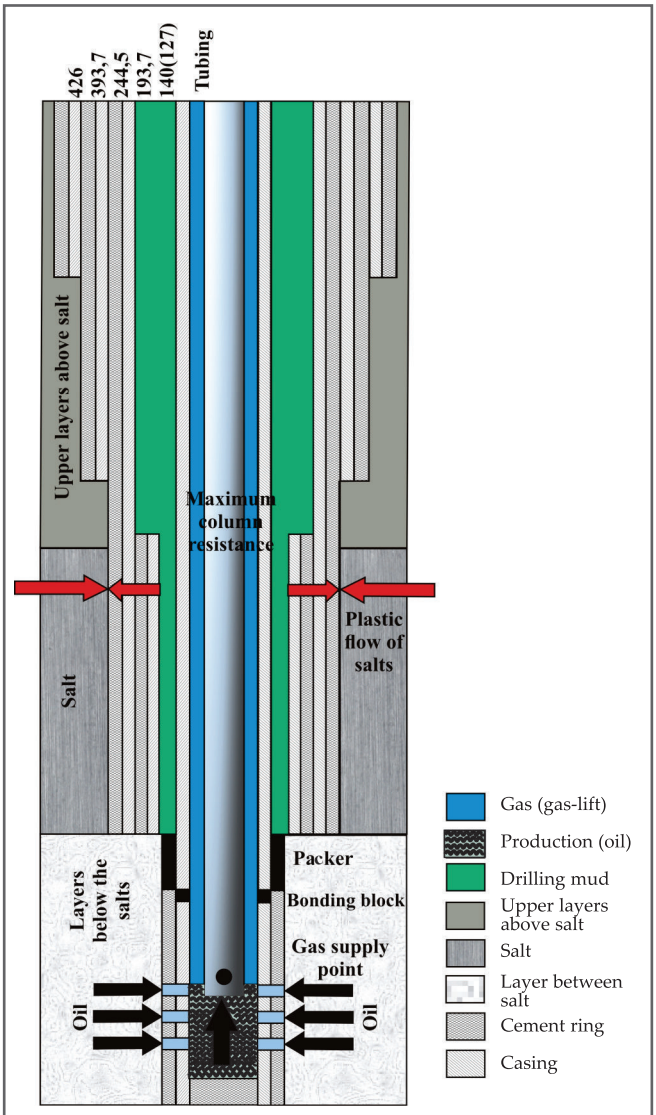

Fig. 4. Principal scheme of reinforced production well casing (packer version)

Figure 3 shows the proposed method of «active casing resistance method» during operation for secured wells. This method involves active pressure management inside the well, which can improve casing stability and minimize the risk of casing buckling due to rock pressure.

The internal hydrostatic pressure in the annulus plays an important role in neutralizing the effect of external pressure on the casing strings, which greatly facilitates their working conditions against buckling. This proposal can be realized in two main ways.

In the first case, according to the recommendations, a 193.7-mm-diameter countersunk «liner» casing is run and cemented at a depth of 2150 to 2830 metres. After reaching the design depth, the first section of 139.7 (or 127) mm diameter production casing is run into the well and cemented with a light cement slurry. Then the second section of casing is installed in the well, and the drilling fluid density is increased to the design value.

The lower part of the second section of the production string is equipped with a packer of appropriate diameter from the outside. It can be either a hydraulic packer or a swellable packer (details on the design and operating mechanism of the inflatable packer will be presented below). The depth of the packer is chosen to be below the lower boundary of the salt deposit but above the upper pay zone. After cementing and connecting the second casing section to the first using existing methods, the packer is brought into the working position, which allows the well to be split into two sections [18].

The lower section will be cemented to the pay zones, while the upper section will counteract the pressure of the salt deposits in the string. The inter-column zone is filled with drilling mud. After the outer packer is brought into operation, tubing (tubing) is run into the well and the density of the drilling fluid is reduced to the required value where the pay zones will be perforated [19]. Then the tightness of the lower part of the intercolumn space is checked. The drilling fluid left in the intercolumn space must have heat-resistant and thixotropic properties to prevent solids and weighting agents from precipitating.

Figure 4 shows a schematic diagram of a well device using the «active resistance method of support». Perforation, well development and transition to overlying pay zones are carried out using conventional technologies.

The disadvantage of the first variant is the impossibility of opening between the parts of the production string borehole, which may limit the possibilities for further repair and maintenance. However, the advantage of this option is the increased reliability of the string: the external buckling pressure is resisted by two anchored casing strings and two cement rings, as well as the additional hydrostatic pressure of the drilling fluid. This creates a more stable system that can withstand significant loads.

In the second variant, the second part of the production string is lowered without using the packer. Further operations are performed similarly to the first option. This approach retains all the advantages of the first variant, but additionally allows work overing or lifting the second part of the production string to the surface. This creates the possibility of opening their parts when the well reaches the end of its service life.

To simplify anchoring technology, a downhole isola-

tion system such as BAKER HUGHES' REPACKER or HALLIBURTON's SHELLPACKER can be considered as an external column packer. Packers of these designs are swellable elastomeric elements that are installed in the bodies of the connecting pipes. When swelling, they do not reduce the internal diameter of the pipes, which allows maintaining the required flow capacity (figs 5, 6).

REPACKER packer components can be installed directly onto the casing body on the rig. This greatly simplifies the installation process and increases the efficiency of the packer installation. The number of packer segments is determined only by the length of the casing to be attached and its installation distance in the wellbore, which provides flexibility in design and allows for adaptation to different conditions.

The packer swelling time is calculated taking into account the safe descent time of the packer to the installation depth and the type of drilling fluid used. This time should be optimized to avoid potential problems during installation. During swelling, the packer diameter can increase up to 200%, which creates a significant pressure on the borehole wall and ensures a reliable seal [20].

Depending on the type of packer used, the packer section has a unilateral load capacity ranging from 350 kg/cm² to 1000 kg/cm². This allows the packer to effectively resist external pressure and provides additional protection against buckling of the casing. The high load capacity of the packer makes it an effective tool for combating problems associated with the plastic flow of salt deposits and improves the overall durability and reliability of the well structure.

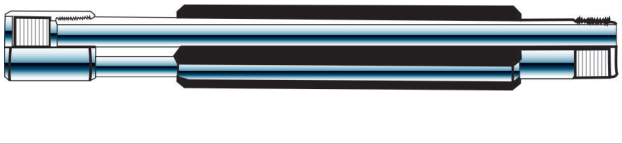

Fig. 5. BAKER HUGHES REPACKER swelling packer

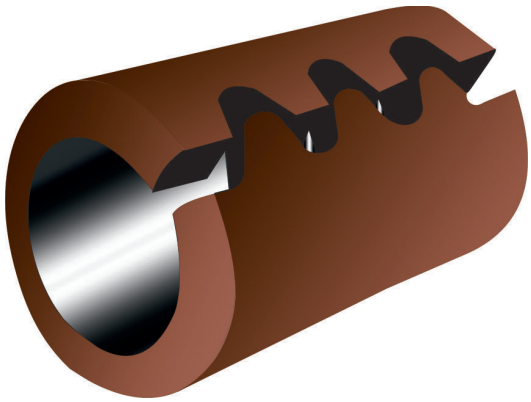

Fig. 6.REPACKER — screw-in replaceable packer element

Discussion

In the course of experiments and observations, the effectiveness of the proposed method was noted in conditions where traditional casing stringing technologies were insufficient. In the 28 wells analysed for casing deformation, it was found that the use of active resistance significantly reduced the likelihood of casing buckling, especially when the plastic flow of salt deposits pressurized the casing.

This was also investigated by M. Dutkiewicz et al. [21], where the results confirmed that the effectiveness of the active resistance method for casing deformation lies in its ability to minimize the risk of structural damage under the influence of external forces. This method is based on the use of special compensating devices that help to keep the strings in a stable state, preventing them from buckling. As a result of using active resistance, longer casing life can be achieved, which is critical for well safety and reliability.

Studies by F. Benedetto et al. [22] also showed that the analysis of casing string buckling risk reduction in wells shows that the introduction of modern technologies and monitoring systems significantly increases the predictability of string behaviour under load. A systematic approach to evaluating the mechanical properties of materials and operating conditions allows more accurate prediction of possible deformations. Thus, the use of active resistance in combination with analytical methods can significantly increase the efficiency of well operation and reduce financial losses from emergencies.

It should be noted that the application of the active resistance method requires a comprehensive approach to casing design and operation. A crucial aspect is the selection of suitable compensating devices, which should correspond to specific geological conditions and well characteristics. In addition, regular monitoring of casing condition and analysis of its behaviour under the influence of various factors will help to identify potential risks and adapt protection methods in a timely manner, resulting in improved overall system reliability.

One of the key findings was that the internal hydrostatic pressure in the annulus partially or completely neutralized the effect of external pressure on the casing. This made it easier for the casing to perform under buckling conditions. Based on the data obtained, it was possible to argue that the active drag method allows for a stable environment inside the well, where the mud column pressure acts as a counterbalance to the external pressure, which significantly increased casing strength.

Z. Laaouar et al. [23] concluded that neutralizing the external pressure by hydrostatic action in the annulus is a key strategy to protect the casing from deformations caused by pressure changes. The hydrostatic pressure of the drilling fluid provides a counterbalance to external forces, allowing balance to be maintained and preventing string buckling. This is especially relevant in high-density environments, where the risk of deformation is greatly increased.

In a study by Y. Guan et al. [24], the authors revealed that the role of internal mud pressure in preventing column deformation cannot be underestimated, as it directly affects the stability of the entire structure. Maintaining a proper pressure level helps not only to neutralize external loads but also prevents flooding of the annulus, which can lead to accidents. Thus, proper management of internal mud pressure is an important aspect of casing reliability and longevity during drilling.

These results support the above study by demonstrating that proper management of internal mud pressure is direct-

ly related to casing safety and durability. When external pressures are significantly higher than internal pressures, casing strings become vulnerable to deformation and possible damage. Consequently, the application of scientifically based approaches to pressure control in the annulus can significantly reduce the risk of accidents and increase the efficiency of well operation.

In addition, the use of two sections of casing with packer capability was particularly successful. In one of the wells studied, a special casing was installed that provided strength at a level that exceeded equivalent rock pressure. This indicates that designs based on the active resistance method can effectively cope with the challenges posed by the plastic flow of salts, as evidenced by the reduction in string deformation compared to conventional methods.

The work of A. Shokry & A. Elgibaly [25], who also found that the use of two-section columns with packers for strength reinforcement is an innovative approach that can significantly improve the structural stability against external loads. Such columns provide better stress distribution and prevent the concentration of forces in vulnerable zones, which is critical in complex geological conditions. The packers installed between the sections additionally contribute to sealing and protection against fluid leakage, which increases the reliability of the entire system.

In turn, Z. Digby et al. [26] concluded that the successful use of active resistance in plastic flow of salts also confirms the effectiveness of modern technologies in drilling. Active resistance allows controlling and minimizing deformations resulting from plastic flow, which is especially relevant in areas with high salt content. Combined with two-section strings, this creates an additional layer of protection, ensuring the durability and stability of drilling operations in challenging environments.

These findings are consistent with the theses presented in the previous section, as they point out the importance of integrating modern technology into casing string design. In particular, the use of two-section packer strings, along with active resistance, demonstrates how an integrated approach can significantly improve the strength and reliability of drilling structures. Thus, the research results confirm that the combination of different methods and technologies not only improves resistance to external loads, but also contributes to effective management of risks associated with string deformation in complex geological conditions.

However, some limitations and disadvantages of the proposed method were also revealed in the process of analysis. For example, in cases where the internal density of the drilling fluid did not reach the required values, the effect of counteracting the external pressure was reduced. This emphasizes the importance of careful selection of drilling fluid parameters and properties to achieve optimal results. In addition, the use of packers requires additional costs to install and maintain them, which can increase overall drilling and operating costs.

M. Khan et al. [27] also conducted a study, the results of which confirmed that the limitations of the active drag method due to mud properties play a significant role in the overall system performance. For example, drilling fluid properties such as viscosity and flowability can affect the ability of active drag to compensate for external loads. If the drilling fluid does not meet the required characteristics, it can lead to a decrease in the efficiency of the method and, consequently, an increased risk of string deformation.

R. Ashena et al. [28] also found that the effect of mud density on the efficiency of resisting external pressure is a key factor determining the success of the active drag method. Higher mud density can create a greater hydrostatic effect, which improves the balance of forces in the annulus and reduces the likelihood of string buckling. However, excessive density can cause additional problems, such as increased casing stress and performance degradation, which highlights the need to optimize mud parameters to ensure reliable operation of the entire system.

By comparing the data obtained from the studies, key aspects that influence the effectiveness of the active resistance method can be identified. In particular, the influence of drilling fluid properties, such as density and viscosity, correlate directly with the results obtained in casing strength tests. This emphasizes the importance of a comprehensive approach to mud selection and tuning, which can significantly improve system reliability in high external pressures and complex geology.

Despite the identified disadvantages, the results of the study show that the active resistance method has clear advantages that can significantly improve the reliability and durability of casing strings in difficult geological conditions. Practical application of the active resistance method can significantly improve the level of safety during well operation, which, in turn, has a positive impact on the efficiency of field development. These aspects make the method very relevant and expedient for application in well drilling in conditions when traditional technologies fail to cope with the arising problems.

J. Ding et al. [29] concluded that the advantages of active resistance in geological conditions with plastic flow of salts lie in its ability to effectively resist deformations caused by dynamic changes in underground conditions. In such situations, active resistance allows better control of the stresses developed in the columns, thus reducing the likelihood of damage. This is particularly relevant in areas where the plastic flow of salts can lead to unstable conditions, causing significant mechanical stresses on the structure.

G. Jiang et al. [30] revealed that the increase in safety and durability of strings in difficult drilling conditions is the result of the introduction of active resistance, which makes this method an important tool in modern drilling. The use of techniques that maintain string stability significantly reduces the risk of accidents and contributes to more efficient operations. As a result, not only is the reliability of drilling systems improved, but also repair and maintenance costs are reduced, making drilling in difficult geological conditions more cost-effective and safer.

When analysing the results of the study, it becomes clear that the use of active resistance under conditions of plastic salt flow significantly improves the deformation resistance of casing strings. These results support the hypothesis that optimizing the drilling process for specific geological conditions is the key to improving safety and durability of the structure. Thus, integrating active resistance techniques into drilling practices can be an essential step towards reducing risks and improving the efficiency of operations in challenging environments.

In conclusion, the study confirmed the effectiveness of

the active resistance method as a way to increase the strength of casing strings under salt plastic flow. The obtained results open new horizons for further developments and improvements in the field of drilling and well operation technologies. Successful implementation of the proposed method requires further research and adaptation to the specific conditions of various fields, which will help to further improve the level of well safety and reliability.

Conclusions

1. The study of drilling in salt deposits has revealed significant problems associated with inelastic deformation of salt formations. This results in shrinking well diameters, loss of casing and, most dangerously, string buckling. This can result in drilling stoppages and substantial additional costs. The problem is especially acute for Turkmenistan, where large salt deposits are being developed. The need to reinforce wells both during drilling and operation is emphasized by the example of the Galkynysh field.
2. When drilling into salt deposits using any technology, equipment or drilling fluids, it is important to point out that time is the key factor in successful drilling. The rate of opening and fixing of the saline interval affects the success of subsequent drilling to the design depth without complications, as well as the further operation of the well. The correct execution of these operations can increase its service life by more than 10 years.
3. To solve this problem, an approach involving the application of the «active resistance method» is proposed. This method is based on creating internal pressure in the casing strings that exceeds the rock pressure, which helps to prevent their deformation. The method involves using two casing strings and pressurizing them through drilling mud with special properties. This method can be used in fields with sections of chemogenic sediments to increase the long-term reliability of the casing strings and extend the service life of the wells. In the future, this method of fastening, after additional research, can be applied even in the presence of elastic clay-like deposits in the cross-section of the well, prone to inelastic deformations that lead to the destruction of the casing.
4. The results of the study confirm the effectiveness of this method in conditions of plastic flow of salt deposits. The importance of the development and application of non-traditional methods of well strengthening is obvious to ensure the safety and durability of drilling operations in difficult geological conditions.
5. One of the limitations of the study is the insufficient availability of field data on real well operation conditions, which may limit the accuracy of modelling and generalization of results. It is necessary to further investigate the mechanisms of interaction of different types of salts with casing strings and their influence on string deformation at high temperatures and pressure during well operation.

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