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DETERMINATION OF THE REQUIRED SEALING INTERVAL LENGTH IN TECHNOLOGICAL WELLS USING BENTONITE SLEEVES

Introduction. *In-situ recovery (ISR) is widely used for the extraction of uranium and other mineral resources. Maintaining the integrity of the productive horizon and preventing the migration of leaching solutions and radioactive substances are essential for environmental protection and the safe operation of technological wells.*

Problem Statement. *Conventional well-sealing methods are limited in terms of efficiency, durability, and cost. Their major drawbacks include incomplete filling of fractures and voids, erosion of sealing materials, lengthy installation procedures, and the risk of casing damage, particularly in deep and deviated wells.*

Purpose. *This study aims to develop a new technology for sealing the annular space using bentonite sleeves and to substantiate a theoretical method for evaluating the mechanical strength of the sealing assembly.*

Materials and Methods. *The study is based on geological and technical data from technological wells and on the physical and mechanical properties of bentonite sleeves, casing strings, and drilling fluids. The research methodology includes a review of the scientific literature and patent sources, analysis of field applications of the proposed technology, and calculation of the shear stress acting on the bentonite sealing assembly under external loading.*

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Results. *A novel well-sealing assembly based on a system of bentonite sleeves has been developed. The proposed analytical approach has demonstrated that the resulting shear stress remains significantly below the allowable limit over a wide range of installation depths, sealing interval lengths, and formation pressures. Functional relationships describing the effects of installation depth, sealing interval length, and formation pressure on the loading conditions of the sealing assembly have been established. The influence of the principal operational parameters on the shear stress within the waterproofing assembly has also been determined.*

Conclusions. *The proposed sealing assembly provides reliable isolation of the productive horizon even at considerable installation depths and elevated formation pressures. The developed calculation method makes it possible to determine the minimum required sealing interval length as a function of installation depth and formation pressure, thereby ensuring an adequate safety margin while minimizing material consumption and reducing sealing costs.*

Keywords: well sealing, in-situ recovery, bentonite sleeves, sealing interval length.

In-situ recovery (ISR) mining is a selective extraction method in which the valuable mineral component (e.g., uranium) is dissolved directly within the ore body through the controlled circulation of a leaching solution. The dissolved mineral is subsequently recovered as a pregnant leach solution and pumped to the surface for further processing (Fig. 1) [1].

The type of leaching solution used for in-situ recovery depends on the mineralogical composition of the ore. Aqueous solutions of sulfuric, hydrochloric, and nitric acids with a pH of 0.1—1.5 are most commonly used [2, 3].

The implementation of in-situ recovery mining requires reliable sealing of the annular space between the casing strings of injection and production wells.

Well sealing in uranium ISR operations comprises a set of engineering measures designed to prevent the migration of drilling fluids, uranium-bearing leaching solutions, and groundwater between different hydrogeological horizons, while protecting the surrounding environment from contamination.

Conventionally, the annular space is sealed by forming a cement sheath within the designated interval. This is achieved by pumping a cement slurry with a density of at least 1.8 g/cm^3 through a plain tubing string positioned in the annular space between the casing and the borehole wall [4, 5]. After the cement has hardened, the quality of cementing and the location of the cement plug are verified using geophysical logging methods. As a final step, the annular space above the cement plug is filled with gel cement having a density of at least 1600 kg/m^3 [6].

The conventional sealing technology has several significant limitations:

- a high risk of incomplete placement of the sealing slurry within the annular space, particularly in deep and highly deviated wells [7];
- the formation of stagnant zones of sealing slurry where the casing comes into contact with the borehole wall [8];
- considerable time required for slurry preparation, well flushing, running an additional tubing string, and cementing operations;
- a high risk of casing damage, especially at sections with pronounced curvature or threaded connections [9].

In uranium in-situ recovery operations, maintaining complete hydraulic isolation of the wellbore and casing strings is particularly important because any loss of integrity may result in the migration of leaching reagents and radioactive substances beyond the productive horizon. The effectiveness of well-sealing operations depends directly on the selected sealing technology, which must account for the geological and hydrogeological conditions of the deposit, the physicochemical properties of the surrounding rocks, and the operating conditions of the well [10].

The principal technologies used for sealing technological wells include cementing, polymer-based

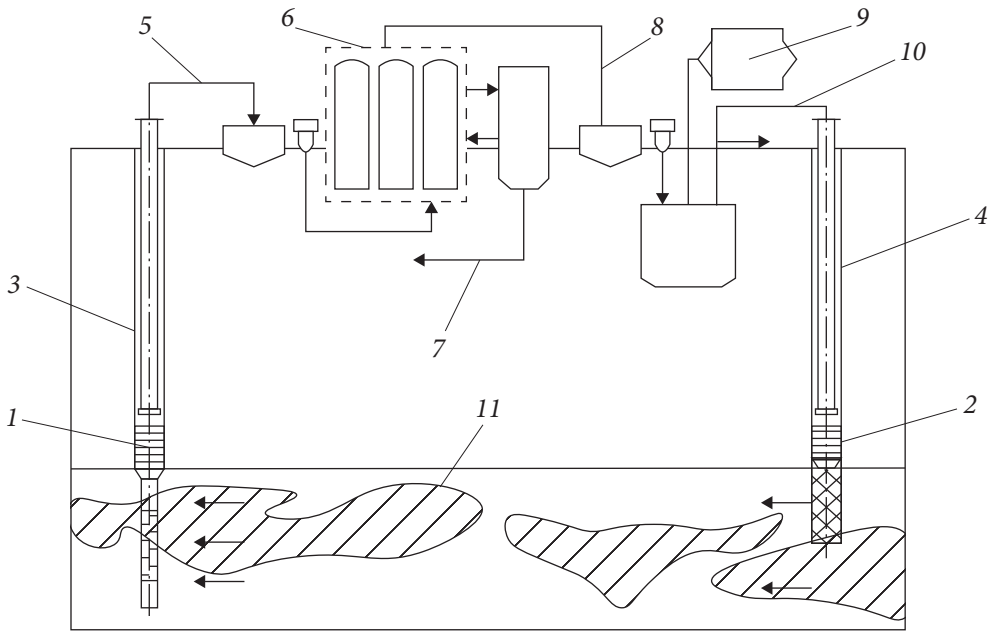


Fig. 1. Schematic process diagram of in-situ recovery (ISR): *1, 2* — packers; *3* — production well; *4* — injection well; *5* — pregnant leach solution; *6* — metal recovery unit; *7* — metal concentrate; *8* — leaching solution; *9* — leaching solution concentration unit; *10* — injection of leaching solution into the well; *11* — ore being leached

sealing systems, bentonite- and clay-based materials, and physicochemical methods involving the injection of silicate-, acrylate-, and other polymerizable solutions [11—13]. Cementing, which involves pumping cement slurry into the annular space or into damaged sections of the casing, remains the most widely used and cost-effective method because it provides a high-strength sealing barrier. However, this technology may lose sealing integrity under thermal or chemical exposure and often fails to achieve complete filling of fractures and voids within the surrounding rock mass [14].

Polymer-based sealing materials exhibit high fluidity, allowing them to penetrate microfractures and pore spaces effectively, while also providing excellent resistance to the aggressive chemical environments associated with in-situ recovery operations [15, 16]. Nevertheless, their widespread application is limited by their relatively high cost and the need for strict control of the preparation and injection procedures [17].

Bentonite- and clay-based materials are primarily used to create low-permeability sealing barriers. They are environmentally benign and inexpensive; however, prolonged exposure to aggressive leaching solutions may result in erosion, swelling-induced deformation, or degradation of their sealing performance [18].

Physicochemical sealing methods, which involve treating the formation with reagents that induce coagulation or gel formation within the pore space, make it possible to isolate even fine-grained and highly fractured formations [19, 20]. Their principal advantages include a high penetration capacity and the ability to seal localized problem zones without major well rehabilitation [21]. However, these methods require specialized equipment, strict control of the chemical processes, and often provide only a temporary sealing effect [22, 23]. Consequently, the selection of a well-sealing technology should be based on a comprehensive assessment of the hydrogeological conditions, the chemical

composition of the leaching solution, the condition of the casing strings, and the expected service life of the well in order to ensure long-term protection of groundwater and the surrounding environment during uranium extraction.

Reference [2] shows that the sealing integrity of technological wells used for ISR operations begins with appropriate well design. Essential measures include the use of double casing strings, continuous cementing to the surface, verification of cement quality by cement bond logging and acoustic or radiometric logging, and pressure testing before the well is placed into operation. The study also identifies channeling along the casing caused by inadequate cement bonding and corrosion-induced degradation of the casing as major integrity risks. These findings highlight the importance of selecting corrosion-resistant casing materials and performing periodic inspections of both the cement sheath and casing barriers throughout the well life cycle.

The review presented in [24] identifies unintended fluid migration beyond the productive horizon through high-permeability pathways and anthropogenic conduits — primarily along wellbores and the annular space — as the principal threat to well integrity during ISR operations. The authors propose a multi-barrier protection strategy that combines proper well design and cementing, controlled hydraulic depression in production wells to maintain inward groundwater flow, a dense network of monitoring wells, and regular chemical and hydraulic monitoring. The study also demonstrates that detailed hydrogeological characterization and verification of the confining formations above and below the productive horizon are critical for preventing interformational fluid migration.

Reference [25] demonstrates that isotopic and geochemical tracers can be used to evaluate the natural reducing capacity of the host formation and, consequently, the effectiveness of the natural geochemical barrier that complements engineered well sealing. The authors apply uranium isotopes and sulfur tracers within a network of production and monitoring wells to identify zones where residual reducing agents decrease the mobility of U(VI). This approach enables more accurate optimization of the operating regime and local well configuration, thereby improving active hydraulic containment during ISR operations.

Reference [26] demonstrates that stable reducing barriers are formed along the mineralization front, effectively retaining uranium in its reduced oxidation state. From the perspective of well sealing, this finding implies that production intervals and perforations should be positioned so as not to disturb or penetrate these natural barriers. Their presence should also be considered when designing the configuration of injection and production wells in order to minimize the risk of leaching solution migration beyond the target zone.

A study of drill core samples and solid-phase materials collected after ISR operations [27] reveals the coexistence of U(IV) and U(VI) and identifies iron sulfide and organic phases as local sorption-reduction traps. These findings are important for selecting sealing and plugging materials during well abandonment and decommissioning. The chemical compatibility of cement-based sealing systems with reducing mineral assemblages decreases the risk of secondary uranium remobilization during well intervention and closure operations.

Field investigations conducted at a uranium mining site [28] demonstrate that the containment of leaching solutions is governed not only by hydraulic pressure but also by sorption-desorption kinetics and hydrodynamic dispersion. These results indicate that reliable hydraulic isolation requires maintaining a stable negative hydraulic pressure gradient while avoiding operating conditions that generate rapid pressure fluctuations. In practice, this requires controlling production-rate variations, implementing automated pressure management systems to maintain hydraulic depression, and establishing a sufficiently dense monitoring network capable of detecting migrating solution fronts at an early stage.

A comprehensive review of sealing technologies for horizontal wells is presented in [13]. The authors classify existing methods into mechanical and chemical approaches, describe their applicability to

different well completion systems, and emphasize the need to combine multiple technologies under complex geological conditions. This review highlights the fundamental distinction between methods designed to restrict fluid flow through the wellbore and those intended to isolate specific formation intervals.

An innovative chemical sealing approach is presented in [29], where nanoscale silica is proposed as the basis for advanced sealing systems. Experimental studies have demonstrated the effectiveness of this material in reducing water inflow in a wide range of reservoir types, including fractured formations.

Consequently, nanotechnology has emerged as a promising direction for the development of advanced materials for well-sealing and waterproofing applications [30, 31].

Cementing remains a key component of well sealing because it ensures the long-term structural integrity of the well. An example of the application of self-healing cement systems is presented in [32]. This technology is designed to eliminate microcracks within the cement sheath, thereby improving the long-term durability of the sealing barrier and reducing the risk of inter-annular fluid migration. A similar objective is addressed in [33], where the authors optimize the pore-permeability characteristics of cement stone. They propose a methodology for selecting the porosity and permeability parameters of cement systems to ensure reliable sealing performance in underground gas storage facilities.

Particular attention should be given to sealing performance under extreme operating conditions. Reference [34] investigates the mechanisms responsible for cement sheath degradation in geothermal wells subjected to cyclic thermal and mechanical loading. The proposed model predicts defect development and provides a basis for optimizing cement formulations for such environments. Similarly, [35] examines the integrity of cement sheaths in high-temperature, high-pressure gas wells and proposes measures to reduce thermally induced stresses and improve wellhead pressure control in order to preserve long-term sealing performance.

An innovative engineering solution is presented in [36], where a specialized drainage sealing device has been developed for operation under elevated temperatures and pressures.

The problem of maintaining well integrity in carbon dioxide storage projects is investigated in [37]. The authors have demonstrated that incorporating a protective layer during cementing significantly increases the mechanical strength of the cement sheath and reduces the likelihood of pressure-induced failure. This approach is particularly relevant in view of the growing importance of carbon capture and geological storage technologies.

Water shutoff by means of a thermally activated mixture consisting of a gelation initiator and a gel-forming agent is described in [38]. This technology enables precise control of the gelation process by adjusting the temperature-dependent setting time, allowing the sealing composition to be delivered to the required formation depth before gelation occurs.

Reference [39] proposes a new technology for sealing the bottomhole zone of production wells using novel sealing materials based on sodium silicate and microcement. The proposed system has been shown to significantly reduce the water cut of produced oil.

Despite the wide range of technologies developed for well sealing, the existing literature and patent sources primarily focus on the design of sealing assemblies, the sequence of installation operations, and field performance. In contrast, the quantitative evaluation of the mechanical behavior of sealing assemblies has received comparatively little attention.

In particular, no generalized analytical approach is currently available that makes it possible to:

- quantitatively determine the shear stress acting on a sealing assembly as a result of its interaction with the casing string and the borehole wall;
- evaluate the effects of installation depth, sealing interval length, and formation pressure on the resulting mechanical stresses; and
- determine the minimum required sealing interval length on the basis of mechanical strength criteria rather than empirical recommendations.

As a consequence, the sealing interval adopted in engineering practice is frequently selected with a substantial safety margin, resulting in unnecessary material consumption, or, conversely, without sufficient engineering justification, thereby reducing the reliability of productive horizon isolation, particularly in soft or fractured formations and at greater installation depths.

Therefore, an unresolved problem remains: the development of a quantitative analytical method capable of establishing the relationship between the geometric parameters of a sealing assembly, the geological and hydrogeological conditions, and the shear stress governing its mechanical stability during well operation.

The objective of this study is to develop a new annular sealing technology for ISR wells based on bentonite sleeves and to establish an analytical approach for evaluating the mechanical integrity of the sealing assembly. The proposed method quantitatively determines the shear stress generated by the combined action of drilling-fluid hydrostatic pressure and formation pressure and establishes the relationships among shear stress, installation depth, sealing interval length, and formation pressure. These relationships provide a rational basis for selecting the design parameters of well-sealing systems used in in-situ recovery operations.

The study is based on geological and technical data obtained from technological wells constructed for in-situ recovery (ISR) mining, including information on casing design, productive horizon characteristics, and well operating conditions. The analysis also incorporates field data from the industrial application of a well-sealing technology based on bentonite sleeves, as documented in geological and technical records and operational reports.

The physical and mechanical properties of the bentonite sleeves, casing strings, and drilling fluids are adopted from reference data, laboratory test results, and values reported in the scientific literature and patent sources. The geometric parameters of the wells and the sealing assembly, including casing diameter, borehole diameter, and bentonite sleeve interval length, correspond to those typically used in the construction of geotechnological wells.

The methodological framework is based on a critical review of scientific publications and patent literature addressing well-sealing technologies in order to identify existing approaches, their limitations, and unresolved research problems. Particular attention is given to the application of bentonite-based materials for sealing the annular space.

The performance of the proposed sealing assembly is evaluated by means of an engineering analysis of the shear stress developed within the bentonite sleeve assembly under external loading. The analytical model is derived from the force equilibrium equation and accounts for the hydrostatic pressure of the drilling fluid, the formation pressure, and the self-weight of the sealing assembly. The interaction between the bentonite sleeves, the casing string, and the borehole wall is analyzed using an axisymmetric model under the assumption of strong adhesion, which reflects the operating conditions after bentonite hydration and swelling.

The proposed analytical approach is based on several assumptions consistent with the objectives of the study. In particular, the interaction between the bentonite sleeves, the casing string, and the borehole wall is considered within an axisymmetric loading scheme that accounts for the dominant loading factors, namely the hydrostatic pressure of the drilling fluid, the formation pressure, and the self-weight of the sealing assembly. This simplification is appropriate for the preliminary evaluation of the mechanical integrity of the well-sealing assembly and for assessing the influence of its geometric parameters and installation depth, which are the principal objectives of engineering design for technological wells. A more comprehensive analysis incorporating the rheological behavior of the surrounding media and the heterogeneity of the geological formation remains a subject for future research.

To comply with environmental and sanitary regulations, the construction technology and operational monitoring of technological wells must ensure complete hydraulic isolation of the productive

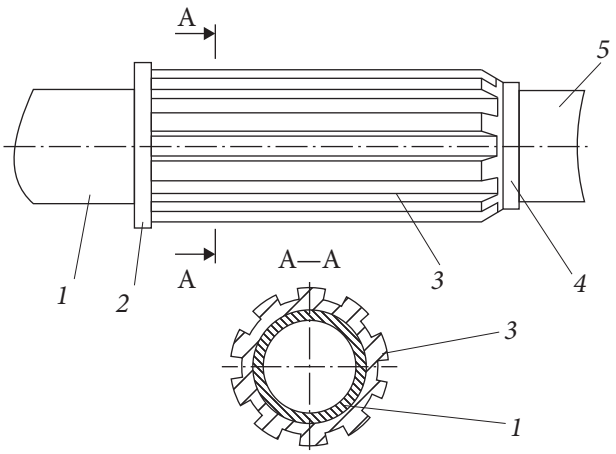


Fig. 2. Configuration of the casing string for sealing the productive horizon: *1* — casing pipe; *2* — upper clamp; *3* — bentonite sleeve with external splines; *4* — lower polypropylene petal clamp; *5* — screen (filter) section

horizon. To address this requirement, a new annular sealing technology has been developed by JSC Volkovgeologiya.

The proposed technology is based on a new sealing element consisting of a series of bentonite sleeves. The sleeves are attached to the drill string by special clamps and lowered to the designated sealing interval. Upon contact with the water phase of the drilling fluid, the bentonite undergoes hydration, resulting in a several-fold increase in volume relative to its dry state. To improve mechanical strength, each sleeve is manufactured as a multilayer structure. As the sleeves swell, their rough, ribbed outer surface forms a strong bond with both the casing string and the borehole wall, creating a dense and reliable hydraulic seal around the productive formation.

Before installation, the casing string (Fig. 2) is equipped with the following components: a filter of the required design, a lower polypropylene petal-type clamp that protects the bentonite sleeves from mechanical damage, a set of bentonite sleeves secured individually with construction foam, and an upper steel clamp that fixes the sleeve assembly in place. Experimental testing of the assembled casing system has shown that the swelling time of the bentonite sleeves is approximately 20 h in drilling fluid and 16 h in water, representing a reduction of about 25%. After 16 h of hydration in water, the bentonite assembly has reached approximately 80% of its ultimate swelling capacity. Extensive field testing of the proposed well-sealing technology has confirmed the effectiveness of bentonite sleeves for isolating productive formations [40].

The effectiveness of the proposed sealing technology has been confirmed through the successful operation of more than 200 technological wells in which it has been implemented [41].

However, one important engineering issue remains unresolved: the minimum number of bentonite sleeves required along the casing string to ensure reliable hydraulic isolation of the productive horizon from the overlying geological formations while minimizing the cost of manufacturing and installing the sealing assembly. This issue is of considerable practical importance because well-sealing operations account for a substantial portion of the total cost of constructing technological wells.

Despite the positive field performance of the bentonite sleeve technology, the geological service of JSC Volkovgeologiya has proposed increasing the sealing interval from 10 m to 40 m. This recommendation is based on concerns that a 10 m sealing interval may not provide sufficient isolation in weak or poorly consolidated formations. However, such an increase would substantially raise the cost of well-sealing operations. Therefore, before extending the sealing interval, it is advisable to develop a theoretical model capable of evaluating the mechanical integrity of the currently adopted 10 m sealing assembly.

A detailed analysis of the field implementation of the proposed technology, based on geological and technical records and its application at the Khorasan 1 uranium mine, indicates that the bentonite sleeve assembly is typically installed over a total interval of approximately 10 m at depths of 500—510 m within clayey siltstone formations. The porosity and fracture characteristics of the

host rocks are not reported in the available documentation. Because these parameters directly influence sealing performance, they should be included in future geological and technical records and considered when determining the required length of the bentonite sealing interval.

A schematic representation of the proposed sealing system is shown in Fig. 3. The figure illustrates the casing string, the production tubing used to recover the pregnant leach solution, and the bentonite sleeve assembly, which forms a hydraulic seal between the casing and the borehole wall, thereby isolating the productive formation from the surrounding geological strata.

The well-sealing assembly installed at a depth of H is subjected to the hydrostatic pressure exerted by the drilling fluid column acting on the upper annular surface bounded by diameters d and D. The drilling fluid has a density of 1200 kg/m^3, and the corresponding hydrostatic pressure is denoted by P_1. From below, the lower annular surface of the sealing assembly, defined by the same diameters d and D, is subjected to the formation pressure P_2, together with the self-weight of the sealing assembly. Under the action of these loads, the well-sealing assembly is subjected to shear loading due to the forces T_{sf1} and T_{sf2} acting at the contact with the casing string of diameter d and with the borehole wall of diameter D.

Based on these loading conditions, the force equilibrium equation for the sealing assembly has been derived as follows:

$$\rho_f g\mathrm{H}\frac{\pi(D^2-d^2)}{4}+\rho_{bent}gL\frac{\pi(D^2-d^2)}{4}-$$
$$-\sigma_{ss1}\pi dL-\sigma_{ss2}\pi DL=P_2\frac{\pi(D^2-d^2)}{4}, \qquad (1)$$

where ρ_f is the drilling fluid density; g is the gravitational acceleration; H is the installation depth of the well-sealing assembly (i.e., the height of the drilling fluid column above the sealing assembly); ρ_{bent} is the density of the sealing assembly; L is the total length of the bentonite sleeve assembly; P_1 is the hydrostatic pressure of the drilling fluid; P_2 is the formation pressure; σ_{ss1}, σ_{ss2} are the allowable shear stresses acting at the interface between the sealing assembly and the casing string of diameter d and at the interface between the sealing assembly and the borehole wall of diameter D, respectively; for the present analysis, $\sigma_{ss1} = \sigma_{ss2} \approx$ $\approx$ 2.1 MPa has been assumed [42, 43], and the interaction between the bentonite sleeves and the casing string has been considered to represent perfect adhesion.

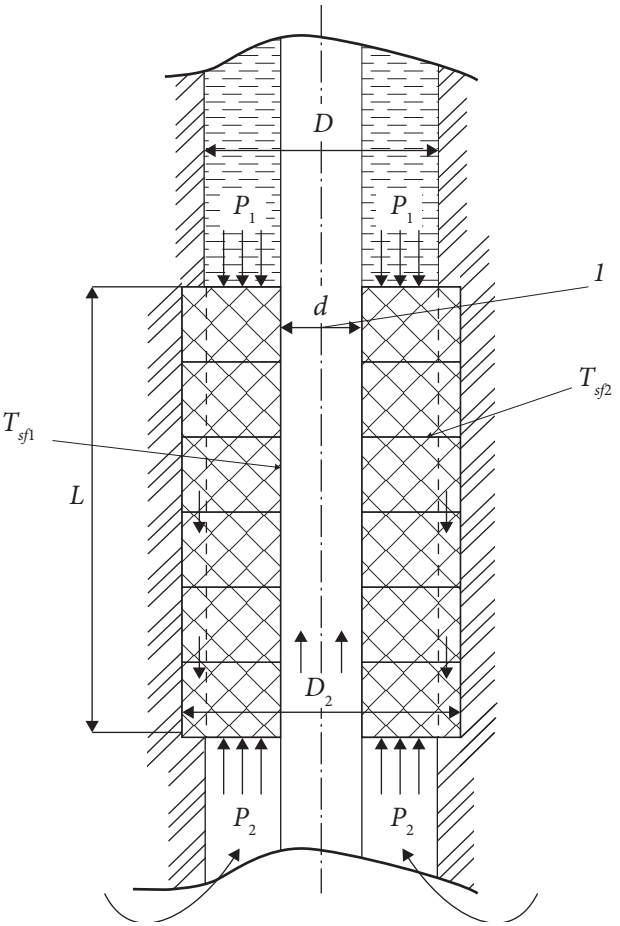


Fig. 3. Schematic of productive horizon sealing using bentonite sleeves: d — casing pipe diameter; D — borehole diameter; D_2 — diameter of the bentonite sleeves after expansion; P_1 — hydrostatic pressure of the drilling fluid; P_2 — formation pressure acting from the productive horizon; L — length of the bentonite sleeve assembly; T_{sf1}, T_{sf2} — shear forces acting under external loading

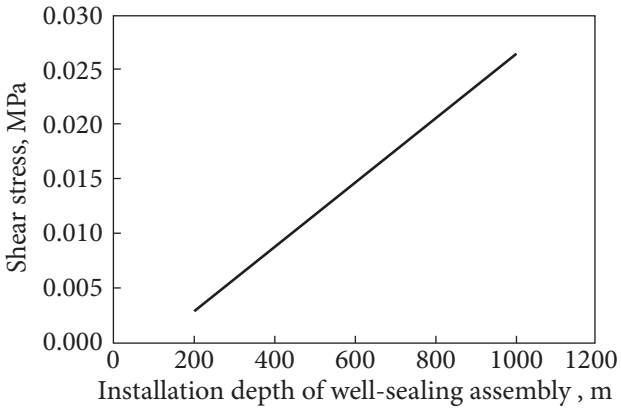


Fig. 4. Effect of the installation depth of the well-sealing assembly H on the shear stress σ_{ss}

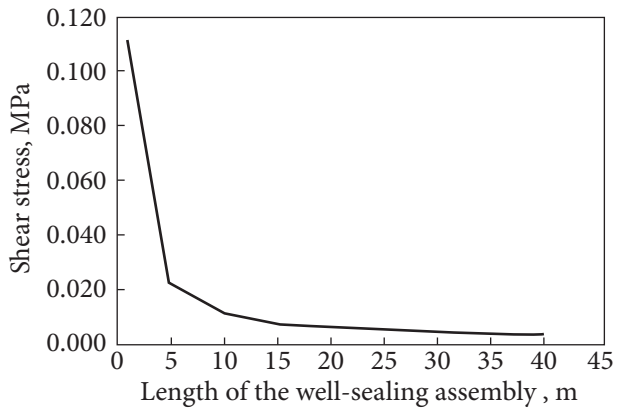


Fig. 5. Effect of the length of the well-sealing assembly L on the shear stress σ_{ss}

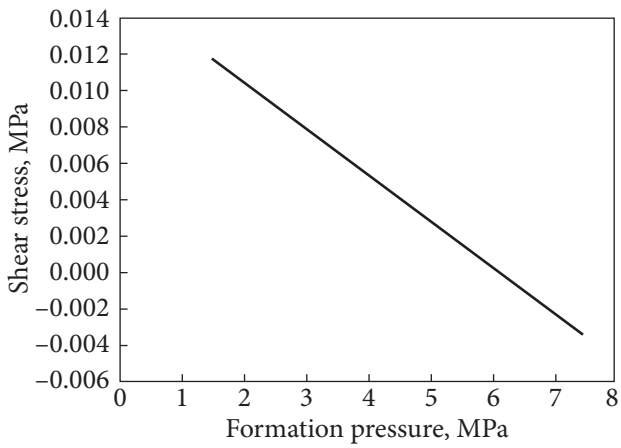


Fig. 6. Effect of the formation pressure P_2 on the shear stress σ_{ss}

From Eq. (1), the actual shear stress σ_{ss} acting at the onset of failure of the well-sealing assembly can be determined under the above assumption:

$$\sigma_{ss} = \frac{\left[\rho_f g H \frac{\pi(D^2 - d^2)}{4} + \rho_{bent} g L \frac{\pi(D^2 - d^2)}{4} - P_2 \frac{\pi(D^2 - d^2)}{4}\right]}{\pi L (D + d)}. \quad (2)$$

Let us calculate the shear stress using the following input data, which are the most representative of the drilling conditions for in-situ uranium recovery (ISR) wells in Kazakhstan [3]: $\rho_f = 1200$ kg/m^3; $D = 0.191$ m; $d = 0.09$ m; $g = 9.8$ m/s^2, $\rho_{bent} = 2800$ kg/m^3; $P_2 = 1.5$ MPa; $H = 500$ m; $L = 10$ m.

Substituting the above data into Eq. (2), we obtain as follows:

$$\sigma_{ss} = \frac{\left[\begin{array}{c} 1200 \cdot 9.8 \cdot 0.785 \cdot (0.191^2 - 0.09^2) \cdot 500 + \\ + 2800 \cdot 9.8 \cdot 0.785 \cdot (0.191^2 - 0.09^2) \cdot 10 - \\ - 0.785 \cdot (0.191^2 - 0.09^2) \cdot 1.5 \cdot 10^6 \end{array}\right]}{3.14 \cdot 10 \cdot (0.191^2 - 0.09^2} = 0.012 \text{ MPa}.$$

The calculated value has been substantially lower than the allowable shear strength, $\sigma_{ss} \approx \approx 2.1$ MPa.

Therefore, the recommendation of the geological service to increase the length of the well-sealing assembly to 40 m "as a precaution" has not been supported by the strength analysis and cannot be considered technically justified.

To evaluate the applicability of the proposed well-sealing assembly under more demanding geological conditions, the effects of the installation depth, H, the sealing interval length, L, and the formation pressure, P_2, have been investigated. An increase in these parameters is expected to result in higher shear stress, σ_{ss}, acting within the well-sealing assembly.

For convenience, the coefficients associated with H, L, and P_2 have been calculated while assuming the same casing dimensions and dril-

ling fluid properties as those adopted in the previous analysis:

$$1200 \cdot 9.8 \cdot 0.785 \cdot (0.191^2 - 0.09^2) = 262;$$

$$2800 \cdot 9.8 \cdot 0.785 \cdot (0.191^2 - 0.09^2) = 611.3;$$

$$0.785 \cdot (0.191^2 - 0.09^2) = 0.0223;$$

$$3.14 \cdot (0.191 + 0.09) = 0.882.$$

As a result, Eq. (2) under the given conditions is written as follows:

$$\sigma_{ss} = \frac{262H + 611.3L - 0.0223P_2}{0.882L}. \qquad (3)$$

Influence of H, L, and P_2 on the shear stress σ_{ss} in Eq. (3) is presented in Table 1 and Figs. 4—6.

As shown in Fig. 4, the shear stress increases almost linearly with the installation depth of the well-sealing assembly. This relationship is explained by the increase in the height of the drilling fluid column above the sealing assembly, which results in a corresponding increase in hydrostatic pressure acting on the assembly.

As the length of the well-sealing assembly, L, increases, the shear stress, σ_{ss}, decreases (Fig. 5). The most pronounced reduction has occurred as the assembly length increases to approximately 10 m. Beyond this value, further increasing the length of the well-sealing assembly reduces the shear stress only marginally.

As shown in Fig. 6, the shear stress, σ_{ss}, decreases almost linearly with increasing formation pressure, P_2. This behavior is explained by the formation pressure acts in the direction opposite to the hydrostatic pressure of the drilling fluid. At a certain value of P_2, these two pressures become balanced, and the shear stress reaches zero. With a further increase in formation pressure, σ_{ss} becomes negative, indicating that the resultant force acting on the well-sealing assembly reverses its direction and is directed upward.

The calculated results have indicated that the proposed sealing assembly based on bentonite sleeves possesses a substantial safety margin with respect to the external loads associated with installation depth and formation pressure. Therefore, the proposed sealing system can be applied at greater installation depths and under higher formation pressures without compromising its mechanical integrity.

The proposed method for determining the required sealing interval offers several important advantages. It is based on an analytical evaluation of the shear stress developed at the interface between the sealing assembly and the borehole wall, thereby establishing a direct relationship between the mechanical strength of the sealing system and its geometric parameters, installation depth, and formation pressure. Unlike existing empirical and semi-empirical approaches, which generally neglect the effects of well depth and variations in formation pressure, the proposed model enables the mechanical behavior of the sealing assembly to be evaluated under realistic geological and operational loading conditions. The resulting analytical relationships

Table 1. **Calculated Shear Stresses σ_{ss} for Different Values of H, P_2, and L in Eq. (3)**

Installation depth of the well-sealing assembly H, m	Length of the well-sealing assembly L, m	Formation pressure P_2, MPa	Shear stress σ_{ss}, MPa
200	10	1.5	0.003
400			0.009
600			0.015
800			0.021
1000			0.027
500	1	1.5	0.111
	5		0.023
	10		0.012
	15		0.008
	20		0.006
	25		0.005
	30		0.004
	35		0.004
	40		0.003
500	10	1.5	0.012
		3.0	0.008
		4.5	0.004
		6.0	0.000
		7.5	–0.003

can be used not only to assess the performance of the sealing assembly but also as an engineering tool for its preliminary design and optimization.

The proposed analytical expression enables the shear stress to be calculated directly for specified values of well depth, sealing interval length, and formation pressure without the introduction of additional empirical correction factors. The parametric analysis has demonstrated the feasibility of quantitatively evaluating the influence of each governing parameter — installation depth, sealing interval length, and formation pressure — on the resulting shear stress. Such capability is generally absent from existing design approaches. The derived relationships define the range of design parameters that ensures the mechanical stability of the sealing assembly and therefore provide a practical basis for selecting optimal engineering solutions.

The present study has developed a mechanical model of the proposed sealing system and has established an analytical procedure for evaluating the strength of a bentonite sleeve sealing assembly intended for geotechnological wells.

The study has also reviewed the existing well-sealing technologies and has examined in detail the proposed method for isolating the productive horizon from the overlying geological formations. The analysis has shown that hydraulic isolation using bentonite sleeves offers significant advantages over conventional sealing methods.

Field experience has demonstrated that a sealing interval of 10 m is sufficient to provide reliable isolation of the productive horizon under typical operating conditions. This conclusion has been supported by the strength analysis of the sealing assembly under the expected service loads. However, when the productive horizon is located within highly fractured or porous formations, an appropriate correction factor should be incorporated into the design calculations to determine the required sealing interval length.

The theoretical analysis and field implementation have demonstrated that the proposed well-sealing technology provides reliable hydraulic isolation of the productive horizon. Its effectiveness increases as the degree of fracturing within the isolated geological interval decreases. The results have also confirmed that a total bentonite sleeve length of 10 m is sufficient to ensure effective sealing under the investigated operating conditions. Furthermore, the analytical calculations have shown that the sealing interval currently adopted in field practice substantially exceeds the minimum length required to maintain the mechanical integrity of the sealing assembly.

The study has established the relationships between the principal operating parameters and the shear stress acting on the sealing assembly. As the installation depth increases, the shear stress increases almost linearly because of the corresponding increase in the hydrostatic pressure of the drilling fluid. Conversely, increasing the length of the sealing assembly reduces the shear stress, with the most pronounced reduction occurring for sealing intervals up to approximately 10 m; beyond this value, further increases in length provide only marginal improvement. An increase in formation pressure decreases the shear stress because it counteracts the hydrostatic pressure exerted by the drilling fluid.

The proposed analytical method enables the minimum required sealing interval length to be determined as a function of installation depth and formation pressure. This approach provides a rational basis for designing well-sealing systems that ensure the required safety margin while minimizing material consumption and associated costs.

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ВИЗНАЧЕННЯ НЕОБХІДНОЇ ДОВЖИНИ ГІДРОІЗОЛЯЦІЇ ТЕХНОЛОГІЧНИХ СВЕРДЛОВИН З ВИКОРИСТАННЯМ БЕНТОНІТОВИХ ГІЛЬЗ

Вступ. Метод підземного вилуговування широко застосовується для видобутку урану та інших корисних копалин. Забезпечення цілісності продуктивного горизонту й запобігання міграції промивальних рідин і радіоактивних речовин є критично важливим як для охорони довкілля, так і для безпеки експлуатації свердловин.

Проблематика. Традиційні методи гідроізоляції свердловин мають обмеження щодо ефективності, довговічності та вартості. Проблемами є неповне заповнення тріщин, можливість розмиву матеріалів, тривалий час підготовки та ризик пошкодження обсадних колон, особливо у глибоких та викривлених свердловинах.

Мета. Розробка нової технології гідроізоляції затрубного простору з використанням бентонітових гільз і обґрунтування теоретичного методу розрахунку на міцність гідроізоляційного вузла.

Матеріали й методи. Матеріалами слугували геолого-технічні дані свердловин, фізико-механічні характеристики бентонітових гільз, обсадних колон і промивальних рідин. Застосовано методи критичного аналізу літературних та патентних джерел, аналізу практики застосування технології на свердловинах, виконано розрахунок напруги на міцність бентонітових гільз під впливом зовнішніх навантажень.

Результати. Запропоновано конструкцію гідроізоляційного вузла з набором бентонітових гільз. Розрахунки показали, що напруга на зріз значно нижча за допустиму, навіть при зміні глибини установки, довжини гільз і пластового тиску. Встановлено залежності навантажень на гідроізоляційний вузол від глибини його встановлення, довжини вузла і пластового тиску, а також закономірності впливу основних експлуатаційних параметрів на напругу на зріз гідроізоляційного вузла.

Висновки. Розроблена конструкція гідроізоляційного вузла забезпечує надійну гідроізоляцію продуктивного пласта навіть при великих глибинах та підвищених пластових тисках. Запропонований метод розрахунку дозволяє обґрунтовано визначати мінімально необхідну довжину гідроізоляційного вузла залежно від глибини його встановлення та пластового тиску, що забезпечує необхідний запас міцності при мінімальних матеріальних витратах.

Ключові слова: гідроізоляція, підземне вилуговування, бентонітові гільзи, довжина гідроізоляції.