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Methods of Improving Operational Reliability of Oil Well Casing

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Oil well casing leak is caused by contact of casing outer surface with formation electrolyte. It is usually associated with an aquifer with a high salt content or absence of a cement ring behind the casing. The only way to reduce external casing corrosion is through cathodic protection. Through cathodic polarization of casing structure, electron content in crystal lattice and electron density will increase, leading to a potential shift towards the cathodic region. At Tatneft enterprises, cathodic protection is carried out according to cluster and individual schemes. The main criterion for cathodic protection is the size of protective current. For a casing, the protective current is considered sufficient if measurements with a two-contact probe show that the electric current directed to the casing has eliminated all anode sites. To determine the value of required protective current, all methods are considered in this work. In addition, an analysis of all methods used to determine the minimum protective current of the casing is provided. Results show that the method of measuring potential drop along casing is one of the most reliable methods for determining the value of protective current.

Keywords: *Corrosion, Cathodic protection, External casing, Profile of the voltage drop, Distribution of currents along the depth*

1. Introduction

1.1 External Casing Corrosion Problems and Cathodic Protection

Despite the significant reduction in oil well casing failures due to corrosion through the use of cathodic protection in oil companies, this problem remains relevant. Practical experience [1-3] indicates that the successful operation of a well depends on considering potential factors that can influence the corrosion process and determine the location of corrosion.

Oil and gas pipes, which are mostly made of low-carbon steel, are susceptible to general and localized corrosion in water environments and soils. Furthermore, general corrosion weakens the mechanical strength of the casing and can result in longitudinal discontinuities of considerable length. In addition, pitting corrosion is a localized form of corrosion that develops on the non-insulated surface against the background of general corrosion. On an insulated surface, it can lead to the formation of caverns with varying depths, up to through holes.

One of the most common causes of electrochemical corrosion of the outer wall of the casing is contact with an electrolyte [1-7]. This type of failure typically occurs in aquifers with high salinity and is characterized by a breach of the cement ring or its absence in the first sections of the column. Moreover, formation waters containing hydrogen sulfide can destroy the cement stone and subsequently cause external wall corrosion. The quality of the cement slurry and the optimal technological solution of bonding play a crucial role in initiating corrosion processes. Additionally, the kinetics of corrosion processes in areas with access to oxygen are determined by its concentration. An effective oxygen absorber is hydrazine, which is especially useful during the first 1-1.5 years after the commissioning of the well. Currently, other chemicals, such as sodium sulfite or ammonium bisulfite, are used as oxygen absorbers due to the toxic nature of hydrazine.

The activity of a corrosive environment is directly related to the soil, its nature, and its resistivity [1-8]. The heterogeneity of geological formations has been identified by some authors as a cause of well breakthroughs. Additionally, studies [1-8] have shown that observed wells operated in soils with a salt layer with a resistance of about 200 Ohm×cm between two shale formations with a resistivity of over 2000 Ohm×cm. In the first case, the soil was classified as “highly corrosive”, while in the second case, it was “moderately or slightly corrosive”.

The basis of many drilling muds is calcium or lime, to which gypsum is often added. A common additive to gypsum solutions used to be starch, which was first used in the United States of America (USA), in Texas [7]. It is a good environment for bacteria to live in, if the solution is not protected by a high salt solution or does not have a bactericidal additive. In the USA in the 80s. many wells were drilled using such starch solutions, but did not have the necessary brines. As a result, the number

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of failures was much higher in these wells compared to wells where starch was not used. The importance of the component composition of drilling muds is obvious. The author analyzed the mean time between first failures of the wells in the cluster, which were operating in one geological formation. Adding of an oxygen absorber can increase the mean time between failure of gel and gypsum-based mud systems by 30 to 50 %. The use of gypsum-based solutions with a pH greater than 9.5 can double the mean time between failure compared to wells drilled using low pH muds. Currently, there are many patented developments in the field of drilling muds, the use of which reduces the risk of such corrosion failures.

In the enterprises of the Republic Tatarstan, in particular, Public Joint Stock Company (PJSC) «Tatneft», cathodic protection, is usually carried out by pad and individual measures. If in the cathodic protection system, one of the wells is not connected to the negative pole of the rectifier, a stray current occurs, which causes the appearance of anode zones. All conductive structures located in the zone of protective currents that are not connected to the negative pole of the rectifier or have no metal connection with the protected object fall into the region of stray currents. This phenomenon is eliminated by drainage of these currents.

The authors of [1–7] described casing pipes contact corrosion cases, when metals randomly, due to the production process of rolling steel, become electrochemically inhomogeneous. During the hot rolling process, dark brown mill scale or a black oxide layer is formed. In a galvanic system, the mill scale becomes a cathode, which is deposited on the non-insulated surface of the steel pipe, from the remaining surface of which the scale is removed. The non-insulated surface of the steel pipe is susceptible to corrosion mainly from mill scale. An example of corrosion is the marking of pipe joints. This phenomenon is exacerbated by a large area of mill scale (cathode) and a small area of non-insulated steel (anode) [9,10].

Currently, there is evidence on the effect of casing material on the duration of well operation until its first failure [6].

Additionally, cathodic protection has been in use since 1913 of the twentieth century. It is the only way to actively protect pipe strings. This protection method works by cathodic polarization of the construction, which increases the electron number in the crystal lattice. This results in an increase in electron density, causing a shift of the potential to the cathode region. The metal's electron density increase prevents the transformation of its atoms into positively charged ions that transfer into solution or corrosion products that remain on the surface. Consequently, the anode ionization reaction of the metal becomes complex [4].

1.2 Evaluation of the reliability characteristics of the cathodic protection system of oil casing strings

As of Jan.01.2018, the cathodic coverage of production wells at PJSC «Tatneft» amounted to 39.4%, and injection wells - 29.2%. The dynamics of the wells' cathodic protection equipment for the period 2000-2016 is shown in Fig. 1.

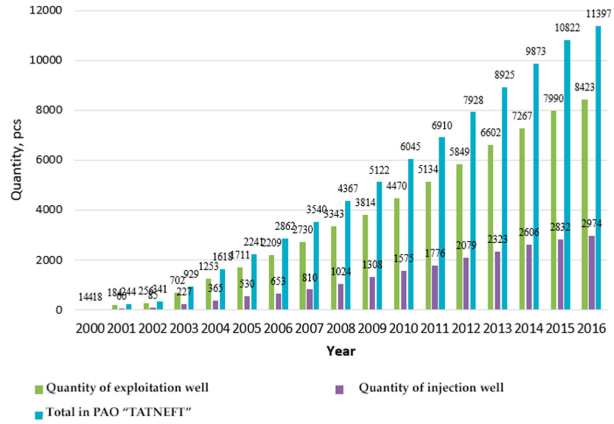


Fig. 1. Dynamics of well equipment with cathodic protection on the territory of PJSC «TATNEFT» for the period 2000-2016

The collection and systematization of field information related to the number of wells in operation, their age, the number of repairs and the frequency of failures (period 2003-2015), allowed us carry out a statistical analysis that allows us to evaluate the effectiveness of the protective measures. The objects of study were the production and injection wells PJSC «Tatneft» in the context of Oil and Gas Production Department (OGPD) (Aznakaevskneft - AzN, Almetyevneft - AN, Bavlyneft - BN, Dzhalilneft – DzN, Elkhovneft – EN, Leninogorskneft - LN, Nurlatneft - NN, Prikamneft - PN, Yamashneft - YAN). Wells with and without cathodic protection, broken down by age: 0 - 5 years; 6-10; 11-15, 16-20; 21 - 25; 26-30; >31 years old.

A criterion for the effectiveness of cathodic protection is to reduce failures of casing strings (Fig. 2). The experimental data are approximated by corresponding curves indicating the confidence coefficient of the selected trend model with the initial data.

Analyzing the obtained dependences, we can conclude that the cathodic protection for injection wells has a significant effect on wells with a life of up to 25 years. The decrease in the effect of protection for this type of well older than 25 years is apparently due to the increased influence of internal corrosion processes, which the cathodic protection does not affect. For producing wells critical age limit of failure is 26-30 years, which, most likely, due to the aging of cement stone. As expected, the youngest wells are least affected by corrosion - with a lifetime of up to 5 years. The same equivalent number of failures in this age group of wells with and without cathodic protection is associated with the rise of the cement ring to the wellhead and the use of modern cement slurries.

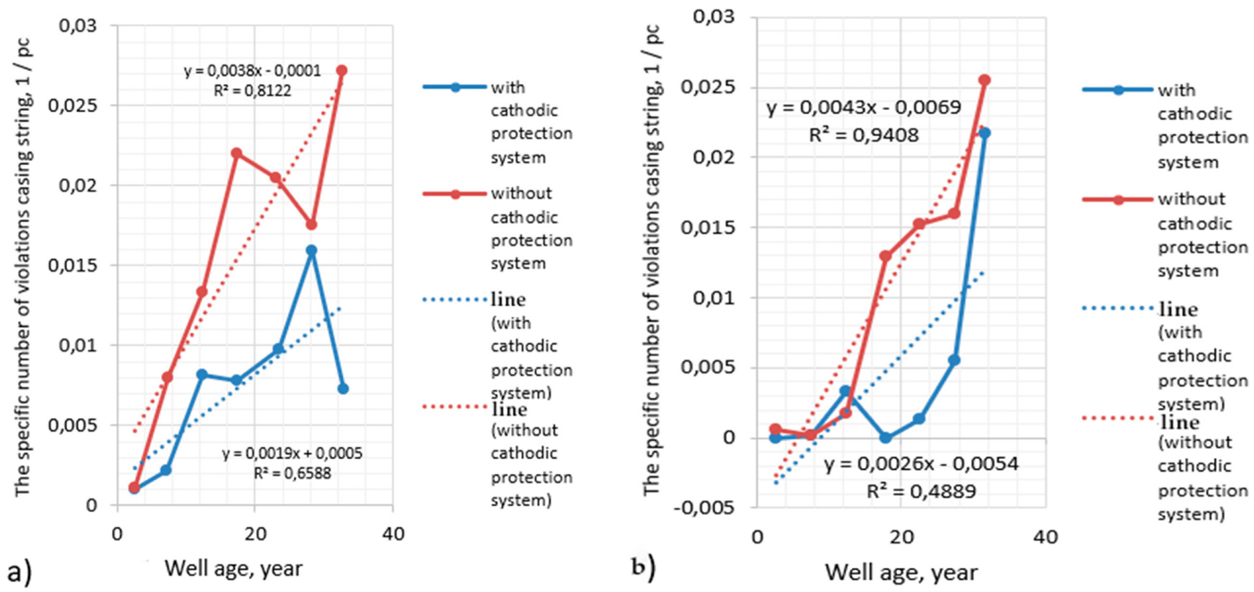


Fig. 2. Comparative dynamics of the specific frequency of disturbances in production (a) and injection (b) wells depending on the cathodic protection equipment for the period 2003-2015

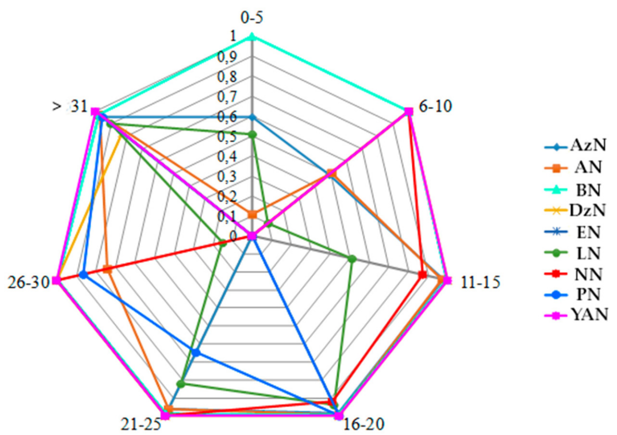


Fig. 3. The effectiveness of cathodic protection technology for producing wells of various age categories in the context of OGPD for the period 2003-2015

The reverse failure response can be estimated from the effectiveness of cathodic protection (degree of which characterizes the reduction in the corrosion rate of the cladding tubes as a result of cathodic protection). Mathematically, this is defined as the difference between the specific frequency of disturbances in casing strings of wells without $n(t)$ and with cathodic protection $n_3(t)$, referred to the specific frequency of disturbances without cathodic protection:

$$Z = \frac{n(t) - n_3(t)}{n(t)} \qquad (1)$$

The effectiveness values for individual OGPD reach 1, and its average value is in the range of 0.5 - 0.6 (Fig. 3). For injection wells, this indicator on average sludge composition is from 0.4 to 0.5.

The highest efficiency of cathodic protection is observed for production wells with lifetime of 11 to 25 years in separate oil and gas production units, as evidenced by the values of the reduction failure coefficient, defined as the ratio of the specific number of failures without cathodic protection to the specific number of failures with cathodic protection (Fig. 3). For injection wells, an indicator value of 4 to 8 is observed in OGPD AN, BN, AzN.

The reliability of facilities is best characterized by the probability of failure-free operation — the probability that no failure occurs within a given operating time (i.e., in a given time interval corresponding to the age of the well), mathematically determined by the ratio of the difference between the total number of wells of age N and the number of failure of wells n (t) age t to the total number of wells:

$$P(t) = \frac{N - n(t)}{N} \qquad (2)$$

The linear dependencies obtained from the mean values (excluding extreme points) show that the probability of failure-free operation is reduced to 0.9 for the old fund of both types of wells without cathodic protection (Fig. 4). When predicting this indicator for unprotected wells with an age of about 40 years, the value decreases by 0.1 and is about 0.8. At the same time, protected wells retain this probability up to 0.98 during the entire operational period.

In this case, the average probability of failure, i.e. the probability that within a given operating time (in a given time interval corresponding to the age of the well) there is at least one failure:

$$Q(t) = 1 - P(t) = \frac{n(t)}{N} \tag{3}$$

for unprotected wells is up to 0.15.

These data confirm the need for necessarily execution of cathodic protection technology with the set optimal parameters for improving the efficiency of the well and extend the life of trouble-free operation. One of the possible options for monitoring the effectiveness of wells from a corrosion point of view will be considered below by examples of facilities of PJSC «Tatneft» (Fig. 5).

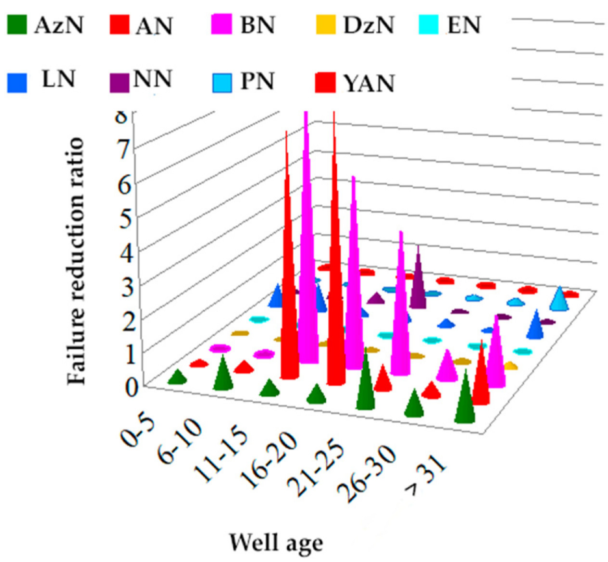


Fig. 4. Failure reduction coefficient for producing wells depending on their age for the period 2003-2015

2. Experimental Methods

To implement cathodic protection, iron-silicon electrodes of the brand ZHK-1500 were used. The electrodes contain 14-15% carbon, 3-5% chromium, and the rest iron. The length of the electrode was 1500 mm, with a diameter of 40 mm. They were lowered into a separately located well with a depth of 30 meters, 15 ZHK-1500 electrodes were used, and a clay solution was poured into the well from above.

Additionally, an anode cable was connected from the ZHK-1500 electrodes to the mouth of the casing located 30-40 meters from the anode grounding. The protective current was supplied from a PD-600 cathodic protection station with a power of 600 watts. The required protection current was 8-10 A.

Measurement of the potential was performed using a probe installed in the well casing. Contact with the casing was made using an electrical signal sent from the surface of the earth, which brought the probe contacts into full contact with the casing. The process of contacting the casing was carried out every 25 meters along the column.

Furthermore, the voltage drop between two contacts was measured by a voltmeter, and a curve of the voltage drop along the casing was plotted, with anodic areas clearly marked. Measurements were carried out with the cathodic protection station both on and off.

2.1 Methods for determining the optimal electrical parameters of cathodic protection

The main parameter of cathodic protection is the value of the protective current [11-15]. For casing constructions, the protective current is considered to be sufficient if the measurement results show that the electric current directed to the casing eliminated all the anode sections. There are a number of methods for determine the required cathodic protection current:

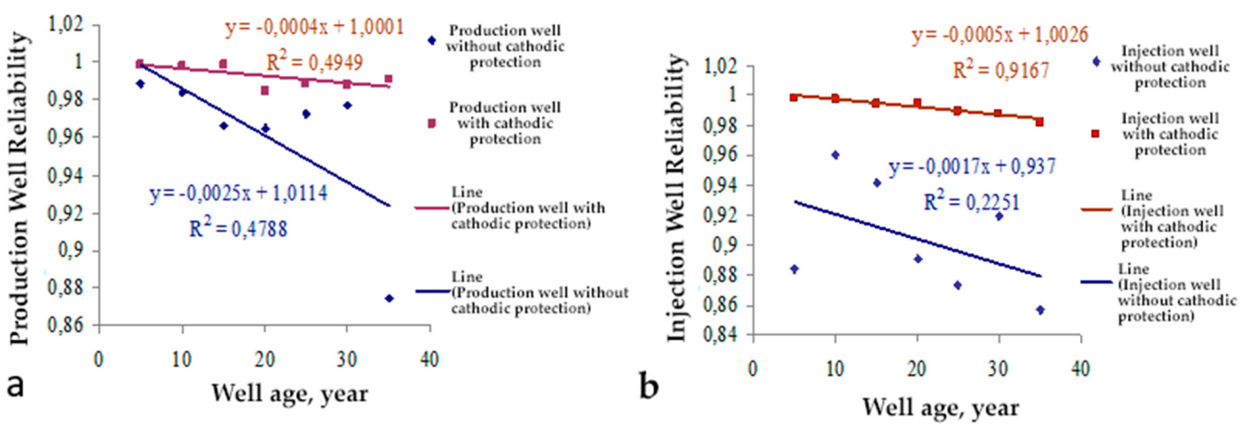


Fig. 5. The probability of failure of production and injection wells depending on their age and equipping with cathodic protection

- a method for determining the voltage drop profile on pacemaker;
- a method of polarization curves (electric logging);
- a method for calculating the potential shift in the wellbore and the resistance value in the well / soil system;
- a method for modeling cathodic protection of a well.

In particular, the method of for determining the voltage drop profile at the pacemaker is used, in the PJSC «Tatneft» and is based on the calculation of the distribution of the protection current density over the depth of the casing strings of oil wells.

The proposed consideration of our method of calculating the current density distribution over the depth of casing is based on the materials guidance document (GD) 153-39.0-803-13 «Instructions for electrochemical methods of protection of casing wells and underground pipelines from soil corrosion», which was developed and tested in PJSC «Tatneft». The difference of the proposed method is the fact that the change in the cross-sectional area of the metal and the change in the area of the outer surface of the column sections along its height are additionally taken into account.

The aim of the investigation was to identify and remove the anodic spots on operating column according to the improved method.

Before starting of the investigation, the casing string was pulled out of the borehole, the casing string was thoroughly cleaned from sediments, washed and passed with a template with of 100 mm diameter and of 10 m length. To obtain the profile of the voltage drop, the two-pin probe was lowered into the casing of the well on a seven-core logging cable using a geophysical elevator. The voltage drop between probe contact terminals was measured using a millivoltmeter (or microvoltmeter) with an input resistance of at least 1 M Ohm. The measurement of the voltage drop was made when the probe stopped its downward movement not less than 30 seconds after the probe stopped and the clamp made contact with a surface of the column.

When investigating from the wellhead to the conductor shoe (for a three-stage column) or the shoe of a technical column (for a four-stage column), measurements were taken every 7.5 m, then to the production casing shoe every 50 m.

The polarizing current of the cathodic protection during the investigation was 9, 7, 6, 0 A. The same current was set at the neighboring wells, which were less than 100 m away from the test string. During the determination of the steady-state (natural) potential, the current was switched off at all neighboring wells. At each of the listed current values, the column was polarized for 24 hours, and at a current of 0 A (cathode protection off), the column was depolarized for 10 days until a stable value of the natural potential of the column mouth was established.

According to the results of the study, the profile of the voltage drop between the contacts of the probe along the depth of the column was obtained. The values of the current flowing in the

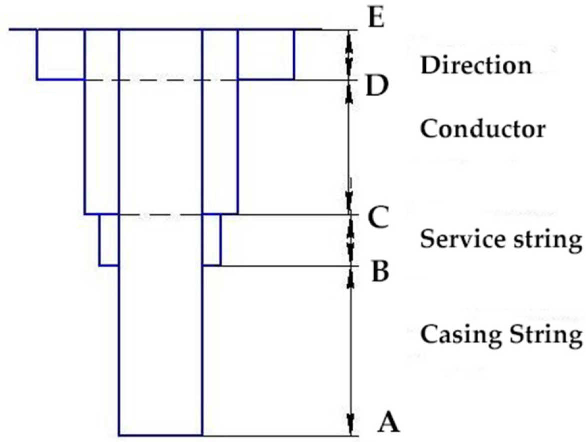


Fig. 6. Diagram of a four-stage casing string

section of the column between the two contacts of the probe were calculated taking into account the change in the cross section of the column in height, which accordingly leads to a change in the value of the resistance of the sections between the contacts of the probe (Fig. 6).

The protection of the casing against macro-galvanic corrosion was determined by eliminating the anode zones on the voltage drop curve. The current corresponding to the elimination of anode zones was taken as the minimum protective current.

The scientific novelty of the article lies in the fact that measurements of protective potential along the casing string were made for the first time with cathodic protection turned on. The minimum protective current value for the casing string was determined. Based on the measured voltage drop curve, the most vulnerable depths in terms of corrosion were identified, where aggressive layers affecting the outer surface of the casing string are located.

3. Results and discussion

3.1 The results of the proposed methodology trial

The distribution of the voltage drops between the probe contacts in depth by the example of the casing string of well 22505 OGPD «Bavlyneft» with the cathodic protection off (natural state of the string) and two protection currents of 6 and 12 A is shown in Fig. 7 and Table 1.

Analysis of experimental data on the distribution of the voltage drop over the depth of the casing has shown that abrupt changes occur at depths of 50, 100, 150, 250, 300, 350, and 850 m. The changes in the stress drop may be related to a change in the resistance of the casing. These may be related to a change in the resistance of the casing string in the area of observation or to the characteristics of the flow of current through the casing string.

When calculating the values of the current flowing through

Table 1. Technical characteristics of well casings

Well 22505 OGPD «Bavlyneft»	Height, m	Diameter, m	Wall thickness, m
Direction	32	0.324	0.0095
Conductor	274	0.245	0.0089
Production string	1757	0.146	0.0077
Design life, years	30		

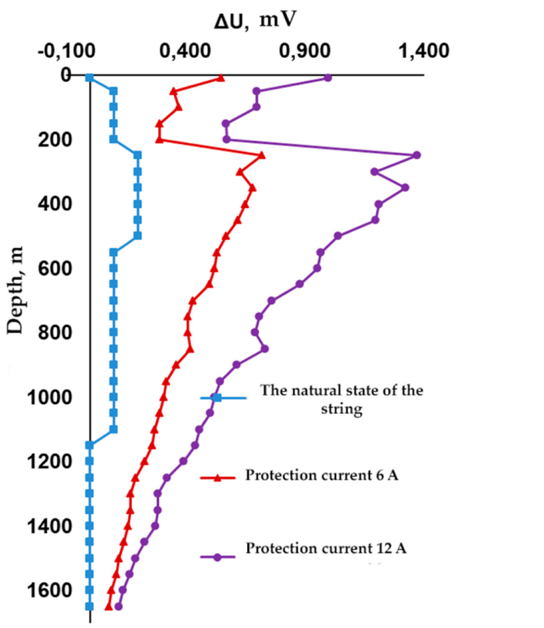


Fig. 7. Profile of the voltage drop between the contacts on the probe depth of the well casing 22505 OGPD «Bavlyneft»

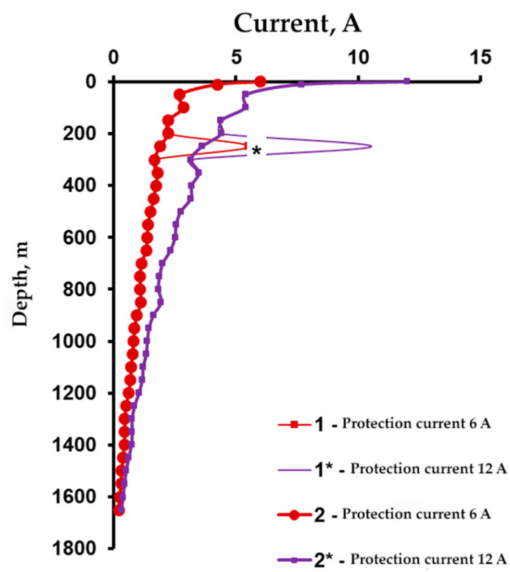


Fig. 8. Distribution of currents along the depth of the casing string of well 22505 OGPD «Bavlyneft» at a protection current of 6 and 12 A: 1 - calculation according to the geometric characteristics of the casing string; 2 - calculation taking into account the position of the metal contact between the sections

the corresponding sections of the casing string, it was taken into account that the casing string consists of three sections (production string, conductor, direction) that differ in cross-sectional area [16,17]. The distribution of currents along the length of the casing string is shown in Fig. 8.

The results of calculating the distribution of currents along the depth of the casing using its geometric characteristics (Fig. 8, curves 1 and 1 *) showed that at a depth of 250 m there is a sharp increase in current strength (5.53 A and 10.54 A at protective currents 6 and 12 A, respectively), followed by the same sharp decrease. A probable reason for this current increase is the mismatch of the beginning of the next section (conductor) with the position of the point of metal contact between the production casing and the conductor (centralizer position). Therefore, in the calculations of the current strength corresponding to a depth of 250 m, the resistance of the production string was used. Corrected dependences reflecting the change in current strength along the depth of the casing are shown by curves 2 and 2* (Fig. 8).

The observed decrease in the current flowing through the production string at a depth between 350 and 300 m is explained, in our opinion, by the appearance of stray current flowing from the production string to the conductor. At a depth of between 100 and 50 m, a similar decrease in current is observed, due to the flow of current from the conductor to the direction.

An analysis of the distribution of the density of the protective current of the cathodic protection along the depth of the casing (Fig. 9) indicates that the pacemaker is under the cathodic protection throughout the entire depth, with the exception of the anode sections in the depth range of 300-350 and 800-850 m. The anode current density for the first interval was 0.0057 and 0.014 A/m^2, for the second - 0.0011 and 0.0049 A/m^2 for protection currents of 6 and 12 A, respectively.

The obtained trends are preserved for a number of other wells. Below are the tax results for well 2161 of the OGPD «Bavlyneft».

The distribution of the voltage drops between the probe contacts along the depth of the casing with the cathodic protection switched off (natural state of the string) and the

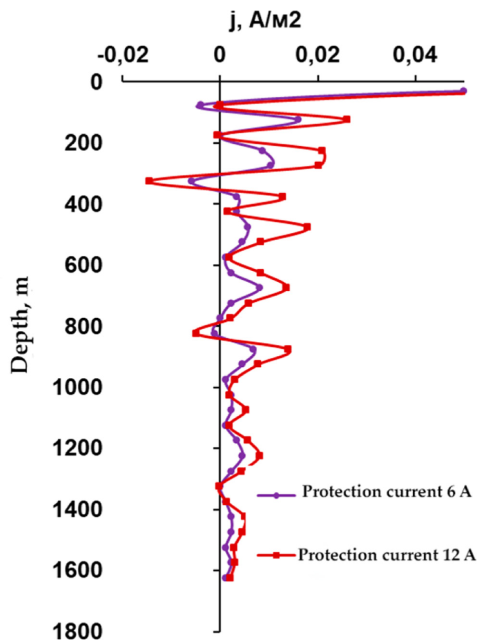


Fig. 9. Distribution of current densities along the length of the casing string of well 22505 OGPD «Bavlyneft» with a protection current of 6 and 12 A

protection current of 5 A is shown in Fig. 10. The distribution of currents along the length of the casing is shown in Fig. 11.

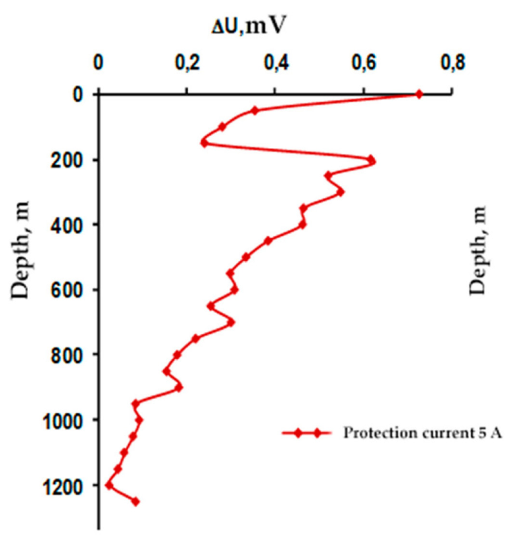
The results of calculating the distribution of currents along the depth of the casing using its geometrical characteristics (Fig. 11, curve 1) showed that at a depth of 200 m there is a sharp increase in the current strength of 4.9 A at a protection current of 5 A, followed by the same sharp decrease. A probable reason for this current increase is the mismatch of the beginning of the next section (conductor) with the position of the point of metal contact between the production casing and the conductor (centralizer position). For this reason, the resistance of the conveyor casing was used in the calculation of the current corresponding to a depth of 200 m. Corrected dependences reflecting the change in current strength along the depth of the casing are shown by curve 2 (Fig. 11).

The observed decrease in the current flowing through the production string at a depth of 300 m is explained, from our point of view, by the appearance of stray current flowing from the production string to the conductor.

An analysis of the results of the distribution of the protective current density along the depth of the casing, (Fig. 12), indicates that the production string throughout the entire depth is under

Table 2. The results for well 2161 of the OGPD «Bavlyneft»

Well 2161 OGPD «Bavlyneft»	Height, m	Diameter, m	Wall thickness m
Direction	50	0.324	0.0095
Conductor	203	0.245	0.0089
Production string	1272	0.146	0.0085
Design life, years	30		



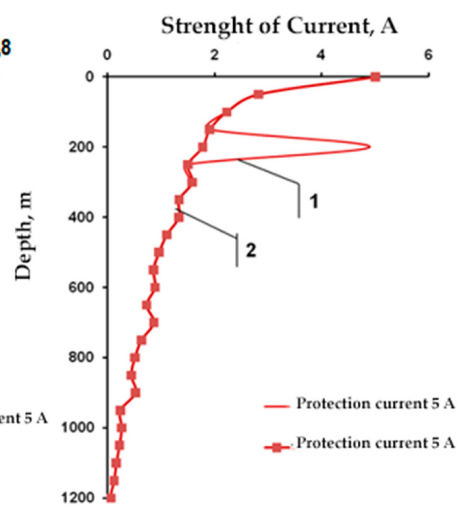


Fig. 10. The voltage drop between the contacts of the probe distribution of a well casing depth № 2161 OGPD «Bavlyneft» (left)
Fig. 11. Distribution of currents along the depth of the casing string of well 2161 OGDP «Bavlyneft» at a protection current of 5 A: 1 - calculation according to the geometric characteristics of the casing string; 2 - calculation taking into account the position of the metal contact between the sections (right)

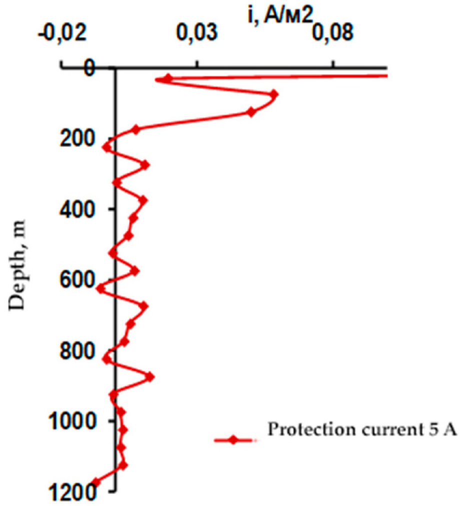


Fig. 12. Distribution of current densities along the length of the casing string of well 2161 of OGPD «Bavlyneft» with a protection current of 5 A

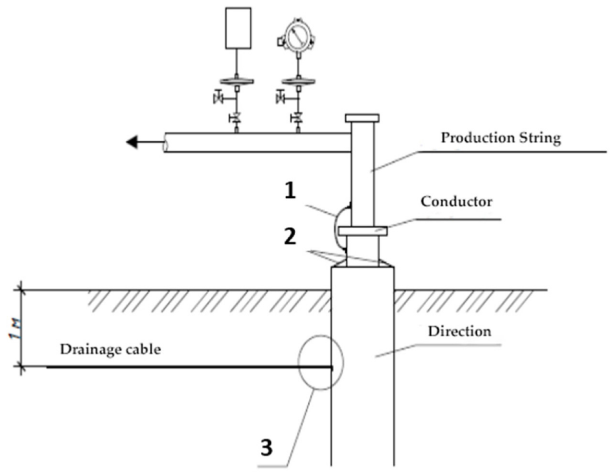


Fig. 13. Electrical connection diagram of the elements of the casing string: 1 - jumper «string – conductor»; 2 - jumper «direction – conductor»; 3 - connection point of the drainage cable

the cathodic protection, with the exception of the anode sections in the depth interval 200 - 250 m (the area of the conductor shoe), where bipolar effects, and current from the production string flows to the conductor. The appearance of anode zones in the depth intervals of 600 - 650, 800 - 850 m is probably associated with the appearance of corrosive macropairs.

3.2 The influence of the casing string connections on the distribution of the protection current along the depth of the borehole

The influence of the connection diagram of the elements of the casing string with the cathodic protection station on the distribution of the protection current density along the depth of the borehole was observed. Two variants of the connection diagram are proposed: in the first case there were no steel bridges between the elements of the column, and in the second case they took place (Fig. 13).

The research was carried out on the casing string of well 24173 of the OGPD «Leninogorskneft», which consists of four sections: direction, conductor, technical string and production string.

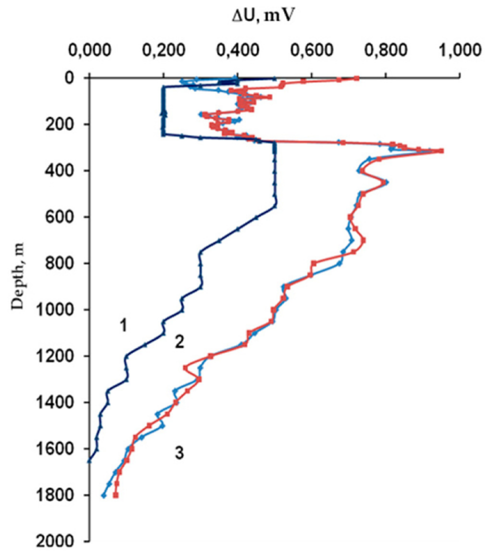


Fig. 14. Distribution of the voltage drop between the probe contacts along the depth of the casing: 1 - the natural state of the string, 2 - the elements of the string are connected by jumpers, 3 - the jumpers between the string elements are absent

Table 3. The results for well 24173 of the OGPD «Leninogorskneft»

Well 24173 OGPD «Leninogorskneft»	Height, m	Diameter, m	Wall thickness m
Direction	30	0.426	0.012
Conductor	90	0.320	0.0095
Technical string	300	0.245	0.0089
Production string	1870	0.168	0.0089
Design Life, year	30		

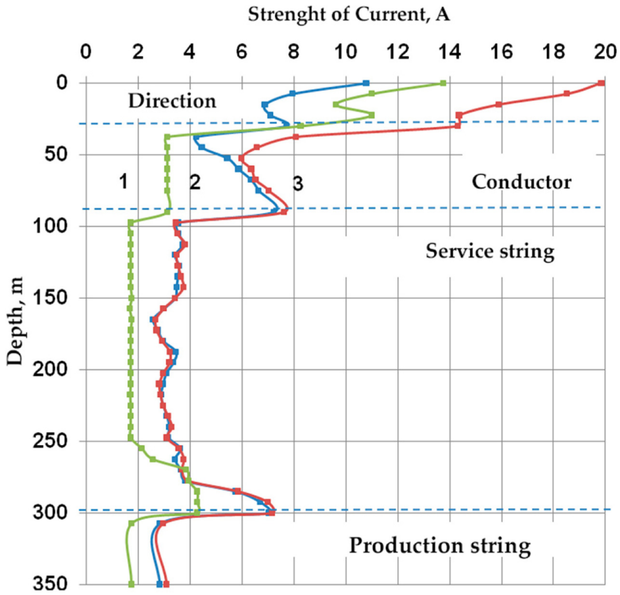


Fig. 15. Strength of currents along the depth of the casing: 1 - the natural state of the column; 2 - the elements of the column are connected by jumpers (protection current 6 A), 3 - the jumpers between the elements of the column are absent (current protection 6 A)

The voltage drop at the well casing was measured 30 seconds after the probe stopped: to a depth of 300 m every 7.5 m, and at great depths every 50 m.

The distribution of voltage drops between the probe contacts along the depth of the casing of the well with the cathodic protection switched off (the natural state of the casing in the absence of jumpers) and two different circuits for connecting the casing elements with cathodic protection is shown in Fig. 14.

The distribution of currents along the length of the casing to a depth of 350 m is shown in Fig. 14. The values of the currents in the area of 90-350 m for two options x of the connection scheme (Fig. 14, curves 2 and 3) practically coincide.

The distribution of the protection currents along the depth of the casing (Fig. 15, curves 2 and 3) shows that at a depth of 30, 90 and 300 m there is a sharp increase in current strength, the peak value of which exceeds the protection current of 6 A.

The reason for the jumps in the current values is the mismatch of the beginning of the next section of the column with the position of the point of metal contact (at a depth of 300 m between the production and technical columns; at a depth of 90 m between the technical column and the conductor; at a depth of 30 meters between the conductor and the direction). This leads to the fact that the calculation of the current strength, the value of the cross-sectional area is taken into account, taking into account the appearance of a new structural element, while there is no electrical contact between these elements at the considered depths.

The observed decrease in the strength of the current flowing through the production string at depths preceding the appearance of a new column element is explained by the appearance of a stray current flowing down from one element of the column to another.

At depths up to 90 m, the connection pattern of the elements of the casing string affects the distribution of the protection current along the depth of the well (Fig. 15 curves 2 and 3), while the presence of jumpers between the elements of the string leads to the fact that most of the current flows through the external elements of the casing string. This conclusion was made on the basis that the calculated values of the current flowing through the production string, in the case of bridges between the elements of the column (Fig. 15, curve 2) are significantly lower than the calculated values of the current in the absence of a bridge to (Fig. 15, curve 3).

In the case under consideration, the analysis of the distribution of the protection current along the depth of the column is complicated by the fact that a stray current flows through the column from the neighboring cathodic systems through the column, which is comparable in magnitude to the protection current. At the wellhead, the protection current in the absence of jumpers between the structural elements is 20 A (Fig. 15 curve 3), of which 14 A is due to stray current (Fig. 15 curve 1).

4. Conclusion

The paper concludes with the following findings:

Firstly, a technique was developed to evaluate voltage drop profiles along the casing, accounting for the cross-sectional area of the casing components, both with and without cathode protection switched on.

Secondly, the developed methodology was applied to estimate the distribution of cathodic protection current density along the height of the casing in wells of PJSC «Tatneft». The results show the probability of bipolar effects in the conductor shoe area, resulting in an increase in local anodic dissolution of the metal with increasing protection current.

Finally, the study investigated the influence of schematic elements of the casing string on current distribution in the example borehole depth No. 24173 of PJSC «Tatneft» OGPD «Leninogorskneft». It was found that the presence of external jumpers between casing elements results in the majority of the current flowing through the external structural elements.

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